Convectively coupled Kelvin waves in aquachannel simulations: 2. Life cycle and dynamical-convective coupling

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Abstract This second part of a two-part study uses Weather Research and Forecasting simulations with aquachannel and aquapatch domains to investigate the time evolution of convectively coupled Kelvin waves (CCKWs). Power spectra, filtering, and compositing are combined with object-tracking methods to assess the structure and phase speed propagation of CCKWs during their strengthening, mature, and decaying phases. In this regard, we introduce an innovative approach to more closely investigate the wave (Kelvin) versus entity (super cloud cluster or “SCC”) dualism. In general, the composite CCKW structures represent a dynamical response to the organized convective activity. However, pressure and thermodynamic fields in the boundary layer behave differently. Further analysis of the time evolution of pressure and low-level moist static energy finds that these fields propagate eastward as a “moist” Kelvin wave (MKW), faster than the envelope of organized convection or SCC. When the separation is sufficiently large the SCC dissipates, and a new SCC generates to the east, in the region of strongest negative pressure perturbations. We revisit the concept itself of the “coupling” between convection and dynamics, and we also propose a conceptual model for CCKWs, with a clear distinction between the SCC and the MKW components.

1. Introduction

The close correspondence between Matsuno’s [1966] modes and the outgoing longwave radiation (OLR) spectral peaks associated with the Intertropical Convergence Zone (ITCZ) variability, as seen on a wave number-frequency diagram, was found by Takayabu [1994] and Wheeler and Kiladis [1999, hereinafter WK99], and since then the concept of convectively coupled equatorial waves (CCEWs) has been widely used. In particular, the term convectively coupled Kelvin waves (CCKWs) applies to the overlap between Matsuno’s Kelvin (k = –1) curves and the spectral power ridge associated with observed “superclusters” or “super cloud clusters” (SCCs) [Nakazawa, 1988; Takayabu and Murakami, 1991], despite the theory’s neglect of basic state flow and nonlinearities from coupling with convection.

Theoretical Kelvin waves have a speed of \( c_k = \sqrt{gh_p} \) (where \( h_p \) is an equivalent depth), and they propagate faster than both observed and simulated CCKWs, with speeds at about 10–22 m/s. In turn, observed Kelvin waves in the lower stratosphere have phase speeds closer to those of theoretical Kelvin waves: about 30–40 m/s [Kiladis et al., 2009].

The reasons for this discrepancy have been extensively studied, and today there are two widely accepted theories. The first corresponds to the effect of convection on the static stability felt by waves [Neelin and Held, 1987]: within the envelope of the CCKW, upward motion generates parcel saturation, condensation, and latent heat release, which results in an overall increase in buoyancy and a reduction of static stability. A straightforward way to consider the direct relation between propagation speed and vertical stability is to express the equivalent depth in terms of vertical stability for the dry atmosphere: under some assumptions [Kiladis et al., 2009], \( h_p = N^2/\bar{\omega} \), where \( \bar{\omega} \) is a constant and \( N \) is the Brunt-Vaisala frequency; hence, it yields \( c_k = \sqrt{N^3/\bar{\omega}} \).

Many theories have been proposed for explaining the dynamics of the CCKWs, but none yet have become universally accepted. Some of the more widely accepted ideas are wave-conditional instability of the second kind (wave-CISK) [Hayashi, 1970; Lindzen, 1974], wind-induced surface heat exchange (WISHE) or evaporation-wind feedback [Neelin et al., 1987; Emanuel, 1987], and the stratiform-instability/vertical-mode theory [Mapes, 2000; Khoury and Majda, 2006; Kuang, 2008]. This last theory also provides an alternative explanation for the slower propagation of CCKWs compared to their dry counterparts.
An analysis and comparison of these three theories with observed CCKWs was performed by Straub and Kiladis [2003b, hereinafter SK03]. They argued that not only are these theories not mutually exclusive but also the dynamics associated with observed CCKWs have elements from each (see the conceptual models of CCKW in their Figures 1 and 6). Nevertheless, a shortcoming of all these studies is that the proposed dynamics are difficult, if not impossible, to apply across the entire life cycle of the CCKWs. While such positive feedback mechanisms can be used for explaining the strengthening and mature stages of CCKWs, they cannot satisfy the weakening and dissipation phases. In other words, what processes break the wave-CISK, WISHE, and/or stratiform instability feedback, leading to wave decay? And what mechanisms generate a new CCKW prior to its strengthening?

The initiation of observed CCKWs has been attributed to certain regions on the globe, connected in turn with midlatitude forcing [Straub and Kiladis, 2003a; Liebmann et al., 2009]. However, Earth’s horizontal inhomogeneities cannot be the only drivers of CCKWs since they also appear in simulations without topographic features, such as idealized zonally homogeneous and meridionally symmetric planets. Furthermore, CCEWs are generated in extremely simplified two-dimensional (zonal-vertical) models, even without rotation [Numaguti and Hayashi, 2000].

Two-dimensional cloud-resolving models explicitly represent cloud-scale motions and their diabatic effects, overcoming the well-known uncertainties of cumulus schemes. The requirement of computationally expensive, <10 km grid spacing is compensated by the elimination of the meridional coordinate, and hence, they provide a useful tool for studying tropical modes of convection, as used by Oouchi [1999]; Peng et al. [2001]; Grabowski and Moncrieff [2001]; Liu and Moncrieff [2004]; and more recently, Tulich et al. [2007] and Tulich and Mapes [2008]. The major finding of these works was the hierarchy (in terms of different spatial and temporal scales) of both leftward and rightward propagating waves, with great resemblance to more realistic CCEWs, as seen by Hovmoller diagrams and power spectra. One of these tropical waves corresponds to the Kelvin mode, although in absence of planetary rotation effects the waves are referred to as convectively coupled gravity waves (CCGWs). Moreover, such simplified models allow a more straightforward assessment of theoretical concepts such as wave-CISK, WISHE, and stratiform instability.

Nasuno et al. [2007] studied tropical variability in a computationally expensive cloud-permitting aquaplanet configuration of the NICAM model [Satoh et al., 2005]. The multiscale organization of convection was analyzed, in terms of the two-way interaction of CCKWs (synoptic scale) with mesoscale and convective-scale features. The temporal evolution of small-scale entities embedded in the CCKWs was linked to the structure and propagation of the waves. Nasuno et al. [2008] continued the work with the same set of simulations but focusing on large-scale properties of CCKWs. The disadvantage of their approach is the short length of the experiments (90, 40, and 10 days for resolutions of 14, 7, and 3.5 km, respectively): their data set favored the analysis of strengthening, mature, and decay stages of relatively small convective elements but not the larger and longer-lived SCCs.

Some of the aforementioned aspects of CCKW dynamics, and others, are still part of ongoing research, such as the relationship between CCKWs and the ITCZ [Sobel and Neelin, 2006; Peters et al., 2008; Bellon and Sobel, 2010; Dias and Pauluis, 2011]. Also, the coupling mechanisms between convection and dynamics can vary among different CCEWs or among different time and space scales of a given type of wave, as analyzed by Yasunaga and Mapes [2012a, 2012b] with observations and reanalysis.

Nolan et al. [2016] analyzed the mean ITCZ as well as tropical and midlatitude circulations produced by aquachannel and aquapatch simulations and compared them to results from aquaplanet simulations. Blanco et al. [2016] presented a sensitivity analysis of CCKWs to model domain and resolution using a similar modeling framework. In this study, the set of simulations of Part I is used again for the investigation of structures and propagation speeds for the early, mature, and decaying stages of CCKWs.

This paper is organized as follows: details about the method employed for our analysis are given in the next section, and their results are shown in sections 3 (propagation speeds of each stage) and 4 (composited structure of each stage). The analysis of the interaction between the super cloud clusters (SCCs) and the moist Kelvin wave (hereinafter MKW) is treated in section 5. Finally, section 6 presents the summary and conclusions of this study.
2. Data and Methodology

We use the same set of six Weather Research and Forecasting (WRF) simulations as in Part I, which arise from a combination of three domain configurations: the aquachannel, the high-resolution (HR) aquapatch, and the nested aquapatch, and two sea surface temperature (SST) profiles: the observed (OBS) and control (CTRL) functions from the Aqua-Planet Experiment (APE) [Blackburn and Hoskins, 2013]. The data for the analysis spans 1 year, except 6 months for the nested aquapatch cases, and all model outputs were saved every 6 h. More details about the model and the simulations can be found in Part I. Also, the same methodologies are applied here for the computation of normalized power spectra, CCKW speeds, and composites. A new feature is the application of a subjective method to characterize and analyze different stages of the CCKW life cycle, which is explained in detail below.

A “subdivision” approach has been recently presented by Yasunaga and Mapes [2014] for the analysis of faster versus slower components of observed CCEW. They started by identifying contiguous regions of faster and slower phase speeds on a normalized power spectrum, and the subsequent filtering and compositing were applied to the fast and slow components separately. Instead, for our study, the subdivision is applied in physical rather than spectral space: we first identify, select, and “break” CCKWs into three stages by examining Hovmoller diagrams of OLR intensity. For each of these three life cycle categories we compare propagation speeds and structures, without knowing a priori whether any significant differences will be found.

We initially evaluated the possibility of applying the CCKW tracking algorithm method described in Part I with some modifications. A straightforward approach would be to assign each time level into one of the three stage categories, for the entire length of the simulation. However, we wish to exclude weak or nonexistent CCKW events (for instance, at a given time in which a former CCKW has already dissipated but a new one has not yet formed). Even neglecting such cases, two CCKWs at different stages of their life cycle could coexist in time. Since such complications occurred frequently, we took a different approach to identify more accurately each of the stages.

A subjective selection process was applied, which is schematically depicted in Figure 1, and also compared with the algorithm used in Part I. The method consists of a direct visual inspection of OLR phase troughs on a CCKW-filtered Hovmoller diagram (averaged in the 15°S to 15°N band). Only well-defined, “ideal” CCKW stages are selected. We eliminate very weak CCKWs, slow-evolving stages (i.e., a CCKW that takes too long to either strengthen or decay), and stages where there is a splitting into (merging of) two waves with different phase speeds during the weakening (strengthening) phase. We emphasize “ideal stages” rather than “ideal waves,” meaning that for a given CCKW, one or two stages can be excluded from the analysis while keeping the remaining two or one.

The rest of the process is applied subjectively as well. Once an ideal CCKW stage has been selected, we simply draw straight line segments across a 60 h period (10 time intervals), as depicted in Figure 1b. Sometimes shorter segments of 48 h (eight time intervals) are drawn to capture short-lived events. Each dot in Figure 1b represents the CCKW axis at a given time, and the slope of the line segment is its propagation speed for that stage. Since each ideal stage is treated independently of the others, a single CCKW for which its three stages were included in the analysis could have three slightly different propagation speeds. This allows for the analysis of different mean propagation speeds at different phases of the CCKW life cycle.

The number of selected cases for each of the 18 sets (3 stages × 6 simulations) is shown in the top half of Table 1. The maximum number of cases is 15 for the mature stage of the OBS aquachannel simulation, while the minimum is 5 for both the early and decay stages of the OBS nested aquapatch case, although this is partly due to the shorter integration period (half a year).

The total number of cases multiplied by the total number of output times (in 6 h intervals) used for each case gives the size of the sample (which is also indicated in the heading of each of the composites in Figures 3–7.)

It is important to point out that in our sample described above there is no overlap in time for any of the selected stages. That is, if there were two CCKWs of similar amplitude coexisting in time, the pair of events was removed. Typically, the superposition occurred for a decaying wave and a strengthening one to the east.
The reason of such procedure is to prevent wave number 2 signals when analyzing the mean structure of a CCKW (section 3.2).

3. Early, Mature, and Decay Stages of CCKWs

3.1. Phase Speeds and Local Zonal Flows

Table 2 shows the mean phase speed for each set. The mean velocity value obtained from the objective algorithm (see Part I) for the entire integration period is smaller than the computed speed for any of the stages. In other words, the “ideal CCKW” propagates slightly faster than the “mean CCKW,” and this is simply a correction to the objective algorithm calculation, which computes speeds for every time step (unless there is a jump

(see example in Figure 1). The reason of such procedure is to prevent wave number 2 signals when analyzing the mean structure of a CCKW (section 3.2).

Table 1. Number of CCKW Cases Selected for Each of the 18 Sets, Organized by Stage and Simulation

|                      | Aquachannel | HR Aquapatch | Nested Aquapatch |
|----------------------|-------------|--------------|------------------|
|                      | CTRL   | OBS | CTRL | OBS | CTRL | OBS |
| Stage early          | 10     | 11  | 11   | 12  | 11   | 5   |
| Stage mature         | 14     | 15  | 9    | 11  | 8    | 6   |
| Stage decay          | 11     | 8   | 10   | 14  | 11   | 5   |
| Total                | 35     | 34  | 30   | 37  | 30   | 16  |
| Total in $\Delta T_p$| 350   | 340 | 260  | 370 | 240  | 128 |
| Simulation in $\Delta T_p$| 1464  | 1440| 1440 | 1440| 720  | 720  |
| $\Delta T_p$ ratio (%)| 23.90 | 23.61| 18.06| 25.69| 33.33| 17.78 |
from one wave to another) regardless of the wave intensity. In relative terms, the increase in speed ranges from 2.8% for the OBS aquachannel case to 16.0% for the OBS HR aquapatch.

Interestingly, the phase speed at the dissipation stage is slightly greater than for the other two stages. The difference ranges from 0.06 m/s to 1.98 m/s, and the mean increase over the 12 deviations is 1.06 m/s (6.77% faster). Comparing decay versus mature stages, these results could be explained by the static stability theory for reduction of CCKW speed described in the introduction: there is less moisture and precipitation for the weakening wave compared to those at its peak intensity, resulting in a weaker coupling between dynamics and convection, which results in a faster motion. But on the other hand, such an argument could not be used to explain the difference of phase speeds between decay and strengthening stages, provided that they both have similar convective development.

To address a possible connection between dynamical processes and these speed differences, we constructed the mean equatorial zonal flow for each of the stages. Figure 2 depicts the vertical profiles for the CTRL and OBS aquachannel simulations. There are no significant differences when considering zonal means for the entire domain ([U]), dotted curves). The nearly identical [U] values for the three stages mean that domain-scale flow varies little with CCKW activity. Subsets of the equatorial zonal wind are also shown in two other longitude segments: at the CCKW axis ([U]CCKW, solid curves) and as a zonal mean but restricted to a 4000 km width containing the axis ([U]CCKW, dashed curves). A clear and interesting feature arises in the zonal flow within the CCKW as it evolves: the local equatorial flow in the troposphere changes progressively from a positively to a negatively sheared structure. In low levels, easterlies become westerlies; between 7 and 13 km, the opposite takes place. This transition occurs between the early and mature stages.

| Table 2. Mean Propagation Speed (in m/s) of CCKWs at Each of the Stages for Different Simulations |
|-------------------------------------------------------------|
| Aquachannel HR Aquapatch Nested Aquapatch |
| Algorithm   | CTRL  | OBS  | CTRL  | OBS  | CTRL  | OBS  |
| Stage early | 19.11 | 16.58 | 15.32 | 11.12 | 17.57 | 12.53 |
| Stage mature | 20.70 | 16.60 | 16.85 | 12.87 | 20.10 | 13.43 |
| Stage decay | 19.78 | 16.91 | 16.53 | 12.31 | 19.33 | 14.29 |
| Mean over three stages | 20.41 | 17.05 | 17.18 | 12.90 | 20.05 | 14.38 |

![Figure 2. Zonal wind vertical profiles (m/s) at the equator for early (red), mature (blue), and decay (red) stages and for zonal mean (light dotted lines), zonal mean in a 4000 km width around the CCKW axis (dashed lines), and at the CCKW axis (heavy lines). (a) CTRL aquachannel and (b) OBS aquachannel.](image)
stages, and the mature structure is maintained until wave decay. The shear above the tropopause has the opposite sign as below and is also greatly affected in the early to mature transition. Similar results were found in the four remaining simulations (not shown).

We subsequently analyzed the possibility of a connection between the local low-level flow within a CCKW and its phase speed: at the early stage, the CCKW propagates slightly slower than at the decay stage, and it is characterized by more low-level westerly/less easterly flows than at the decay stage. A low-level vertical integral was computed between 1000 and 700 hPa for both local flows, $\langle U_{CCKW} \rangle$ and $\langle U_{CCKW} \rangle$, and these were compared with the CCKW phase speeds for the six simulations, and for the three stages of the life cycle.

Figure 3. Perturbation (total—zonal mean) composites of OLR for the (a) entire simulation (“all-time” composite) and for the (b) early, (c) mature, and (d) decay stages of the CCKW life cycle, for the OBS aquachannel simulation. The profile of the zonal mean is plotted on the left side.
but no clear correlation pattern were found (not shown). The conclusion is that along the CCKW evolution, changes in local zonal flow are much more significant than changes in propagation speeds.

### 3.2. Spatial Structures

Figures 3–7 show the composited structure of the different stages along the CCKW life cycle for OLR, zonal wind, pressure, and moist static energy (mse) of the OBS aquachannel simulation (very similar results were obtained for the CTRL case; furthermore, we do not analyze composites for the aquapatch simulations since in Part I we showed that there is a partial distortion of the CCKW signal). As in Part I, the zonal mean was subtracted to the field to enhance the CCKW signal, but it is still depicted on the left section of each plot. For each case, four plots are shown corresponding to the “all-time” composite (computed using the objective
algorithm throughout the entire simulation, as in Part I), followed by the composites for strengthening, mature, and dissipating stages, respectively. Unlike Part I, we focus here only on the variables that show significant differences among the stages’ composites and/or the all-time composite.

Overall, the extreme values of the perturbations for the mature stage are typically around 80–100% in excess of those in the full composites (even over 200%, 3 times as large, for vertical velocity at 850 mb in some simulations; not shown). This general pattern is not surprising since the averaging in the all-time composites involves periods of weak or no CCKW activity. For early and decaying stages, the factor increase is mostly in the range of 1.6–1.9, although it was found for surface pressure and mse at 200 mb in some simulations that the strongest signal can occur either for the early or decaying stages rather than the mature stage.

Figure 5. Perturbation composites of zonal wind at the equator for the (a) entire simulation and for the (b) early, (c) mature, and (d) decay stages of the CCKW life cycle, for the OBS aquachannel simulation.
OLR (Figure 3) is of particular interest since the subjective selection of CCKW stages was performed using OLR Hovmoller diagrams. Besides the well-defined region of convection at the middle of the domain, negative perturbations also appear westward of the CCKW axis in the early and mature stages, at $x \approx 1.25 \times 10^4$ km. This is associated with coexisting CCKWs, despite our mostly successful screening step to minimize the “wave number 2 effect” as much as possible.

A pair of negative OLR anomalies is located in midlatitudes, about 5000 km ahead of the CCKW axis, and with a diameter of about 1000 km. It appears in the decay stage (Figure 3d) and to a lesser degree, the other two stages and the all-time composite. These lobules are associated with surface vortices at the same location, as depicted by the perturbation wind vectors overlapped on the OLR plots, and are also associated with anomalies in $q_{\text{total}}$ at 500 mb, $w$ at 850 mb, relative humidity at 500 mb, and divergence at 200 mb (not shown).

**Figure 6.** Perturbation composites of pressure at the equator for the (a) entire simulation and for the (b) early, (c) mature, and (d) decay stages of the CCKW life cycle, for the OBS aquachannel simulation.
These midlatitude anomalies seen in those variables, in particular for the decay stage, were often not visible in the all-time composites, due to the much larger period of time over which the average was made, masking the effect of individual synoptic-scale features. In fact, these results are in agreement with the composites obtained by Nasuno et al. [2008]: the CCKW structures diagnosed from a 30 day period of an aquaplanet simulation showed rotational flow patterns prominent from 15° to 30° in both hemispheres and for both high and low levels (their Figures 4c and 4d).

The zonal wind field presents a remarkable feature at the strengthening phase (Figures 4 and 5): the high-level core of negative anomalies is west of the CCKW axis by about 5000–7000 km, and also, it is slightly weaker (about −11 m/s versus −15 m/s for the other two stages). This delay in the position of the approximately 6 km deep core of easterly anomalies is due to a late response (~2–3 days) of the dynamics in high

![Figure 7. Perturbation composites of $mse$ at the equator for the (a) entire simulation and for the (b) early, (c) mature, and (d) decay stages of the CCKW life cycle, for the OBS aquachannel simulation.](image-url)
levels to convection associated to the CCKW (consistent with the changes of the local zonal wind profiles in Figure 2). However, there is no such effect for the upper level divergence (not shown; but discernable with wind vectors in Figures 4 and 5): the core of divergence is collocated with the CCKW axis, and it is mainly produced by the $v$ component. Other thermodynamic variables like $\theta$ (not shown) or mse are also well correlated in middle and upper levels with divergence and OLR.

Figure 6 shows the vertical structure of pressure anomaly at the equator. The first baroclinic mode is dominant, but the structure varies depending on the CCKW stage: among Figures 6a–6d, there are large variations in location and spread of the positive and negative anomaly regions and also the location of peaks within it. The reason for such behavior is that pressure propagates with a different speed than the convection, as will be further explained in the next section.

A sense of fast features passing through the CCKW from west to east is also evident in mse. The vertical cross section at the equator (Figure 7) shows that for middle and upper levels the mse anomalies have nearly the same structure in the four plots. Nevertheless, there is a clear evolution in the boundary layer, characterized by a widening of the positive anomaly region. Evidently, the mse wave in low levels propagates with a speed similar to that of pressure and faster than the OLR wave used to generate the composites. Such patterns were also found for $d_{\text{total}}$ (water vapor and total cloud condensate) and temperature (not shown).

4. Coupling of Convection and Dynamics

4.1. SCCs and Pressure Wave Speeds

In the study of tropical variability, surface pressure (PSFC) has received little attention compared to OLR or precipitation, although it was the analysis of PSFC time series that led to the discovery of the Madden-Julian oscillation (MJO) [Madden and Julian, 1971, 1972]. While the convective signals of the MJO normally vanish in the eastern Pacific, its signals in wind and PSFC continue to propagate farther east as free waves at much higher speeds of about 30–35 m/s [Zhang, 2005].

More detailed analyses of PSFC were carried out by Milliff and Madden [1996] and more recently, Kiranmayi and Bhat [2009]. However, such studies are focused on the observed tropical variability (in particular, the MJO), which can complicate the understanding of the underlying dynamics. The simple 2.5-layer model on a beta-plane aquaplanet of Wang and Li [1994] produced, after the adjustment following the initial perturbation, three distinct waves (their Figures 6 and 7): eastward propagating SCCs ($c \sim 20$ m/s), low-level pressure perturbations associated with a Kelvin mode ($c \sim 50$ m/s), and also a westward moving Rossby mode ($c \sim -17$ m/s).

At this point, it is important to establish a distinction in the CCKW/SCC terminology. The composites obtained from both the objective (algorithm) and subjective (selection of stages) approaches have used filtered OLR as the tracking variable. Therefore, those composite fields and the OLR phase speed values strictly correspond to SCCs, as defined by Nakazawa [1988]: envelopes of enhanced convection/precipitation propagating eastward along the tropics. The reason for such distinction will be understood later.

We investigated the phase speeds of PSFC and SCC waves in our simulations and their connection with structure and dynamics. We applied the algorithm used for the all-time composites (as in Part I) but now replacing minimum OLR by minimum PSFC as a wave tracker. In addition, three other variables were tested: minimum divergence at 850 mb (DIV850), maximum $q_{\text{total}}$ at 500 mb (Q500), and minimum zonal wind at 200 mb (U200).

Figures 8a and 8b show the propagation of the axis of the strongest waves for the five trackers, overlapped onto a single longitude-time diagram. Both plots, which represent half of the simulation period of the OBS aquachannel simulation, provide clear examples of the faster propagation of the wave when the tracking variable is PSFC, as indicated by pink ellipses. Sometimes the PSFC speed does not differ much from OLR, but in these cases it is always found that the PSFC wave leads the OLR wave (and the other waves as well). As anticipated in the previous section, this is the reason why composites of pressure with OLR as a tracker (Figure 6) are so sensitive to the averaging period.

Diagrams for the CTRL aquachannel simulation are also shown (Figures 8c and 8d). Two cases characterized by the late response of the zonal wind to the convective activity are highlighted by red ellipses. In these examples, the U200 algorithm identifies the strongest wave about 3 days later than the other trackers; when
Figure 8. Hovmoller diagrams of the CCKW axis evolution, using different variables as trackers. OBS aquachannel simulation for days (a) 240–300 and (b) 300–360. CTRL aquachannel simulation for days (c) 180–240 and (d) 300–360.
it does, the wave axis appears at the same location as the other axes. This represents another way to see the late upper level wind response, as shown before in the composites of Figures 4 and 5 and also in the vertical profiles of Figure 2.

To better assess phase speed propagation for the entire simulation period, for all trackers and simulations, the mean phase speeds were computed and results are shown in Table 3. The PSFC wave moves significantly faster than the OLR wave, by about 3 m/s. On the other extreme, the Q500 wave is the slowest, with a mean speed of 11.59 m/s, 4 m/s less with respect to the speed of the OLR wave. DIV850 is the tracking variable with the smallest discrepancy against OLR.

Different algorithms do not necessarily follow the same wave: this is due to differences in the time at which each of the variables reaches its peak (or trough) and to differences in relative strengths if more than one wave is present. The fact that different algorithms might follow different waves means that the algorithms are independent from one another. Hence, it is of interest to analyze relative east-west displacements in the peak of a given variable in the vicinity of the OLR trough. This requires an additional constraint: the algorithm is set to track the three most intense crests/troughs at a time for a given variable, and the one closest to the OLR trough is selected from these (either absolute or secondary maxima). The “control” tracking algorithm is for OLR, and therefore, it remains unchanged. The goal of this approach is to assess the positive or negative lag for each of the variables versus OLR.

Results of this OLR-centric tracking procedure are depicted in Figure 9, in which distributions of these zonal displacements are quantified for both aquachannel simulations. A positive lag for each tracker with respect to OLR indicates that the ridge/trough for that variable is ahead (eastward) of the OLR minimum. The generally small lag between OLR, DIV850, and Q500 indicates that these three variables are highly correlated with the SCC life cycle.

The most significant displacements are for PSFC, followed by U200. Note that neither the PSFC biases are exclusively eastward nor the U200 biases exclusively westward. Again, this result explains the strong sensitivity of PSFC composites obtained with OLR as a tracker to different averaging periods. Therefore, the

| Table 3. Mean Propagation Speed (in m/s) of CCKWs for Different Trackers |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                | Aquachannel                    | HR Aquapatch                    | Nested Aquapatch                |
|                                | CTRL  | OBS | CTRL  | OBS | CTRL  | OBS |
| OLR                            | 19.11 | 16.58 | 15.32 | 11.12 | 17.57 | 12.53 |
| Q$_{\text{total}}$ 500 mb      | 14.93 | 13.74 | 10.75 | 9.40  | 10.94 | 9.76  |
| DIV 850 mb                     | 19.83 | 17.33 | 12.88 | 12.11 | 16.64 | 13.93 |
| U 200 mb                       | 21.03 | 17.14 | 17.31 | 10.12 | 18.98 | 14.23 |
| PSFC                           | 22.91 | 19.68 | 17.25 | 13.46 | 19.47 | 17.11 |

Figure 9. Box plots with distribution of zonal lag of each variable versus OLR for the (left) CTRL and (right) OBS aquachannel simulations. The edges on the box correspond to the 25th and 75th percentiles; median is represented by the central line, and the mean value is represented by a circle. The red crosses represent the values beyond 2.7 standard deviations.
composite for the entire simulation period (Figure 6a) could be representative of the average pressure structure to a first-order approximation but not for the composites for each of the stages (if PFSCs were used as the tracker of SCCs, the composited structure of OLR and other well-correlated variables would show a much broader pattern in the zonal direction and also strong sensitivities to short averaging periods; in fact, this was found in the preliminary work of Blanco et al. [2014]). However, despite the biases for upper level wind in Figure 9, the composites shown in Figures 4b–4d and 5b–5d are robust and representative of each of the stages because, though lagging behind, U200 moves with similar speed as OLR.

Figure 9 also shows that for the Q500 tracking algorithm, there is a strong sensitivity when constraining to OLR. When the condition to follow the same wave than OLR is imposed, the mean and median of the lag Q500-OLR is nearly 0. In contrast, when such restrictions are removed, Q500 propagates much slower than OLR (Table 3). We will refer to this difference in section 4.3.

### 4.2. SCC and Pressure Wave Interactions

To further analyze the interaction between SCCs and pressure waves, both OLR and PSFC anomalies averaged between 15°S and 15°N band are plotted together on a single Hovmoller diagram (Figures 10 and 11). This representation is advantageous compared with Figure 8 for two reasons. First, it shows raw data, and hence, sensitivities due to algorithms are removed. Second, it provides more detail about the evolving structures.
along their eastward propagation, in particular, in terms of the hierarchy of convection in the tropics: SCCs, cloud clusters (CCs), mesoclusters (MCs), and individual deep cumulus clouds (Cs), as similarly defined in Nasuno et al. (Table 4 lists the average spatial and temporal scales of these convective structures.) Due to model resolution, though, the smallest resolvable convective element is the CC.

These diagrams finally suggest an answer to the question of why the convective envelopes decay. As mentioned earlier, convection lags behind the pressure wave (whose envelope has a zonal extent of \( O(10^4 \text{ km}) \)), and it also propagates at a slower speed. But in addition, it is evident from Figures 10 and 11 that when the separation is sufficiently large, the SCCs simply dissipate. Additionally, new clusters form ahead, initially approximately collocated within the peak of minimum pressure. Perhaps the clearest example to illustrate this general pattern corresponds to days 295–320 (0 < x < 2.5 \times 10^4 \text{ km}) of the OBS aquachannel case, which will be analyzed later in more detail.

Overall, there is discontinuous propagation of the SCCs along the tropics, which contrasts with the much more stable and continuous nature of the pressure wave, and such discontinuity is linked to the slower phase speed of the SCCs. The pressure wave is predominantly wave number 1, while this is not the case for the convective envelopes, since sometimes two or more coexist in time, at different stages of their life cycles (typically a strengthening SCC ahead of a decaying one). Admittedly, this SCC discretization is sometimes not clear due to varying speeds and zonal extents of CCs and SCCs.
was provided by the vertical composites at the equator of the study area. The next step of our analysis is to assess whether other variables move as fast as the pressure wave. A hint of such behavior is shown in Figure 7, where the positive anomalies of MSE1000 (Figure 7d) are well correlated with each other, qualitatively both contributing to moist static energy perturbations. The contribution to the MSE500 (Figure 12b) is much better correlated with OLR than MSE1000, not only in terms of propagation speed but also in small-scale feature correspondence. Likewise, the positive anomalies of Q500 (not shown) have very similar phase and speed than those for MSE500 and OLR: therefore, the much slower speed velocity of Q500 compared to OLR obtained from the tracking algorithm is not representative of the actual propagation. Surface convergence propagates even slower than OLR (not shown), while zonal wind at 10 m propagates with similar speeds as OLR, but its signal is significantly discontinuous in time (not shown). These results suggest that zonal wind and convergence dynamically respond in low levels to the SCC activity.

The evolution throughout the entire integration period was carefully analyzed for the six WRF simulations. While the aforementioned characteristics are either always or mostly present, we also found some particular features. For the CTRL aquachannel case, one event was found in which the pressure signal splits into faster and slower components (at day 10 in Figure S1 in the supporting information). Note that for PSFC, there are some wave number 2 cases (days 195–215 in Figure 10 and similarly in Figure S1), but after lowering the thresholds used for plotting the contours, the wave number 1 pattern is recovered most of the time (not shown). Despite the wider range of propagating speeds of the SCCs, which differ from the nearly constant-speed pressure waves, occasionally both waves propagate at the same speed, although they remain out of phase (such as days 190–192 and 204–215 in Figure 10); the result is a long-lived mature SCC. At times the pressure signal is weak, and the associated cumulus activity is less organized, and somewhat scattered (days ~65–80 in Figure S4). But surprisingly, there is evidence of SCCs lacking significant PSFC anomalies (days 120–125, 143–146, and 172–180 in Figure S3 and 90–105 in Figure S4). These results suggest that zonal wind and convergence dynamically respond in low levels to the SCC activity.

### Table 4. Acronyms Used in This Paper for the Description of the Hierarchy of Tropical Convection, Following Nasuno et al. [2007]

| Acronym | Definition | Time scale | Length scale |
|---------|------------|------------|--------------|
| SCC     | Super cloud cluster | 7–16 days | 1000–4000 km |
| SCS*    | Superconvective system | 0.5–2 days | 500–1500 km* |
| CC      | Cloud cluster | 1.5–3 days | 100–400 km   |
| MC      | Mesocluster | 4–10 h    | 10–40 km    |
| C       | Deep cumulus cloud | 1–2 h    | 1–4 km     |

*The superconvective system was defined in Chen et al. [1996], although it is more typically referred to as tropical mesoscale convective complex (Maddox, 1980). Such system is characterized by a continuous, nearly circular or elongated very high cloud top (for a given OLR or temperature threshold) exceeding a given area or effective diameter.

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4.3. Moist Kelvin Waves

The next step of our analysis is to assess whether other variables move as fast as the pressure wave. A hint was provided by the vertical composites at the equator of *mse* (Figure 7), *T* (not shown), and *q* total (not shown). In these, there is a much larger variation in the boundary layer of the CCKW signal for the different stages (notice the extended low-level positive anomaly of *mse* in Figure 7d). A priori, from these composites alone it is not possible to know whether this pattern is due to a faster propagation (as for PSFC) or is a coherent signal representative of each of the stages (as for U200). Raw Hovmoller diagrams were computed for days 295–340 of the OBS aquachannel simulations and are shown in Figure 12.

Positive *mse* anomalies at surface (MSE1000) propagate with nearly the same speed as the PSFC wave (Figure 12a). Looking closely, it appears that this speed corresponds to an envelope (“group velocity”) of smaller-scale features with varying zonal extents, life spans, and speeds: overall, these entities propagate westward very slowly or are even stationary. These pulses of moisture and heat are scattered and intermittent with varying strength and are in fact connected with the CCs comprising the SCCs.

In order to verify whether temperature and/or moisture perturbations produced the MSE1000 behavior, both variables were plotted separately (Figures 12c and 12d). As can be seen, *q* and *T* are well correlated with each other, qualitatively both contributing to moist static energy perturbations. The contribution to the field from each of the three components (*mse* = *gz* + *c* p *T* + *Lq*) was quantified: it was found that they represent different orders of magnitude: 4.32 × 10^4 J/kg (geopotential), 4.20 × 10^4 J/kg (latent heat), and 3.01 × 10^5 J/kg (sensible heat), respectively (MSE1000–3.42 × 10^5 J/kg).

MSE500 (Figure 12b) is much better correlated with OLR than MSE1000, not only in terms of propagation speed but also in small-scale feature correspondence. Likewise, the positive anomalies of Q500 (not shown) have very similar phase and speed than those for MSE500 and OLR: therefore, the much slower speed velocity shown in Table 3 for Q500 compared to OLR obtained from the tracking algorithm is not representative of the actual propagation. Surface convergence propagates even slower than OLR (not shown), while zonal wind at 10 m propagates with similar speeds as OLR, but its signal is significantly discontinuous in time (not shown). These results suggest that zonal wind and convergence dynamically respond in low levels to the SCC activity.
Figure 12. Hovmoller diagrams averaged in the 15°S to 15°N band for days 295–340 of the OBS aquachannel simulation. (a) PSFC (pink) and MSE1000 (blue), (b) OLR (black) and MSE500 (blue), (c) PSFC and temperature at 2 m ($T_2$; green), and (d) PSFC and humidity at 2 m ($Q_2$; orange). Contours for OLR and PSFC are the same as in Figure 11. For MSE1000, the range is $3.30 \text{ to } 3.43 \times 10^5 \text{ J/kg}$, and values greater than $3.37 \times 10^5 \text{ J/kg}$ are plotted, using nine contours. For MSE500, the range is $3.24 \text{ to } 3.34 \times 10^5 \text{ J/kg}$, and values greater than $3.28 \times 10^5 \text{ J/kg}$ are plotted, using 10 contours. For $Q_2$, the range is $13.1 \text{ to } 17.6 \text{ g/kg}$, and values greater than $15.6 \text{ g/kg}$ are plotted, using eight contours. For $T_2$, the range is $23.3 \text{ to } 26.5 \text{°C}$, and values greater than $25.5 \text{°C}$ are plotted, using six contours.
(heating forcing). In turn, vertical velocity at 850 mb is better correlated with OLR, although it exhibits a much noisier and scattered signal (not shown).

Based on this evidence, we introduce the concept of moist Kelvin wave (MKW) to characterize a phenomenon that is physically different than the SCCs: the latter are shorter-lived entities that can coexist in time and propagate somewhat slower. Furthermore, the MKW is a lower tropospheric phenomenon, while the SCC is a deep tropospheric feature. Since strictly dry Kelvin waves occur in the upper troposphere and stratosphere [Flannaghan and Fueglistaler, 2012], we opted for this new definition (the distinction between dry Kelvin waves, moist Kelvin waves, and super cloud clusters is analogous to the separation of dry, moist, and saturated/cloud air in atmospheric thermodynamics; in this regard, super cloud clusters could be also referred to as convective/precipitating Kelvin waves). The association of the MKW and SCC terms with the CCKW concept will be assessed in the next section.

To study in detail the evolution of a SCC from its mature to its decay stages and its relationship with the MKW, we focus on days 301–319 of the OBS aquachannel simulation. Figures 13–17 show an 18 day sequence of horizontal structures for OLR, PSFC, and mse at multiple levels.

Both SCC and MKW structures and propagation speeds are clearly identifiable in Figure 13 by the dashed OLR contours and PSFC shadings. The SCC originates around day 300 in the center of the pressure anomaly region, and by day 301 its axis is at $x = 0.3 \times 10^4$ km (Figure 13a). For a few days it experiences a rapid intensification as it propagates eastward, despite the increasing zonal displacement with respect to the PSFC wave. Day 307 (Figure 13c) is representative of the SCC’s mature stage, characterized by a compact structure and deep convection (as indicated by the red contour, encircling a region of smoothed OLR $> 180$ W/m$^2$), and by that time, its axis is ~6000 km westward of the PSFC wave axis. These snapshots show several CCs comprising the SCC, which sometimes merge producing a superconvective system (SCS; see Table 4). For example, the SCS in Figure 13c extends over 1500 km meridionally and about 300 km in the zonal direction, using the 120 W/m$^2$ threshold. Nevertheless, both CCs and SCSs typically last less than 2–3 days (SCCs have a life span of ~10 days), and therefore, the ones that appear to the east every 3 day interval are actually new systems. New CCs form ahead of the SCC, and they constitute its leading part. By days 310–313, the SCC is slowly transitioning to the dissipation stage; even though initially the SCC is still compact and vigorous, most of its convective activity is off the region of strong negative pressure anomalies. Another indicator of the weakening SCC is the weaker values for the smoothed OLR field (no red or blue contours), despite cores of strong precipitation associated with CCs (raw OLR). Three days later, the CCs comprising the SCC are more scattered, and although new CCs form to the east, they are detached from the main structure (Figure 13f). By day 319, the SCC has dissipated, even though a few isolated CCs still continue to form (Figure 13g).

Shaded OLR plots are shown in Figure 14 for a better appreciation of the actual intensity of the different convective systems. Notice that throughout the sequence, the PSFC wave particularly favors the development of new cells of shallow convection at the equator (OLR $> 180$ W/m$^2$ at $x = 0.8–1.1 \times 10^4$ km on day 301, at $1.6 \times 10^4$ km on day 307, etc.), which later grow into deep CCs (at $x = 1.2–1.4 \times 10^4$ km on day 307, at $2.4 \times 10^4$ km on day 313, etc.), characterized by very low OLR values ($< 140$ W/m$^2$). In turn, the newly formed CCs constitute the leading part of the SCC after they merge, while to the central and rear sections the convective activity typically extends meridionally, although the OLR values are somewhat smaller (likely stratiform precipitation in many areas).

During the entire period, the PSFC wave also experiences variations in its structure and intensity, having its peak amplitude (~995 mb) around day 304. Multiple cores within the main PSFC envelope favor, in turn, separate SCC development at those locations, such as at $x = 0.3, 3.1, \text{and } 3.8 \times 10^4$ km on day 301 (Figure 13a), although if the core is relatively weak and/or short lived, the SCC will be short lived as well. In fact, many isolated CCs are remnants of former SCCs (for instance, $x = 0.5–1 \times 10^4$ km at day 313; see also Figure 11).

The horizontal structure of positive MSE1000 anomalies (Figure 15) shows, however, that high values of this variable can locally exist at any location and time. Even when the envelope of the MKW can still be discernible, it does not look like the compact PSFC wave, unless it is smoothed or averaged, like in the $15^\circ S–15^\circ N$ mean of Figure 12a. Remarkably, MSE500 is closely correlated with OLR (Figure 16).

Evidently, the SCC and MKW appear to be vertically linked by one variable. Figure 17 shows an overlay of mse for four vertical levels: 1000, 850, 685, and 500 mb. For each level, a single contour is plotted, which is
Figure 13. Time evolution of the CCKW structure for the OBS aquachannel simulation, in the 15°S to 15°N band, for an 18 day period. Surface pressure values smaller than 1001 hPa are shaded, and OLR contours are overlapped. A zonally periodic 1-2-1 filter was applied one time to OLR to reduce noise (black contours for levels of 120, 150, 180, and 210 W/m²). Also, to facilitate the identification of SCCs rather than strong CCs, the OLR field was smoothed another 50 times, and three envelopes are shown in red, blue, and green dashed contours, for levels of 180, 210, and 240 W/m², respectively.
representative of the peak of positive anomalies in the ITCZ (to facilitate the visualization, the \textit{mse} field has been smoothed with a 1-2-1 filter). From this perspective, the MKW is discernible by the cyan and blue contours (1000 and 850 mb, respectively), while the SCC can be better tracked by the red and black contours (685 and 500 mb, respectively). Not only are the different propagation speeds of the envelopes clear but also the discontinuity at day 313 (Figure 17e) is noticeable, associated with the decay of the old SCC and the new one downstream.

\textbf{Figure 14.} Same as in Figure 13 but for OLR, color filled for values less than 240K.
The sloped structure of convection that appears in the later stages is not due to some form of slantwise convection. Snapshots of vertical cross sections of \(mse\) were computed both at the equator and as a 15°S–15°N mean, and it was found that signals propagate exclusively upward (not shown). In summary, the connection between a SCC and a MKW can be associated with a vertical (~1000–500 mb) structure evolution of large-scale \(mse\), which begins with both envelopes nearly collocated, and continues with a progressively increasing westward tilt with height, until the slow-moving upper section weakens as the SCC dissipates.

Figure 15. Same as in Figure 13 but for \(mse\) at 1000 mb (values greater than 336,000 J/kg).
5. Revisiting the Concept of Convectively Coupled Kelvin Waves

In the previous section, the term CCKW has been mostly left aside while discussing the moist Kelvin and SCCs waves' characteristics and interactions. Evidently, the CCKWs are neither the SCCs nor the MKWs alone, but the coupled system as a whole. Such coupling is complex, as indicated by varying propagation speeds of different variables, and to a lesser degree, by some intermittencies or instabilities, although systematic patterns can be identified. While here we use here the term coupling referring especially to interactions between SCCs.

Figure 16. Same as in Figure 15 but for mse at 500 mb (values greater than 328,000 J/kg).
Figure 17. Time evolution of the $mse$ vertical structure for the OBS aquachannel simulation, in the 15°S to 15°N band, for an 18 day period. A single contour of smoothed $mse$ is plotted for levels 1000 (cyan, $3.41 \times 10^5$ J/kg), 850 (blue, $3.33 \times 10^5$ J/kg), 685 (red, $3.33 \times 10^5$ J/kg), and 500 mb (black, $3.34 \times 10^5$ J/kg). The corresponding high $mse$ values were computed as $\max - (\max - \min)/10$, where $\max$ and $\min$ are the extreme values for the entire ITCZ domain throughout the year, for each pressure level.
and the MKW, in the original definition by WK99, the coupling in the CCKW term refers to the correspondence of OLR power and the Matsuno modes in a frequency-wave number diagram (and additionally, the convection is "well coupled" to many dynamical variables like vertical wind, horizontal convergence, and $mse$, as shown by compositrd horizontal and vertical structures).

To summarize our findings, a conceptual model (Figure 18) illustrates the evolution of a CCKW. Initially, a developing SCC is characterized by an ensemble of vigorous CCs led by shallow convection. The system’s mean OLR signal is closely aligned with the peak of negative pressure anomalies and positive $mse$ anomalies in the boundary layer (Figure 18a). As the system evolves, the MKW propagates faster than the SCC, creating a displacement that increases with time (Figure 18b). Pressure (its entire vertical structure) and OLR have each a distinct characteristic phase speed; however, for $mse$ (as well as $T$ and $q_{total}$), there is a monotonic decrease of speed with height. The positive $mse$ anomaly, now with a pronounced westward tilt with height, corresponds to a shallow (ahead)-deep-stratiform (behind) cloud cover structure which eventually breaks (Figures 18c, 7d, and 17e), starting the transition into the decay stage. During this process, CC elements continue to occur, although in a more scattered, disorganized way (Figure 18d), until most of the convection is suppressed. In turn, the fast-moving MKW favors new development of CCs that organize into a larger feature, an incipient SCC ahead of the remnants of the old one (Figure 18d). The new SCC strengthens as it is initially aligned with the MKW axis, restarting the cycle (Figure 18a). Although not shown by our conceptual model, the decaying and strengthening SCCs often coexist in time, as shown in Figures 10 and 11. The a–d cycle repeats itself, although in occasions, the SCC propagates nearly at the same phase speed as the MKW hence extending its lifetime, and other times, the MKW decays inhibiting SCC formation. Note that for clarity, a four-stage life cycle has been used for this conceptual model in opposition to the three-stage separation, as used for convenience in the analysis of section 3.

Figure 18. Conceptual model of the CCKW evolution in terms of MKW-SCC interactions: (a) strengthening SCC, (b) mature SCC, (c) decaying SCC, and (d) dissipation of old SCC and genesis of a new SCC. The blue rectangle represents the tropical sea surface, while the pink oval denotes the region of negative surface pressure anomalies. Deep cloud elements represent the cloud clusters (CCs), otherwise shallow cumulus or stratiform clouds. The horizontal arrows represent the propagation speeds of moist Kelvin wave (pink) and SCC (black), and their length represent the relative magnitudes. See details in text.
We have reviewed previous studies on CCKWs that analyzed or described properties and established distinctions between convective/precipitating and moist Kelvin waves. As mentioned earlier, Wang and Li [1994] analyzed SCCs and pressure waves but using a simplified theoretical model. Due to its limitations, the speed of their simulated Kelvin wave exceeded that of the SCC by an unrealistic factor of ~2.5.

The simplified 2-D simulations of Oouchi [1999] and Numaguti and Hayashi [2000] analyzed the westward propagation of CCs within the eastward moving SCCs and found evidence of internal gravity waves (IGWs) propagating in both directions. The role of the eastward moving IGW was found to be important, since they trigger the formation of new CCs that constitute the leading part of the SCC. In particular, they found that there are slow and fast modes of IGW, with speeds of ~12 m/s and 25 m/s, at levels of 600 and 870 mb, respectively, while their SCC moves on average at 8 m/s. Interestingly, Numaguti and Hayashi introduce conceptual models for the CC-SCC interaction in a longitude-time domain (their Figures 11 and 15), although there are many differences with the model presented here. In their case, the IGWs (fast Kelvin modes) result as a by-product of convective process, and additionally, the deeper the mode, the faster it is. In our aquachannel simulations, there is no evidence that the moist Kelvin mode (shallow and fast component) is caused by SCC (deep and slow component) activity, although could still be modulated by it. Ultimately, the Numaguti and Hayashi conceptual model is oriented to explaining dynamics of SCC-CC-MC interactions for a self-sustained SCC that once formed, does not dissipate.

The consideration of the pressure wave separately from the SCCs was also addressed by Nasuno et al. [2008]. For the 40 day period of their aquaplanet explicit convection simulation, they analyzed the composite structure of the MKW ($k = 1$, c = 23 m/s) and compared it with the corresponding structure of the SCC mode ($k = 3-5$, c = 17 m/s). They found significant differences, and then analyzed the interaction of the two modes, concluding that it is bidirectional. Nasuno et al. argued that the wind field of the $k = 1$ mode is forced by convection (SCCs), and in turn, once the pressure wave is excited, it facilitates the development of more convection through low-level convergence and moisture buildup in the east (wave-CISK mechanism). Nevertheless, in the limited period of their study, there is a single case of decaying SCC and arising of a new one ahead, both embedded in the pressure wave.

This dissipation-genesis pattern, which represents in Nasuno et al. [2008] a “case study,” is repeatedly observed in our 1 year aquachannel and aquapatch simulations. Additionally, while focusing on composited structures of both modes can provide important information, it does not permit the analysis of the zonal lag evolution between the pressure and SCC waves, which appears to be fundamental for the understanding of their coupling. Again, the interpretation of the “CCKW” term varies: Nasuno et al. [2008] treat the waves independently as two convectively coupled modes (i.e., the coupling is for each mode, between the dynamics and convection). Instead, our perspective is that the interaction is itself the coupling of those two “modes,” which are equally important elements of the CCKWs.

Remarkably, many points in common were found between our simulated CCKWs with aquachannels and the observations of CCKWs analyzed by SK03. In particular, several aspects from our results can be explained by (and provide additional support for) the proposed CCKW dynamics in SK03:

1. The genesis of a SCC requires a preexistent fast-moving MKW, which provides the initial forcing. Such forcing mechanism is based on evaporation produced by enhanced surface winds, which moistens the boundary layer.
2. The positive temperature anomalies in the lower troposphere (also contributing to positive mse anomalies) are provided by shallow convection (precursor of CCs). Such warm low-level perturbations inhibit deep convection (large convective inhibition (CIN); low convective available potential energy (CAPE), “suppressed phase”).
3. The SCC strengthens as the deep convection is triggered (increased CAPE). This is possible as the convection wave lags behind the MKW: the cooler boundary layer destabilizes the column in low levels (reduced CIN). In turn, the organized convection affects the large-scale circulation, which feeds back with more low-level convergence, evaporation, and precipitation (WISHE and wave-CISK mechanisms).
4. The increasing separation between SCC and MKW is directly linked to an increasing westward tilt of height of mse. Deep convective cloud tops merge, forming large regions of precipitation (some big enough to be regarded as superconvective systems). The 3-D structure of the system, shallow (ahead)-deep-stratiform (behind) convection is supported by the stratiform instability theory.
Of the five-component SCC life cycle defined by genesis, strengthening, mature stage, weakening, and dissipation, SK03 addressed only the first three. Evidently, neither of the wave-CISK, WISHE, or stratiform instability (all positive feedback) mechanisms can be applied to the remaining two.

In summary, the evidence found here in addition to previous studies let us propose that for the CCKW phenomenon, there is a coupling phase (from genesis to mature state, as portrayed by SK03) and a decoupling phase (from decay to dissipation) characterized by the detaching of the SCC from the MKW due to its slower propagation, until it vanishes. These two phases can further be separated into more stages to account for specific features, as described for our conceptual model of Figure 18.

Finally, as anticipated earlier, the concept of phase speeds and horizontal and vertical structures of "CCKWs" used for Part I strictly corresponds to "SCCs," because those were obtained by tracking the most intense SCC (OLR) wave. We have kept this designation because the CCKW term has mostly replaced SCC in the literature since WK99 (occasionally the SCC term is preferred over CCKW, when the entity identification method is used instead of the wave/power spectrum approach, to study for instance the hierarchy of tropical convection, as was the case in Yamada et al. [2010]). We believe that the equivalence can still be kept in most cases, not only because precipitation is typically the variable of interest when studying CCKWs (and CCEWs in general) but also because all structures (convective and dynamical) are coherently coupled in a time average sense (even pressure and mse to a first-order approximation). However, when CCKWs are analyzed in terms of temporal evolution and particularly, in terms of stages of life cycle, the SCC-MKW distinction becomes necessary.

6. Summary and Conclusions

This work has introduced an experimental modeling approach for the study of CCKWs, overcoming the traditional wave-versus-entity dichotomy for this tropical phenomenon. Both event-centric (SCC) versus wave (Kelvin) concepts have been applied here, providing elements that help elucidate CCKW dynamics.

Several theories have been proposed to explain CCKWs, such as frictional-CISK, wave-CISK, WISHE, and stratiform instability feedback mechanisms, but the applicability of these instabilities is restricted to the origination and strengthening of CCKWs. Instead of analyzing the time-mean structure and propagation properties, more connected with the mature stage (as we did in Part I), here the focus was put on the different phases along the CCKW life cycle to try to understand why they originate, strengthen, and dissipate.

We employed a subjective methodology to select cases for each of the three stages of the life cycle using CCKW-filtered OLR diagrams. Although we considered the same six WRF simulations as in Part I, we mainly focused on the two aquachannel cases (domain length equal to an Earth's circumference at the equator), since in the shorter aquapatch domain some of the spatial structures of CCKWs are distorted.

SCCs were found to propagate nearly at the same speed throughout the entire integration period, regardless of their stage of development. Overall, minor differences in composited structures were found among the stages but with a few important exceptions. The zonal flow within the SCC region exhibited variations in the entire depth of the troposphere. In particular, there is a late dynamical response of upper level wind to the organized cumulus activity, evidenced by the lack of strong easterly perturbations collocated with the SCC axis in the early stage composite (Figures 4b and 5b).

When this life cycle stage analysis was applied to the pressure and mse fields, the composite structures exhibited noticeable changes in patterns as different samples of the simulation were considered (Figures 6 and 7). The CCKW tracking algorithm with surface pressure (PSFC) as tracking variable showed that the pressure wave leads the OLR wave (associated with the SCC) and it also travels about ~3 m/s faster (Figure 8). In particular, by overlapping fields of OLR, PSFC, and mse it was found that a SCC decays when its axis lags too far westward of the trough in the PSFC wave or ridge in the surface mse wave (Figures 10, 11, and 13). From this evidence we introduced the moist Kelvin wave (MKW) concept, for a phenomenon that is conceptually different from either a dry Kelvin wave or a SCC, in terms of phase speed and also location in the vertical. The MKW is slightly faster than the SCC, and it occurs in the lower troposphere. Typically, when the old SCC dies, a new one forms ahead, nearly collocated with the MKW. The MKW is usually wave number 1 and long lasting, although it occasionally dissipates as well (altogether with the embedded SCCs). The propagation of the warm and moist anomalies
within the boundary layer is similar to that of pressure (~21 m/s), but in midlevels (~500 mb), the phase speed is in closer agreement with that of the SCC (~18 m/s). The westward tilt with height of mse increases with time and ultimately the signal in midlevel weakens, as the SCC dissipates (Figure 17).

These results suggest a reevaluation of the “convectively coupled Kelvin wave” concept as introduced by Wheeler and Kiladis [1999], after the great overlap between observed symmetric OLR signals on a normalized power spectrum and the linear Matsuno Kelvin mode. The coupling also applies to the coherence of OLR structures with patterns in many other dynamical and thermodynamical variables, as shown in composite analyses. But our findings show that negative pressure anomalies and positive mse anomalies in the boundary layer are not well correlated with OLR at all times, with important implications. The coupling concept is reinterpreted in this work in terms of SCC-MKW interactions, particularly in terms of their phase speeds and zonal separation. Such coupling lasts as long as the SCC keeps intensifying or maintains its strength, while a “decoupling” characterizes the weakening and dissipation stages of the SCC.

A conceptual model (Figure 18) was proposed to highlight the evolution of a CCKW, with clear distinctions between the SCC and the MKW. It was found that many of the elements of the wave-CISK, WISHE, and stratiform instability theories are applicable to the genesis, strengthening, and mature stages of our simulated SCCs, in agreement with the analysis of SK03 for observed CCKWs. Yet this work has analyzed the life cycle of SCCs mostly in a qualitative fashion, and complementary quantitative analysis is needed to support our findings.

Despite the fact that the pressure wave is steady for most of the time in all the simulations, further research is needed to understand why MKWs decay at times and how they can reappear. Also, if the modulation of the convective envelopes by the moist Kelvin wave is clear, the net effect of the former onto the latter is not. Further research will be conducted to assess to what degree SCCs affect the magnitude and propagation speed of MKWs. In addition, the exploration of the MKW-SCC interaction in observations or reanalysis will be subject of future investigation. Such evidence might provide additional support to the understanding of the MKW as a dynamical mode distinctly different from a SCC or a dry Kelvin wave.

The life cycle of SCCs found in our WRF aquachannel cases is similar to results obtained with other idealized simulations. For example, Figure 16 of Blackburn et al. [2013] shows 30 day Hovmoller diagrams of precipitation in the −5° to 5° band for 16 models of the APE experiment, for the CTRL case. The eastward propagating signal with speeds of ~15 m/s is the dominant feature for most of the models. Moreover, the intensity of these SCCs varies in time, with clear cases of strengthening and decay phases, occasional periods of weak and disorganized (synoptic-scale) convection. More examples of the evolution of SCCs are provided in Figure 4 of Khouider and Han [2013], who also used the WRF model and performed sensitivity tests to nesting and to explicit convection, and in Figure 2 of Frierson [2007], obtained with the simplified Betts-Miller cumulus scheme. In particular, the aforementioned work of Nasuno et al. [2008] identified both components of a CCKW (the pair of SCCs and the associated pressure wave) for an aquaplanet cloud-resolving simulation. Therefore, all these previous studies support our present results using the WRF model, despite the simpler aquachannel domain, the selected prescribed SST profiles, and the suite of parameterizations.

In turn, realistic simulations as well as observational studies also show similar evolution of SCCs, with the particularity that the Pacific and Indian Oceans are preferred locations of enhanced CCKW activity (Figure 7 of Tulich et al. [2011]), while Central America and Africa are regions of suppressed activity. This situation is clearly evident in the Hovmoller diagrams of Figures 8 and 9b from WK99 and Figures 5 and 15 from Roundy and Frank [2004], indicating that sea-land distribution and topography presumably play a significant role in SCC activity. Nevertheless, as shown by results from idealized simulations, episodic strengthening and decay of SCCs are intrinsic to CCKW dynamics.

Although the evolving spatial structure of SCCs has been described here in term of smaller-scale components (Figures 10, 11, and 14), the propagation characteristics of CCs within SCCs were not analyzed in depth, since the focus was put on the SCC-MKW propagation. A careful visualization of 6 h interval sequences of OLR as well as other fields yielded several recognizable patterns of propagation that cannot be circumscribed to the generally accepted idea of westward moving CCs within eastward moving SCCs. This topic will be the main objective of a forthcoming paper.
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