Convectively Coupled Kelvin Waves: Structure and Variability Analysis with Different Model Configurations

Joaquin E. Blanco
University of Miami, joaquin_eb@hotmail.com

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CONVECTIVELY COUPLED KELVIN WAVES: STRUCTURE AND VARIABILITY ANALYSIS WITH DIFFERENT MODEL CONFIGURATIONS

Joaquín E. Blanco
The Intertropical Convergence Zone is characterized by a hierarchy of transients within a large range of spatial and temporal scales that propagate both eastward and westward with varying speeds in synoptic-scale-like waves. Among these tropical structures, the Convectively Coupled Kelvin Waves constitute one of the most significant in terms of contribution to the total ITCZ variability. The first part of this work analyzes the sensitivity of simulated CCKWs to domain size, horizontal resolution and forcing, using the WRF model. The simulations are performed using two types of idealized domains: the “aquachannel” (an oceanic surface with the Earth dimensions, but extending to the latitude of 60 degrees in both hemispheres on the beta plane), and the “aquapatch” (similar configuration as the aquachannel except for its longitudinal extent, which is 1/3 of the former, or approximately 13000 km), with both cases using periodic boundary conditions. The aquapatch is integrated in low and high resolution, and also in a doubly-nested configuration, in which convection is solved explicitly in the innermost grid. The model intercomparison is carried out throughout the use of several techniques such as power spectra, filtering, wave tracking and compositing, and it is extended to some simulations from the “AquaPlanet Experiment”. The second part of this work addresses a
topic that has not previously been studied: the life cycle of the CCKWs. A subjective technique is applied to isolate early, mature and decay stages, and then spatial structures as well as propagation speeds of each phase are compared, resulting in some distinctive differences. Moreover, this analysis reveals a “de-coupling” between super cloud clusters and the pressure wave, which is found to be connected with the dissipation of the clusters.
To Laura Venegas, RIP

To Matilde Nicolini and Juan Ruiz
Acknowledgments

I am sincerely grateful to my advisor, Dr. David S. Nolan, for his guidance and support during these 3 years. I also want to thank my committee members, Dr. Brian E. Mapes and Dr. Stefan Tulich for their contribution to this work.
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CHAPTER 1. INTRODUCTION

We begin this chapter with a brief chronological overview of research on Convectively Coupled Kelvin Waves (hereinafter CCKWs), including theoretical studies, observations and simulations. Theories for the dynamics of CCKWs are treated separately in section 2. Section 3 addresses the Aqua-Planet Experiment (APE), framework for the design of our simulations. The objectives of this thesis are described in the last section.

1.1 Historical background of the CCKWs

Zonally propagating convective activity represents a significant component of the total variability along the intertropical convergence zone (ITCZ). Westward propagating convective clusters along the Equator coexist with eastward propagating cumulus activity, organized in a hierarchy of time and spatial scales. CCKWs are envelopes of enhanced convection with zonal scales of 3000-7000 km that propagate eastward in a range of velocities that is typically between 10-22 m/s. The coherent structure of the CCKWs can remain distinguishable over weeks, and they can be sometimes tracked all the way around the globe. The individual cells within the CCKWs propagate westward with slower speeds and a lifetime of 1-2 days. These observational characteristics were predicted by earlier analytical studies.

The theoretical (dry) Kelvin Waves, were first investigated by Matsuno (1966), who was a pioneer in developing a general theory for Equatorial Waves. Starting from a
simple shallow water model (layer of constant density fluid) on a beta plane, linearizing about a uniform resting atmosphere, assuming oscillatory solutions in time and the zonal coordinate, he obtained the non-dimensional dispersion relation:

$$\omega^2 - k^2 + \frac{k}{\omega} = 2n + 1$$

or in its dimensional form:

$$\frac{\sqrt{gh_e}}{\beta} \left( \frac{\omega^2}{gh_e} - k^2 + \frac{k}{\omega} \beta \right) = 2n + 1$$

which is cubic in $\omega$. Hence, it gives 3 solutions for each meridional mode $n \geq 1$: these are the Equatorial Rossby (ER) wave (westward), and the Inertio-Gravitry (IG) waves (eastward, EIG, and westward, WIG). Odd modes correspond to waves symmetric around the Equator, while even modes are antisymmetric. The special case $n=0$ has only 2 solutions: the Mixed Rossby-Gravity (MRG) wave (westward) and the EIG, while $n=-1$ is another special case because it satisfies the equation for the Kelvin mode dispersion relation, namely, $\frac{\omega}{k} = c = \sqrt{gh_e}$, where $h_e$ is the equivalent depth or equivalent height.

These dry or “free” equatorial waves (once produced, uncoupled to convection or any other forcing) have a zonal structure determined by wavenumber $k$, and a vertical structure determined by wavenumber $m$, which is usually interpreted in terms of the equivalent depth $h$. In terms of meridional structure, the amplitude of the waves decays significantly with latitude (so the waves are called “equatorially trapped”). The north-south extension $L_y$ of the waves is given by the Rossby radius of deformation $Re$ and the meridional mode $n$, such that $L_y < Re \sqrt{2n+1}$, where $Re = (\sqrt{gh_e}/\beta)^{1/2}$. The dispersion curves for the Matsuno waves are plotted in Fig.1.1 for the gravest ($n \leq 2$) modes and for different equivalent depth values.
The Kelvin waves have no meridional velocity, and can be understood as pure non-dispersive gravity waves in the east-west direction with geostrophic balance between zonal wind and meridional pressure gradient. Its horizontal structure is shown in Fig.1.2. Overall, the structure of a dry Kelvin wave resembles that of the convectively coupled Kelvin wave (for both observed and idealized cases): however, the former propagate much faster, about 40-50m/s. In terms of equivalent depths (using $\lambda = \sqrt{g\bar{h}}$ ) theoretical dry waves have a value around 200m, while the typical range for CCKWs is around 12-50m; this discrepancy is addressed in the next section. In contrast, observed lower-stratosphere dry Kelvin waves have phase speeds closer to those of theoretical Kelvin waves: about 30-40 m/s.

The CCKWs were originally referred to as “super cloud clusters” or “superclusters” (Fig. 1.3) because of the aforementioned cloudiness characteristics, which are clearly identifiable in satellite imagery (Nakazawa 1988; Takayabu and Murakami 1991). Some of these early works focused mainly on case studies, but when reanalysis became available, composites of different variables were produced to investigate the structure and dynamics of these waves. Simultaneously, evidence of superclusters appeared in idealized aquaplanet simulations (Hayashi and Sumi 1986; Hayashi and Nakazawa 1989) conducted for investigation of the Madden-Julian Oscillation (MJO).

In the last decades the entire spectrum of Equatorial Waves has become a vast subject of study involving both observed and simulated cases, with special emphasis on their multiple interactions, their linkage to the ITCZ, and to other tropical phenomena such as tropical systems. The seminal work of Wheeler and Kiladis from 1999 (hereinafter WK99) showed that the full equatorial wave family predicted by Matsuno theory can be
seen in enhanced power spectra of satellite-based data such as outgoing longwave radiation (OLR). The overlapping of the Matsuno curves and the OLR spectral peaks, obtained by an enhancement of the raw power spectra when divided by its own smoothed field (Fig.1.4), yielded the modern concept of Convectively Coupled Equatorial Waves (CCEWs). It is remarkable that this correspondence in dispersion characteristics and also structure arises without considering the potential effects of basic state flow and despite potential nonlinearities arising from coupling with convection. Takayabu (1994) had anticipated the approach of WK99, although his dataset was not as robust, but more importantly, the correspondence between linear modes and observations within the power spectra was not immediate since these were not normalized (absence of “spectral peaks”).

Furthermore, the work of WK99 led to the widely used technique consisting of filtering the data in the frequency-wavenumber space within a power spectrum to isolate the different CCEWs (Straub and Kiladis 2002; Roundy and Frank 2004; Roundy 2008). This procedure enables an optimal visualization of the propagation of a particular equatorial mode in filtered Hovmoller diagrams, which in turn can be used for making composites to study the structure and dynamics, and also to compute the amount of variance explained by a given wave over the total ITCZ variance.

1.2 CCKW theories

The reasons for the propagation speed difference between dry and convectively coupled Kelvin waves have been extensively studied, and today there are 2 main accepted theories. The first is the effect of convection on the static stability felt by waves (Gill
1980; 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 relation between CCKW speed and vertical stability is predicted by the formula derived by Tian and Ramanathan (2003) from a theoretical first baroclinic mode model: it is given by

$$c_x^2 = \frac{R_d \Delta m \Delta p}{c_p p_m}$$

where $\Delta m$ is the gross moist stability (a time-mean, mass-weighted vertical integral of moist static energy), $\Delta p$ is the tropospheric depth and $p_m$ is the midtropospheric pressure.

A simpler 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),

$$h_e = \frac{N^2}{g\lambda}$$

where $\lambda$ is a constant and $N$ is the Brunt-Vaisala frequency; hence it yields

$$c_x = \sqrt{\frac{N^2}{\lambda}}.$$

A different theory, developed by Mapes (2000) suggests that the higher mode structure in the vertical is responsible for the reduction in speed of waves. The model used is truncated to the first two internal vertical normal modes, namely: the convective (first) mode with an associated dry gravity wave speed of 52m/s (or $h_e=275$m) and the stratiform (second) mode characterized by a gravity wave speed of 23m/s ($h_e=54$m).

Under this two vertical mode setting and the proposed “stratiform instability” mechanism (when CAPE dominates, waves are damped by convection, when convective inhibition dominates, large-scale waves are generated), not only can the relatively slow phase speeds of CCKWs be explained, but also their tilted structures. An important factor is the separate treatments of shallow convection (which is nearly always present) and deep convection (which exhibits great space-time variability). The stratiform instability
mechanism has been further developed by Khouider and Majda (2006) and Kuang (2008).

The reduced stability theory assigns a large effect to moisture on the first internal mode of the troposphere. However, notice that for the stratiform instability theory, the wave speed of the stratiform mode is somewhat larger than the speed of more realistic (or observed) CCKWs, so that the effect of gross moist static stability should not be dismissed. Additionally, other models such as that of Frierson et al (2011), lack a strong second-mode forcing (heating) and yet the CCKW simulation is realistic in propagation speeds and in higher-mode vertical structures.

There is no single well established theory for explaining the dynamics of the CCKWs. However, there are widely accepted concepts, which are contributions from many different ideas developed over decades. Some of the most famous theories are: Wave-CISK (Conditional Instability of the Second Kind), Wind-Induced Surface Heat Exchange (WISHE), and the stratiform-instability vertical-mode theory described above.

Hayashi (1970) considered the feedbacks between deep convection and large scale equatorial waves. In his theoretical models, convection could intensify (destabilize) the wave in some cases through purely inviscid processes not dependent on surface drag or surface thermodynamic fluxes. Lindzen (1974) termed this destabilization wave-CISK, to distinguish it from Charney and Eliassen's (frictional) CISK: the simplest interpretation of the wave-CISK mechanism is that latent heat release from deep convection induces wavelike circulations that favors further convection via low level convergence.

The evaporation–wind feedback or WISHE (Neelin et al. 1987; Emanuel 1987) is a positive feedback mechanism between the ocean and atmosphere in which a stronger
ocean-to-atmosphere heat flux results in a stronger atmospheric circulation, which results in a strong heat flux. WISHE is based on the Quasi-Equilibrium (QE) concept (the basis for adjustment-type cumulus schemes like Betts-Miller and Arakawa-Schubert), which considers that the buoyancy adjustment time scale of convection is short compared to the lifetime of their resulting large-scale disturbances, and that the production of instability by large-scale forcing due to radiation and heat fluxes is balanced by its removal via large-scale convection, either instantaneously or with a lag time of some hours. The role of convection in WISHE is not to act as a heat source, as in wave-CISK, but instead to rapidly redistribute boundary layer moist entropy changes throughout the vertical column, leading to column vertical changes.

A comparison and analysis of these simple theories with observed CCKWs was performed by Straub and Kiladis (2003b). The 3 theories were not originally intended to account for the detailed structures of CCKWs, but were formulated to explain the fundamental mechanisms of the convective-dynamical instability. However, Straub and Kiladis conclude that the dynamics associated with real CCKWs have elements from each of these theories, as can be appreciated by their conceptual model for CCKWs (shown here in Fig. 1.5), and its comparison against the other 3 representations.

Midlatitude features are associated with the initiation of observed CCKWs, as shown by several studies. For instance Straub and Kiladis (2003a) found that Kelvin wave convection originating over the western Pacific was preferentially preceded by an extratropical Rossby wave train activity emanating out of the southern Indian Ocean storm track. In turn, Liebmann et al (2009) presented evidence that sea level "pressure
surges” propagating from extratropical South America northward along the eastern slope of the Andes into the deep tropics often preceded Kelvin wave activity over the Amazon.

However, these horizontal inhomogeneities cannot be the only drivers of CCKWs since they are also found in absence of topographic features, like in the case of idealized zonally and meridionally symmetric planets. Furthermore, midlatitudes themselves could not force the generation of CCEWs, since these are observed in extremely simplified two-dimensional (zonal-vertical) models, even without rotation. Therefore, the simplification of the problem, either in numerical modeling or in theoretical studies such as the exposed above, constitutes an excellent tool to isolate the key processes that lead to the development of CCKWs, and in particular, their generation, maintenance and dissipation.

Two-dimensional cloud resolving models (2D-CRM) 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 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 easterly and westerly propagating waves, with great resemblance to more realistic CCEWs, as seen by Hovmoller diagrams and power spectra. One of these modes corresponds to the CCKWs, although in absence of planetary rotation effects the waves are referred to as convectively coupled gravity waves (CCGWs). Moreover, the simplified models allowed a more straightforward assessment of the theoretical concepts such as stratiform instability.
On the other hand, Nasuno et al (2007) and Nasuno et al (2008) also focused on tropical variability but using a costly aquaplanet CRM configuration of the NICAM model (Satoh et al 2005). The multiscale organization of convection was analyzed, in terms of the 2-way interaction of CCKWs (synoptic scale) with meso-scale and convective-scale features (such as cloud clusters, super convective systems, cold pools). Additionally, they studied the interactions between planetary (k=1) and super cloud cluster (k=3-5) modes of the CCKWs. The disadvantage of this approach consists of the short length of the experiments (90, 40 and 10 days for resolutions of 14, 7 and 3.5 kms, respectively), which presumably affects the robustness of their analysis in terms of spectral mode decomposition and compositing. The physical processes behind the strengthening, mature and decay phases in smaller scale entities embedded in the CCKWs are explained for the 7km and 3.5km runs. However, there is no explanation proposed for the decaying of the CCKW itself and formation of a new one ahead (with only 1 event in the 40-day period).

Despite the widespread use of idealized models to study the processes associated with CCEWs, complex GCMs can still be useful. The recent work of Seo et al (2012) used the NCEP CFS model with the relaxed Arakawa-Schubert (RAS) cumulus scheme to perform a series of simulations in which different subroutines within that scheme were individually deactivated: namely: the shallow convection (EXP1), the cloud-top convective detrainment (EXP2), convective downdrafts (EXP3), convective rainfall evaporation (EXP4) and large-scale rainfall evaporation (EXP5). Their results were also compared with the control simulation (full RAS processes) as well as observations, and it was found that the representation of CCKWs in all experiments was fairly good, with the
exception of EXP1 and EXP2: for these, the CCKW spectral peaks for OLR were dramatically diminished.

The shallow convection mechanism works via extending vertical mixing above the boundary layer (BL) and therefore increasing (decreasing) moisture above (in) it: the moistening of the lower atmosphere above the BL is a precondition for deep cloud formation. When it is turned off, there is a large increase in BL clouds, which produces drizzles and light rain, and in turn this cool the boundary layer stabilizing it, leading to less intense deep convection thereafter. On the other hand if the cloud-top convective detrainment is deactivated, latent heating is also suppressed and then convection-induced moist and dry static energies and ice water are zeroed out, affecting greatly the vertical profile of diabatic heating. When this mechanism is present, there is a supply of water vapor and condensate from deep cumulus clouds to environment and stratiform clouds. When both low-level and high-level effects are present, there is a positive feedback among low-level environmental humidity, deep cumulus convection, and stratiform cloudiness, which is in agreement with the moisture-stratiform stability of Mapes (2000).

Some of the aforementioned as well of other aspects of CCKW dynamics are still part of ongoing research, like studying cause-effect relations between CCKWs and the ITCZ. One of the net effects of the tropical eddies (i.e.: the CCEWs) on the ITCZ morphology is to make it broader than it would be in their absence (Sobel and Neelin 2006; Peters et al 2008, Bellon and Sobel 2010). Other studies have focused on the opposite roles of cause-effect interactions played by each: for instance, Dias and Pauluis (2011) found evidence of modulation by the ITCZ of the phase speed of CCKWs. Therefore, the CCKW-ITCZ interaction is bidirectional.
1.3 The Aquaplanet Experiment

Since the CCKWs (and all the CCEWs) are modes of variability of the ITCZ, their analyses are highly important to the understanding of the overall ITCZ dynamics. Many studies have address observational aspects as well as numerical simulations of the ITCZ, both realistic and idealized, and several topics remain as active research. The ITCZ and its associated peak rain rates do not precisely follow the latitude of peak sea-surface temperatures (SSTs), and certainly, some model configurations produce a “double ITCZ” (Mechoso et al 1995; Lin 2007). Even for the idealized aquaplanet simulations, conditions at the lower boundary play a central role in determining the distribution of rainfall; the other major factors that considerably affect the ITCZ nature are the cumulus and atmospheric boundary layer schemes (Nolan et al 2010; Tulich et al 2011).

The Aquaplanet Intercomparison Project (AIP) was proposed by Neale and Hoskins (2001a) as a coordinated comparison of AGCM simulations with idealized prescribed SST distributions, while all other model parameters remain the same, with the main objective to analyze the precipitation organization in the tropics (Fig. 1.6, top). They used the Met Office Model to show that different SST profiles in the tropics could dramatically affect the ITCZ morphology, from a well-defined peak on the equator to a broad and weak “double ITCZ” (Fig. 1.6, bottom). The Aqua-Planet Experiment (APE, Blackburn and Hoskins 2013) was subsequently designed as a continuation of the AIP, but in a much more robust, systematic and comprehensive way, using not only the
aforementioned SST profiles but also considering different ACGMs and cumulus parameterizations.

This ultimate project, made as the result of a cooperation of research institutions from 6 countries, had specific goals beyond the time and zonal mean distributions of tropical rainfall; other topics investigated were the impacts on the general circulation, the spatial and temporal variability of the ITCZ (CCEWs), the extratropics, and the interactions among them (Blackburn and Hoskins 2013; Blackburn et al 2013). The AIP and APE frameworks constitute an unsurpassable tool not only for the design of idealized simulations for this thesis, but also for the comparison and/or validation of results where possible.

1.4 Objectives

The ultimate goal of this work is to contribute to the understanding of structure and propagation characteristics of CCKWs and its two-way interactions with the ITCZ. These topics will be investigated through the use of idealized simulations with the ARW-WRF model, with a sensitivity analysis to model configuration, and in particular, SST profile, cumulus schemes and horizontal resolution.

1.4.1 The Aquachannel and the Aquapatch

While many studies have used real-earth circulation models to investigate the tropical structure and variability, other employed either full-physics models on regional domains
(Toma and Webster 2010a,b; Evan et al 2012), or intermediate complexity models (Neelin and Zeng 2000; Wang, et al 2010; Sobel and Neelin 2006; Bellon and Sobel 2010), and even a fewer number developed analytical models (Held and Hou 1980; Lindzen and Hou 1988; Fang and Tung 1999). Since ITCZ sensitivity to cumulus schemes is considerable, cloud-resolving models seem to be an important approach (moreover, eliminating cumulus parameterization could make results less sensitive to other model choices). However, high-resolution grids make the simulations extremely computationally expensive.

For this purpose, the model type used in this thesis an idealized tropical channel (Nolan et al 2007; Nolan et al 2010): the domain is on a beta-plane and limited meridionally (up to 60° latitude), but covers the entire Earth circumference with periodic boundary conditions like the aquaplanet. Also the “aquachannel” model can implement nested channels along the equator to solve convection explicitly along the ITCZ. The development of tropical channel models is recent but promising: not only have they been used for idealized simulations (Khoudier and Han 2013), but also for realistic representation of tropical phenomena like double-ITCZ on the West Pacific, and observed tropical cyclones and CCKWs (Tulich et al 2011, Ray et al 2012).

One of the specific objectives of this work is to show to what degree the ITCZ and CCKWs structures and variability obtained with this type of model differ from those obtained with more realistic (Earth-like domain) but computationally expensive models, such as the used for the APE project. Moreover, a sub-version of this model, the squared-domain “aquapatch” (shortening the zonal direction to 1/3 of the aquachannel length) is tested for the same purposes. A set of aquachannel and aquapatch simulations is
conducted, and a systematic analysis of CCKWs is carried out focusing on the differences (or similarities) in results among the various model configurations. Since there are obvious benefits in terms of computational costs of using an aquapatch rather than an aquachannel, and the latter instead of an aquaplane, the natural question that yields is which is the maximum acceptable order or error (in term of model differences). In other words, what is the cost-benefit relation of using an aquachannel or aquapatch rather than an aquaplane?

1.4.2 The different stages of the CCKW life cycle

The theories presented in Section 1.2 tend to focus on the explanation of the overall CCKWs (or more generally the CCEWs) properties, in terms of spectral peaks and propagation speeds, variance, and spatial structure of dynamic and thermodynamic variables, for the entire period of observations/simulations. These features are not analyzed in terms of the different phases of the wave cycle, namely the early, mature and decaying CCKWs.

In particular the feedback mechanism hypothesis could be applied to the dynamics of the already formed, self-sustained mature phase, but not necessarily to the transitions into or out of this stage. For instance, what processes break the wave-CISK, WISHE and/or stratiform instability feedbacks, leading to wave dissipation? What forces those feedbacks to start? Theoretical explanation of these processes remains pending and this thesis will hopefully represent a contribution to this topic.
The second specific objective of this work is then the investigation of structure properties and propagation speeds for the 3 different stages of the wave. The rationale is that resulting differences among these are useful for association and/or support of the CCKW theories. Details about the method employed for this purpose are explained in next chapter.

Recent work by Dias and Kiladis (2014) showed that the influence of the basic state zonal flow on observed CCEWs varies significantly depending on the vertical profile of the wind (seasonality and regionality were considered) as well as on the type of wave itself. In the absence of seasonality and zonal asymmetries, and focusing on CCKWs, the Doppler shift effect is studied with our simulations, since different model configurations produce different mean zonal flows. The correlation between differences in CCKWs propagation speeds and differences in the mean barotropic flow are studied for our set of simulations, and in particular, for each stage of the CCKW life cycle.
Figure 1.1: Matsuno’s dispersion curves for the symmetric (a) and antisymmetric (b) Equatorial modes, for equivalent depths values of 100m 50, 25, 12 and 6 meters.

Figure 1.2. Schematic representation of the horizontal structure of a dry Kelvin wave. Shading indicates divergence (red) and convergence (blue), and ellipses indicate regions of low (blue) and high (red) pressure. Example for a planetary wavenumber \( k=6 \) (\( L_x=60^\circ \)), and a meridional trapping scale of \( 6^\circ \). Reproduced from Yang et al (2007).

Figure 1.3: Hovmoller diagram of a Super Cloud Cluster (A) over the Western Pacific Ocean. Adapted from Nakazawa (1988).
Figure 1.4: Antisymmetric (a) and symmetric (b) OLR power spectra, normalized by background power. Superimposed are the dispersion curves of the even (a) and odd (b) meridional mode-numbered equatorial waves for equivalent depths of 12, 25 and 50m, respectively. From Wheeler and Kiladis (1999).

Figure 1.5: Schematic longitude-height diagrams for wave-CISK (a), WISHE (b), stratiform instability (c) and observed CCKWs (d). Except for the background easterly flow in WISHE, vectors represent anomalous wind fields, and the letter W (C) represents warm (cold) anomalies. Adapted from Straub and Kiladis (2003b).
Figure 1.6: SST profiles (in °C) for axisymmetric aqua-planet experiments from the Intercomparison Project (a). Time and zonal mean of total precipitation (in mm/day) for the same set of experiments using the Met Office Model (b). From Neale and Hoskins (2001a, 2001b).
CHAPTER 2. DATA AND METHODOLOGY

The design of our set of simulations is treated in the first section. Details about the model parameters and physical schemes are provided. The subsequent sections describe the different methodologies applied to the model outputs to develop our analysis, namely: the space-time spectral analysis to obtain normalized power spectra (section 2), the Kelvin filtering technique (section 3), the algorithm for tracking CCKWs (section 4) and the generation of composites and computation of propagation speeds (section 5). Finally, section 6 describes the APE dataset which was used to extend our model intercomparison analysis.

2.1 Model and simulations

The model used for all simulations in this study is version 3.4.1 of the Weather Research and Forecast model (WRF). The idealized simulations are performed in an equatorial \( \beta \)-plane domain (no map factors) with no topography. The grid extends from 60\(^\circ\)S to 60\(^\circ\)N (\( L_y \approx 13200 \text{km} \)) with free-slip walls at the north and south boundaries, and has periodic boundary conditions in the zonal direction. Vertical spacing is variable in the range of 100-450m, with model top at about 26km (level 50).

A set of 4 configurations are used for the longitudinal extent and resolution (see sketch in Fig. 2.1):
1) The “aquachannel”: an oceanic surface with the Earth circumference at the equator as longitudinal extent \( (L_x \sim 40000\text{km}) \), and a resolution of 139km \((288\times 96\text{ points, } 360^\circ \times 120^\circ)\)

2) The low resolution (LR) “aquapatch”: same configuration than the aquachannel except for its shorter length \((96\times 96\text{ points, } 120^\circ \times 120^\circ)\)

3) The high resolution (HR) aquapatch: grid spacing of 46.35km \((288\times 288\text{ points, } 120^\circ \times 120^\circ)\)

4) The nested aquapatch: nesting is applied twice along the equator to obtain two finer grids: 15.45km spacing from 20°S to 20°N \((864\times 288\text{ points})\) and 5.15km spacing from 13.33°S to 13.33°N \((2592\times 576\text{ points})\). Within the latter grid convection is solved explicitly (cumulus scheme turned off).

Also, another set of simulations are performed by changing the model set-up in the prescribed SST profile (model forcing): the cases “control-SST” (CTRL) and “observed-SST” (OBS) profiles from the AIP/APE projects are used. These profiles were shown in Fig. 1.6 and given by the formulas:

For \( \varphi \) between \([-60^\circ: 60^\circ]\), and 0 outside

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

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

A total of 7 experiments are considered in this thesis. The LR aquapatch is considered to be a transition case between the aquachannel and the HR aquapatch, and therefore only the CTRL version is used. Also, 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 from Ly=13.33º to 20º, and the coarser grid from Ly=20º to 30º (also indicated in Fig. 2.1)

The Tiedtke scheme (Tiedtke 1989) is used for cumulus parameterization, and the Goddard GCE scheme (Tao et al 1989) for cloud microphysics. There is diurnal cycle and the Goddard scheme is used for both SW and LW radiation (Chou and Suarez, 1999). Solar radiation is set to a permanent equinox, with diurnal cycle. The boundary layer is parameterized with the Yonsei University (YSU) scheme (Hong et al, 2006). Minimum surface wind speed for computing surface evaporation in the surface layer is set to 1 m/s.

Spin-up time is 1 year and simulations are integrated for another year in most cases (with the exception of the nested simulations, which are integrated only for half a year). No seasonality is considered. The initial conditions consist of a state of rest for the entire domain, and a vertical structure given by a thermodynamic sounding. The model time step is 120s for both 139km and 46.35km grids, while for the nested aquapatch case, 60s and 20s are used for the 15km and 5km grids, respectively. For the nested simulations, data is saved only in the coarser grid, and for all simulations, data is saved every 6 hours.

Finally, it is worth pointing out some sensitivities to changes in the aforementioned parameters and physics schemes. For example, in the case of the variable controlling the evaporation flux in the surface layer, it was found that the mean ITCZ profile changes significantly when the threshold value is increased from 1 to 3 m/s (not shown). In turn, preliminary results obtained using the Kain-Fritsch cumulus scheme appeared highly unrealistic in some simulations: all convective activity was found to take place right above the boundary layer (Blanco et al 2014). In terms of the model forcing, we used 2 of the several SST profiles used in the design of the APE experiment, although more
realistic representations of ocean-atmosphere coupling are obtained when using a mixed-layer ocean, in which SSTs are free to respond to evaporation and precipitation. However, model sensitivities to schemes greatly increase under this configuration, as studied by Lee et al (2008): in particular, they found strong zonal-mean flow, exaggerated ITCZ strength, and slower propagation of CCKWs. Last, the fact that no map projection was used (combined with the beta plane approximation), creates a distortion for high latitudes, with an Aquachannel zonal extension of ~40,000 km at +/- 60° latitude, while for the Earth the circumference at such latitudes is ~12,000 km. The increased number of midlatitude systems in the former configuration is likely to affect planetary balance and produce the discrepancies in zonal-mean flow that will be addressed in next chapter (a new WRF simulation considering an aquaplanet surface with meridional walls at +/- 60° latitude would assess this hypothesis).

2.2 Space-time spectral analysis

As stated in the introduction, normalized power spectra proved to be a powerful tool for the analysis of CCEWs for two reasons. It identifies the coupling of convection with each of the Matsuno equatorial modes, and it provides the framework for the filtering of a particular wave type, for subsequent analysis such as tracking and compositing. The steps of the procedure follow the technique of WK99 and are described in this section, highlighting the differences from theirs. As in WK99, the proxy variable for organized
convection in the tropics is OLR. However, power spectra of other variables will also be assessed in this work.

The first step is to apply an antisymmetric-symmetric decomposition for the latitude-dependent variable, i.e.: $\text{OLR}(\phi) = \text{OLRA}(\phi) + \text{OLRS}(\phi)$, where $\text{OLRA}(\phi) = \frac{\text{OLR}(\phi) - \text{OLR}(-\phi)}{2}$ is the antisymmetric (with respect to the equator) component, and $\text{OLRS}(\phi) = \frac{\text{OLR}(\phi) + \text{OLR}(-\phi)}{2}$ is the symmetric component. As seen in the introduction, linear equatorial waves are either symmetric or antisymmetric about the equator.

Then, the mean and linear trend are removed in time, and the boundaries of the series (at $t=0$ and $t=n_t$) are tapered to zero. The data windowing provided by the tapering, ($W(0) = W(n_t) = 0$) permits a continuum at both extremes of the times series, which helps minimize the effects of spectral leakage. The Welch function was chosen, which is given by $W(t) = 1 - \left[\frac{(t - n_t / 2)}{(n_t / 2)}\right]^2$. Little sensitivity to windowing was found in the resulting power spectrum (even with no windowing at all, i.e.: $W(t) = 1$).

After the mean is removed and the variable de-trended and tapered, the spectral technique is applied. The method consists of the decomposition of a two-dimensional OLR field dependent on time and longitude into wavenumber and frequency components for eastward and westward propagating waves. Therefore, since a OLR as a function of time is a three-dimensional field, either a meridional mean is taken from the model outputs in the 15°S-15°N band to compute a single power spectrum, or multiple power spectra are computed for each latitude bin and then averaged. Alternatively, the full time series can be organized in a number of segments with some constant overlap between each pair. Then many power spectra from each segment can be computed, from which a mean spectrum is obtained. The purpose of this is to minimize the loss of data by the
tapering. Both procedures can be applied simultaneously via splitting the time series in \( N \) overlapping segments and considering \( M \) latitude bins, to compute \( N \times M \) spectra. This was used in WK99, in which the OLR power is averaged over 96-day segments (with 60-day overlaps) of the 18-yr record of data, and over all latitudes between 15ºS and 15ºN.

A sensitivity test was performed for the CTRL LR Aquapatch simulation, comparing the 4 possibilities, i.e.: a unique spectrum, and means over \( N, M \) and \( N \times M \) spectra. \( M \) is set to 24 (consistent with the grid spacing). For overlapping times, 90-day periods were used with 60-day overlaps (000-090, 030-120,…, 270-360), yielding \( N=10 \) segments. It was found that the overall pattern in the power spectrum does not significantly change, with the differences being only that smoother plots result when using overlapping segments (see Fig. 2.2). Therefore, for this work, the single spectrum case was used.

The power spectrum computation consists of performing the two-dimensional Fast Fourier Transform (FFT2) of the field, which converts the eastward/westward propagating signals in time-zonal distance space to the spectral peaks in frequency and wavenumber spaces. The resulting raw spectrum can be further improved by highlighting the power associated to the Matsuno modes. This is achieved by the calculation of a background spectrum. Then the former can be divided by the latter, to produce a normalized spectrum. The background spectrum is obtained via averaging the power of OLRA and OLRS spectra and then smoothing with a 1-2-1 filter, which is applied 10 times in frequency space and 40 times in wavenumber. In WK99 10 to 40 times of smoothing was applied in wavenumber, ranging from 10 at low frequencies to 40 at higher frequencies, increasing in two different steps. Each panel of Fig 2.2 shows the base 10 logarithm of the normalized spectrum. To highlight significant power regions,
values are shown above a threshold of 0.1. Also, the log10 spectrum was smoothed and additional 5 times in frequency to reduce noise.

Since the focus on this thesis is on CCKWs, it is the symmetric power spectrum (associated with the symmetric component of OLR) that will be computed and plotted for each simulation. Nevertheless, a brief discussion of the hierarchy of convection in the tropics will be addressed and both symmetric and antisymmetric OLR power spectra will be shown, comprising the totality of the tropical waves’ family (the gravest Matsuno modes). When computing the mean OLRA over the ITCZ, the [0-15ºN] band is actually used instead of the [15ºS-15ºN] band, since otherwise the values would exactly cancel out.

### 2.3 CCKW-filtered Hovmoller diagrams

Before applying FFT2, the two-dimensional (longitude-time) plot (also known as Hovmoller diagram) of OLR depicts the variability of the ITCZ. One of the advantages of the spectral analysis is that one can identify and select a region of power in the wavenumber-frequency space, to isolate the particular wave of interest from the rest of the tropical modes. In this case we will focus on the CCKWs. Through a simple procedure a CCKW-filtered Hovmoller diagram then can be obtained, revealing a clear CCKW signal (all other CCEW types are filtered out), as Fig. 2.3 shows.

The method is as follows: the wavenumber-frequency filtering of the OLR data is performed by taking the inverse of the space–time transform (IFFT2) process including
only those Fourier coefficients that are within the specified region of interest of the wavenumber-frequency domain. Compared to the forward process, however, the inverse process is accomplished by first performing the forward process on the “untapered” Hovmoller diagram (that is, no windowing applied to the time series, but mean and trend still removed). Significant differences of the location of the CCKW axis (as seen by minimum OLR) would appear otherwise near the beginning and end of the simulation period. The CCKW-filtering region was defined after the visual analysis of the enhanced power near the Kelvin mode for the spectra of all the simulations. This area, indicated by the red polygon in Fig 2.2a, is not exactly the same than the corresponding one of WK99 (see their Fig. 6)

2.4 CCKW tracking

A preliminary algorithm was developed to track CCKWs in their eastward propagation, which is independent of the power spectra filtering method (Blanco et al 2014). Instead, several variables (rain rates, OLR, $q_{\text{total}}$ at 500 hPa, divergence at 850 hPa, zonal wind at 200 hPa, and surface pressure) were smoothed and their maxima (or minima) in the tropics were identified as the CCKW axis at 6-hour intervals. The smoothing was essential for avoiding incorrect tracking of the strongest convective cell in the tropics at a given time, since it is not necessarily located within the CCKW region. Fig. 2.4 shows an example of the evolution of a CCKW over a 5-day period, using precipitation and surface pressure as trackers.
The algorithm starts by finding the location of the absolute minimum (or maximum) for the tracking variable in the entire tropical channel, and then a similar value is searched ahead of the position of the CCKW axis at the previous output interval. That is, for the successive times, there is a zonal range of grid points in which the new axis location must be assigned, the limits of which are defined by a pre-determined minimum and maximum propagating speed of the CCKW axis, respectively. Also, after a given number of output intervals, an update is applied by finding again the extreme value of the variable along the ITCZ, to prevent tracking a weakening or nearly dissipated wave.

Despite the application of smoothing and the several artificial constraints just described, the algorithm application was still difficult for the adequate tracking of the eastward-moving “envelope” of storms. In particular, the westward motion of the individual cells is the most problematic feature, as found while testing the algorithm. This complication, exacerbated by sensitivities to different model configurations (domain and resolution changes), plus the tuning of all the aforementioned parameters, led to the use of a different and much simpler algorithm: it involves a CCKW-filtered Hovmoller diagram, as described in the previous section, and hence, reduces the hierarchy of convection modes to only the wave type of interest.

As already stated, the tracking of CCKWs from CCKW-filtered data is straightforward, and an example of its performance is illustrated by the black crosses overlapped on the Hovmoller diagram in Fig. 2.3. However, it is worth giving some comments about the algorithm. Since two or more CCKWs can potentially coexist at a given time, the algorithm tracks the most intense one, but it doesn’t necessarily follow the absolute OLR minimum at each time; instead, it also accounts for the strengthening and weakening
phases of each CCKW. The final result is a smaller number of tracked waves, but throughout longer periods of their lifecycles, and preventing the algorithm from “jumping” onto other wave(s) and then jumping back to the previous, as shown by the comparison of the two sketches of Fig. 2.5.

2.5 CCKW composites and phase speeds

From the CCKW-filtered tracking algorithm, the locations of the CCKW axis for each output interval are stored, for each of the simulations. A new algorithm is applied to compute composites of the CCKW structure, for different 2D and 3D variables. Composites are calculated by shifting the fields in the east-west direction after relocating the CCKW axis to the center of the domain, and then averaging in time. For 3D variables, composites used in this thesis are either horizontal at any given model level (typically surface, 850mb, 500mb or 200mb), or vertical cross sections at a narrow band around the equator.

In all cases, the zonal mean of the composite (time and zonal mean of the raw variable) is subtracted to obtain the perturbation composite. This is necessary because otherwise the CCKW signal (in the east-west direction) would be in most cases masked by the meridional or vertical gradients of the variable (see Fig. 2.6). But in order to illustrate these variations simultaneously, the meridional/vertical profile of the zonal mean field is plotted on the left side of each of the composite on all composite plots in Chapters 3 and 4. Also, for comparison against aquapatch simulations, the full domain of the aquachannel is kept, as well as its true aspect ratio. This setting is more convenient
than other possibilities like cropping the inner third of the domain or alter the scale using a 1:3 aspect ratio; by artificially making a squared domain just like the aquapatch, it either distorts the physical size or neglects the tropical structure away of the CCKW axis.

The CCKW-tracking algorithm enables not only the generation of composites but also, the calculation of mean phase speeds. For each simulation, a histogram is built using the CCKW axis displacement between two consecutive time intervals (with the exception of a “jump” to another CCKW in the tropics, as seen by Fig. 2.5). Histogram categories are the number of grid points which can be associated with true phase speeds by using the model horizontal grid spacing as well as the time resolution of the model outputs (6 hours). Mean, standard deviation, and other statistical parameters are calculated for a better comparison of results among the simulations.

Since easterly propagating CCKW are embedded in the zonal flow, there is a correlation between the intensity of the latter and the mean phase speed of the former. To eliminate the bias of faster CCKWs due to stronger background flow, the mean zonal flow is subtracted. The relative phase speed is useful for the intercomparisons among simulations. This issue was recently addressed in the aforementioned work by Dias and Kiladis (2014) in a study of CCKWs with observations and reanalysis data. They defined the mean barotropic flow as the mass weight of zonal velocity from 1000 hPa to 100 hPa, and the mean vertical shear as the zonal wind at 200 hPa minus that at 850 hPa, both averaged between 15°S and 15°N. We compute here the mean barotropic flow using the same definition, although some other computations will be proposed.
2.6 APE data

As stated in the introduction, the APE experiment is a useful tool for comparison of results with our WRF simulations. Data available from the APE project (Williamson et al 2012) was processed for two Aquaplanet models, namely the GME from the Germany’s National Weather Service (DWD) and the IFS cy29r2 from the ECM-CY29 group at the European Center for Medium Range Weather Forecasts (ECMWF). These two were picked from the 14 participating modeling groups, because of the cumulus parameterization, which is the same than the used in our simulations: the Tiedtke scheme (for ECM-CY29, an enhanced version is used for deep convection, as described in Bechtold et al 2004). Additionally, both CTRL and OBS SST cases were analyzed for each model.

All APE simulations were conducted with fixed equinoctial insolation and diurnal cycle, but were integrated for a longer period, 3.5 years (including a 6-month spin-up). Horizontal resolution is ~1° for DWD and T159 for ECM-CY29, and both models use and updated version from the local Mellor-Yamada (1974) PBL scheme (while the YSU use in our simulations is a nonlocal scheme).

The online APE archive includes these categories of data:

- VAR(t) or global time series: where variables were averaged on the global domain.
- VAR(x,y) or time means for 2D and also 3D variables specified at vertical levels
- VAR(x,y,z) or time means for 3D variables
- VAR(x, y, t): or transients for a reduced set of variables, namely: OLR, total rain, upper-level zonal and meridional wind, mid-level pressure velocity and sea surface pressure.

The last dataset contains the last 365 days of the simulation. Therefore, Hovmoller diagrams, power spectra and CCKW-component of the variance can be computed using the transients’ data, using the same methodology than for our WRF simulations. Unfortunately the lack of vertical dependence of the transients does not permit the generation of vertical composites.
Figure 2.1: a) Aquachannel domain, and comparison with real Earth. b) LR aquapatch, HR aquapatch, OBS nested and CTRL nested domains, respectively.
Figure 2.2: Base 10 logarithm of the normalized OLR-S power spectrum for the [15S:15N] band computed in 4 different ways. a) Single power spectrum for the entire band and full period. b) Average of spectra computed over 10 overlapping segments. c) Average of spectra computed over 24 latitude bins. d) Average of 240 spectra computed over 10 overlapping segments and 24 latitude bins. Red polygon on panel a) indicates CCKW-filtering region. See details in text.
Figure 2.3: Hovmoller diagrams for raw (a) and CCKW-filtered (b) OLR-Symmetric. The crosses on the right panel indicate the locations of the CCKW axis for each time, as determined from an algorithm (see details in text).

Figure 2.4: Sequence every 30 hours of average rain rate (raw field on left, smoothed 550 times in the center) and surface pressure (smoothed 50 times, on right). These smoothed fields were used at every output interval for finding the maximum (minimum) of precipitation (surface pressure) associated with the CCKW axis, of which its x-location is indicated with bars for both variables. From Blanco et al (2014).
Figure 2.5: Example of CCKW-tracking algorithm functioning. From the CCKW-filtered Hovmoller, it first finds for each time the absolute OLR minimum (red) as well as the 2nd order (blue) and 3rd order (green) minima along the domain (all three away from each other), corresponding to coexisting CCKWs of different intensities (a). Using these and initially following the most intense wave, a forward-in-time correction is applied to account for the weakening phase of each wave. A similar backward-in-time correction is then applied to account for the strengthening phase of each wave. Final result is shown on the panel b. Note that this is a different example than that of Figure 2.3.

Figure 2.6: Example of composite (a) and perturbation composite (b) for a given variable, in this case moist static energy (shadings) and wind (vectors) at ~1000 hPa.
CHAPTER 3. STRUCTURE AND VARIABILITY OF CCKWs

This chapter is organized as follows: first the profiles of time and zonal means are shown for all simulations, and for several variables (section 1). For 3D variables, both horizontal profiles at fixed vertical levels and vertical profiles at the equator or other latitude/latitude bands are shown. Focusing on the temporal variability in the ITCZ, section 2 shows the OLR power spectra for the [-15°:15°] band. The CCKW signal is compared among the different cases by looking at the associated wavenumbers and propagation speeds. In section 3, the CTRL aquachannel simulation is taken as a basis for describing the overall CCKW structure, followed by a selection of these composites for the remaining simulations. Additionally, all sections include results from the Aqua Planet Experiment for comparison.

3.1 Time and Zonal Means

Fig. 3.1a shows that, as expected, the ITCZ structure is significantly sensitive to SST profile and resolution. The CTRL simulations show a sharp ITCZ centered on the equator, with precipitation values of 27 mm/day for the Aquachannel, and 31mm/day for both the LR and HR Aquapatches. The only exception is the cloud resolving case, with the peak being at 14mm/day. In all CTRL cases, the rain rate decays to ~12mm/day by 5° latitude. For the OBS simulations there is no uniform behavior. While the OBS Aquachannel case has an ITCZ similar to the CTRL cases (maximum of 17 mm/day), there is a much broader ITCZ for the OBS Nested Aquapatch: values around 6 mm/day in
the [-10°:10°] band, with slight peaks at 4° latitude. And finally the HR Aquapatch is a clear double-ITCZ case, with sharp peaks at ~5° latitude with values of 12mm/day, decaying to 4.5mm/day at the equator and at 11° latitude. When considering together the 2 nested aquapatch simulations (convection is solved explicitly in the tropics), significantly less precipitation is produced near the equator compared with the cumulus-schemed, single-grid counterparts, but this is compensated by larger rain rates in the [5°:20°] band. Finally, all cases reproduce similarly the precipitation in the ± [20°:60°] band, with a secondary peak of 5 mm/day at ~35°.

Since for some simulations the “double ITCZ effect” projects onto some of the dynamical fields, the vertical profiles of the [-15°:15°] mean were analyzed together with the profiles at the equator: by using an ITCZ mean, the spread among the different simulations reduces significantly for some variables. Also, for antisymmetric variables like meridional wind and meridional fluxes, the mean is taken for the northern hemisphere only.

Mean zonal flow is shown in Fig.3.2. While for high latitudes the curves tend to converge (Fig.3.2a), there is significant spread in the [-30°:30°] band at all levels (expect for the [20°:30°] band at 850 mb, not shown), and overall the OBS simulations have a weaker flow than the CTRL simulations. This can be better appreciated in the vertical profiles (Fig.3.2c,e). Also, for both OBS and CTRL sets, the magnitude of the westerly flow is bigger for the Aquachannel, followed by the nested Aquapatch, with the HR Aquapatch being the weakest. In particular, there is a remarkable difference at the equator between 6km and 12km height (Fig.3.2 c): while for the OBS Nested Aquapatch case easterly flow is nearly constant and about ~ - 4.5 m/s, there is westerly flow which
increases steadily with height for the 6 other simulations. Since not only is this variable important as a measure of tropical dynamics but also it strongly affects the CCKW propagation speeds, these wind profiles will be discussed again later.

Fig. 3.3b,d,f and Fig. 3.4a,c,e, show the mean meridional and vertical circulation. The CTRL Hadley cells are stronger than their OBS counterparts. The 2 double-ITCZ cases exhibit a very weak vertical motion at the equator (near zero or even downward motion for some heights), as well as very weak meridional flow at 5°N. These differences diminish substantially poleward.

Within the tropics, the meridional profile of 200mb divergence is well correlated with the precipitation profile (not shown). Meridional profile of total water content (water vapor and hydrometeors) at 500 mb is shown in Fig. 3.1c. It is also similar to the rain and upper-level divergence profiles, although the ratio between strongest and weakest values at the equator is significantly less; e.g., an excess of ~100%, while for the 850 mb profile, the ratio is even smaller, ~20% (not shown). If compared with average precipitation, the ratio between CTRL and OBS cases of the HR Aquapatch is about ~500% (Fig. 3.1a). The rapid decay with height of \( q_{total} \) is reproduced coherently by the 7 simulations, being the differences only near surface (Fig. 3.5e).

The zonal means profiles of relative humidity are shown in panels b, d and f of Fig 3.1. Biggest differences are located at the equator and the rest of the tropical region, but are also present in higher latitudes. In the ITCZ mean, there is a peak within the boundary layer with an average value of RH~85%. Finally, meridional profiles of moist static energy are shown in Fig. 3.7b,d,f. Moist static energy is defined as

\[
ms_e = gz + c_p T +
\]
$Lq$, i.e.: the sum of geopotential, sensible heat and latent heat, and it is proportional to equivalent potential energy: $dmse \sim c_p T d\ln \theta_e$.

### 3.1.1 Comparison with APE simulations

To verify whether the mean structures of the ITCZ obtained with our simulations are in agreement with the aquaplanet simulations from the APE experiment, time and zonal mean structures of the DWD and ECM-CY29 models are shown in Figs. 3.4 and 3.5, and are overlapped with the corresponding curves for some of the WRF simulations previously shown.

The mean precipitation profile (Fig. 3.4a) shows that for the 2 DWD runs and the CTRL ECM-CY29 simulations, the ITCZ peaks at the equator with values in the range of 22-30 mm/day, with a resemblance to the no-nesting WRF simulations (for the DWD cases the OLR values at the equator are significantly lower though). The remaining ECM-CY29 OBS case, is another double ITCZ example, very similar to the HR Aquapatch OBS case.

The vertical profile of zonal wind at the equator (Fig. 3.5c) exhibits a striking difference. The aquaplanet runs have easterly winds in most of the column; it only reverses above ~15km height. By this level, the aquaplanet and aquapatch simulations have a jet of westerly flow. The equatorial superrotational nature of the WRF simulated flows is characteristic of simplified simulations (Kraucunas and Hartmann, 2005). In contrast, the ECM-CY29 and DWD runs have this pattern of general circulation more in agreement with observed climatological values.
For meridional wind at 200mb (Fig. 3.5b), the single-ITCZ aquaplanet cases have a meridional component of the wind well correlated with the WRF single-ITCZ cases, which is weaker for the double-ITCZ cases, ECN-CY29 OBS and HR Aquapatch OBS and the WRF nested aquapatchs. Similarly this pairing can be seen in the vertical profile near the equator (Fig. 3.5d).

The large differences in relative humidity are surprising. In the equatorial boundary layer, aquaplanet simulations have values greater than 90% while in the WRF runs values are smaller than 80% (Fig. 3.4b). Also in the 850 mb level, the atmosphere in midlatitudes for the WRF runs is much closer to saturation (Fig. 3.4c).

### 3.2 Spectral Analysis and CCKW phase speeds

#### 3.2.1 CCKWs on the OLR-S spectra

For the power spectra comparison between Aquapatch and Aquaplanet simulations (Figs. 3.6 and 3.7), it is worth mentioning that wavenumbers are calculated with respect to the length scale given by the domain length (Lx=40000 km for aquachannel and a third of that length for the aquachannel domain); hence, in terms of physical space, the x axis for both plots are equal (e.g.: wavenumber 1 in aquapatch power spectrum equals wavenumber 3 in the aquachannel power spectrum, that is, a scale of 13,300 km, and similarly for other wavenumbers).

The overall pattern is a clear CCKW signal, which is concentrated toward the smallest frequencies and wavenumbers, and the lack of signal associated to the Equatorial
Rossby (ER) and Inertio-Gravity (IG) waves (however, there is ER activity as will be discussed later). For the Aquachannel simulations, the dominant CCKW wavenumbers for the CTRL case are \( k=2 \) followed by \( k=1 \), while for the OBS case, \( k=1 \), followed by \( k=2 \) and \( k=6 \). For the remaining 5 Aquapatch simulations, \( k=1 \) is the dominant wavenumber, followed by \( k=2 \). So in the hierarchy of cumulus organization, it appears that the most repeated pattern is that of a single large envelope of convection propagating eastward along the tropics, with the exception of the Aquachannel OBS case (2 coexisting CCKWs).

Phase speeds can be directly estimated from the power spectra, by simply dividing frequency and wavenumber over any point on the diagram. In particular, since the theoretical (dry or free) Kelvin waves are non-dispersive, curves are straight lines and all points on each have the same propagation speed, given by \( c = \sqrt{\frac{g}{h}} \). All Matsuno modes are plotted for 5 equivalent depths (\( h_e = 6, 12, 25, 50 \) and 100 meters), yielding Kelvin phase speeds of 7.7, 10.8, 15.6, 22.1 and 31.1 m/s, respectively, while the typical equivalent height for a dry kelvin wave is 200m, with an associated speed of \(~44.2\) m/s. Then, the mean speed of CCKW can be qualitatively estimated using these 5 values for simplicity.

Comparing left and right columns on Figs. 3.6 and 3.7, it is clear that for the HR and Nested spectra, the OBS signal is biased more to the right/bottom side of the red polygon with respect to the CTRL signal, meaning slower propagation speeds. For example, for the HR Aquapatch simulations, the \( k=1 \) peaks are associated with waves propagating approximately at speeds of as fast as 30 m/s and as slow as 12 m/s in the CTRL case,
while for the OBS, the speed of the fastest waves is about 18 m/s, and around 9 m/s for the slowest waves.

### 3.2.2 Computed CCKW phase speeds

The above estimated values can be compared with the speeds obtained using the CCKW-tracking algorithm described in the previous chapter. However, with this approach only a single speed can be computed at a time (tracking the strongest wave in case there are 2 or more coexisting CCKWs) and hence, this represents a disadvantage in terms of the information provided by the spectrum (for instance if there was a tendency of the weaker wave to propagate either faster or slower than the tracked wave, it could not be possible to account such effect). But on the other hand, the statistical analysis of phase speeds computed at every output interval can provide useful information. Fig. 3.8 shows these distributions for each simulation.

The mean propagation speeds are shown in the first row of Table 3.1: maximum is 19.12 m/s for the CTRL Aquachannel simulation, and minimum is 11.12 m/s for the OBS HR Aquapatch. As anticipated from the qualitative analysis from the power spectra, the CCKWs propagate faster when CTRL SST are used instead of OBS SST.

This result is primarily due to the fact that the mean zonal flow in the tropics is stronger for CTRL simulations than for OBS, as showed by Fig 3.2. Hence, it is more meaningful to compute phase speeds relative to the background flow, as detailed in the previous chapter. These values are shown in the last row of Table 3.1. Not only is the CTRL-OBS difference significantly reduced for each pair, but also, the overall spread for
the 7 simulations is very small (~2.5 m/s). Relative to the flow, the OBS HR Aquapatch waves are the fastest, rather than the slowest.

The order of the fastest relative speed can in fact change if the mean barotropic flow is computed differently; this was observed after a sensitivity test, using additional latitude bands of 10 and 5 degrees from the equator, and upper bounds of 100 and 150 hPa (not shown). However, this does not modify the general result: the great similarities of relative CCKW speeds for all simulations.

3.2.3 Other CCEWs

Figs. 3.9 and 3.10 show the enhanced power spectra for the antisymmetric component of OLR. The dominating signals are not associated to the Matsuno gravest mode (n=0, the westward Mixed Rossby-Gravity and eastward IG waves); instead there is a correspondence with the curves from the Kelvin mode (Figs. 3.6 and 3.7). This indicates that ITCZ precipitation is not entirely symmetric about the equator (despite the model configuration), and can in fact propagate together with the symmetric component (CCKW).

It is interesting to note that there is also signal associated with the westward ER mode. Like the Kelvin mode, it is another example of a weak antisymmetric signal accompanying the much stronger symmetric signal. The fact that there is not enhanced power of ER mode in the OLR-S spectra shown in Figs. 3.6 and 3.7 is simply because it is dominated by the CCKW component (recall the normalization when dividing by the background spectra).
Finally, there is an apparent MJO component in the OLR-S spectrum for the OBS Nested Aquapatch simulation (Fig 3.7d), which is absent in the other 6 cases. To investigate this, the filtering technique was applied to generate an MJO-filtered Hovmoller diagram (the filtering region is a rectangle with wavenumber ranging from 0 to 6 and frequencies from 0 to 0.05 cpd). Fig. 3.11 shows Hovmoller diagrams in the ITCZ for both MJO and CCKW filters. It can be seen that in periods of 30-60 days, an MJO-like signal is present and characterized as a slow-moving envelope which enhances CCKW activity. It would be desirable to analyze whether this is a persistent or coincidental pattern by running the simulation for a longer period, but the high computational cost is prohibitive.

3.2.4 Comparison with APE simulations

The availability of the APE dataset includes transients of two-dimensional variables for the period of one year, which permit the analysis of tropical variability. Normalized spectra of OLR-S are shown in Fig. 3.12 for DWD and ECM-CY29 models, and for both OBS and CTRL SST cases. Like for the WRF simulations, the CCKW mode is still dominant, and similarly there are variations in characteristic equivalent depth and dominant zonal wavenumber. Qualitatively, for the DWD model the CCKWs propagate slower with the OBS SSTs than with CTRL, in agreement with the finding for our simulations; this does not appear to be the case for the ECM-CY29 model. There are clear signals of ER and IG modes (ER waves are more prominent in the OBS simulations).
Like for the WRF simulations, Fig. 3.13 shows that the Kelvin and Equatorial Rossby (symmetric) modes project onto the antisymmetric spectra; however, for these 4 aquaplanet cases there is a stronger signal associated to the westward ER waves than the signal associated to the CCKWs. The fact that there are many more patches of IG enhanced power present in the Aquaplanet spectra (both symmetric and antisymmetric components) compared to the WRF simulations does not mean that there are less or no waves of this type in the latter, but only the dominance of the CCKW modes: this is a direct consequence (and disadvantage) of the normalization of the spectra.

The spectra for the CTRL SST profile for all APE experiments (including DWD and ECM-CY29) are shown and discussed in Blackburn et al (2013). They were though computed for the [-10°:10°] tropical band and not normalized by the background spectrum. The reason for the latter is that for the intercomparisons among all models, they prefer to retain the overall power instead of highlighting the spectral peaks. The focus here is to compare the dominant modes regardless of the magnitude.

The APE spectra intercomparisons for different SST configurations including OBS, are shown and described in Williamson et al (2013); they were performed for the [-20°:20°] band though, because of the broader ITCZ profiles. While the [-15°:15°] band was used for all shown spectra in this thesis (following WK99), differences in computing the spectra in a broader ITCZ are small: for narrow ITCZs the effect of the larger domain is to reduce the average power somewhat, but the basic structure is retained.

Easterly waves are an additional type of tropical disturbances which together with the MJO are not included in Matsuno’s linear shallow water solutions. These perturbations can sometimes strengthen and evolve into tropical depressions (TD), and even hurricanes.
The corresponding TD region in the frequency-wavenumber domain is around 1/3 to 1/6 cycles per day, and planetary wavenumbers -15 to -7 (i.e.: above the ER curves on the symmetric spectrum). There is no such signal for the WRF simulations, but there is and on both OLR-S and OLR-A spectra for the aquaplanet simulations, in particular for the OBS cases. It is important to notice that there could be either false positives (ER waves Doppler-shifted by easterly background flow, or other type of disturbances with no voriticity) or no detections (masking due to the normalization of the spectra). To find the existence or not of tropical cyclones, a visual inspection of the animation of pressure or precipitation fields is sufficient. These were analyzed for the entire simulation and tropical cyclones were neither found in the any of the 7 WRF simulations, nor for the OBS and CTRL SST settings in Aquaplanet experiments (Williamson et al 2013; Nakajima et al 2013).

Like for the WRF simulations, the CCKW-tracking algorithm was applied on CCKW-filtered OLR-S space-time series to compute the mean propagation speed (Fig. 3.14). Results confirm what was anticipated by the qualitatively comparison of the normalized power spectra: for the DWD model the CCKWs propagate slower with the OBS than with CTRL SSTs, but the opposite stands for the ECM-CY29 model. However, the spread of mean velocities is much less compared to those from the 7 WRF simulations (see first line of Table 3.2).

Interestingly, by additionally expressing these velocities relative to the mean barotropic flow (which is easterly in all cases), the resulting speeds are significantly high for 3 of the 4 simulations (i.e.: \( \geq 17 \) m/s). The exception is the CTRL ECM-CY29 with a value of 12.45 m/s, but still representing a faster propagation than all WRF cases, with
values in the range of 9-11.5 m/s (last row of Table 3.2). From this perspective, relative CCKW phase speeds represent a major discrepancy of our shorter-domain simulations compared to the Aquaplanets’.

It is worth considering in the computation of the mean barotropic flow, whether the 100 hPa and 1000 hPa levels are the most appropriate ones for the top and bottom bounds of the mass-weighted average. By looking at the different zonal mean profiles on Fig. 3.5c, it is readily apparent that if a low-level background flow was used instead, to compute relative CCKW phase speeds, the aforementioned differences would be reduced. To verify so, calculations were repeated replacing the top level of 100 hPa by 700 hPa, and results are shown in Table 3.3. Overall, the spread among the 11 simulation is significantly reduced (but if only the 7 WRF cases are considered, the spread is smaller with the former calculation). In particular the CTRL Aquachannel and CTRL Nested Aquapatch cases with relative speeds of 19.42 m/s and 19.03 m/s respectively, are within the range of speeds of the Aquaplanet simulations (18-21 m/s).

The use of the low-level background flow, introduced here just as a way to minimize the discrepancies of CCKW relative propagation speeds between our WRF simulations and the APE’s, will prove its usefulness in the next chapter, in terms of CCKW dynamics.

3.3 ITCZ and CCKW variances

As stated before, the magnitude of the power on the spectrum (and in particular, the power associated with the CCKW signal) cannot be compared among the simulations due
to the normalization. For this reason, an analysis of the CCKW variance is presented here: not only does it permit the quantification of these differences, but also, it greatly simplifies it by the use of a simple metric.

First, variance was calculated for the time series of each grid point, finally obtaining a mean variance for all longitudes (nearly the same result is obtained by computing variances in space followed by an average in time). The result is the mean variance as a function of latitude, and their root square values (namely, standard deviation) are shown in Fig. 3.15 for OLR and precipitation. Comparing the SD values with the corresponding mean values for precipitation (Figs. 3.15a and 3.4a), a clear correlation arises as the main pattern: the magnitude of the averages equals to roughly 45% of the SD values, for the entire [60S-60N] band. But the importance of the analysis of the ITCZ variability (and not just its structure) is evidenced with some particular examples. While the CTRL HR Aquapatch has nearly the same mean rain rate at the equator than the CTRL LR Aquapatch and both DWD cases (Fig. 3.4a), its SD (~80 mm/day) nearly doubles the values of the other 3 (Fig. 3.15a).

Next, the mean OLR variance at the ITCZ was computed: in first place, the mean values for the [-15°,15°] band are taken, just like for the calculation of the spectra. Then, from the zonal-time series, variance was computed in time and averaged in space, yielding a single value for each simulation, as depicted in Fig. 3.16a. When comparing total ITCZ variability, the maximum value corresponds to the OBS nested Aquapatch (~400 W²/m⁴), followed by its CTRL counterpart (~300 W²/m⁴), while the minimum value is for the OBS ECM-CY29 simulation (~90 W²/m⁴). Notice that for both CCKW
contribution and total variances, values are greater for the CTRL case than the OBS case, with the exception of the Nested Aquapatch.

The CCKW component of the OLR-S variance at the ITCZ was also computed, using the CCKW-filtered zonal-time series of OLR-S instead of the unfiltered zonal-time series of OLR. Results for each simulation are shown in Fig. 3.16b. The magnitude of this variance is greatest for the CTRL Aquachannel case (~120 W²/m⁴), followed by the OBS nested aquapatch (~90 W²/m⁴). On the other hand, the minimum value is of the order of 20 W²/m⁴, for both the OBS ECM-CY29 case and the OBS HR Aquapatch.

More interesting perhaps, is to compare model differences with the CCKW contribution of the variance scaled by the total ITCZ variance, i.e.: to quantify how much of the ITCZ variability is explained by the CCKWs. A significant high value of ~ 45% is obtained for the CTRL Aquachannel and CTRL ECM-CY29 simulations, followed by a 36% value for the OBS Aquachannel case (Fig. 3.16c). For the rest of the simulations, the CCKWs represent a smaller percentage of the total ITCZ variability, between 13% and 23%.

It is important to notice that these variances are variable-dependent. For instance, Nakajima et al (2013) analyze variance for total precipitation instead of OLR, and they found that the corresponding percentage of ITCZ variance explained by CCKW for the CTRL ECM-CY29 model is only 8% (see their Fig.6), instead of the 45% for OLR as shown in Fig. 3.16c. Differences due to changes in the variance computations are also possible.
3.4 Composites of the CCKW structure

3.4.1 CTRL Aquachannel simulation

Figs. 3.17-3.22 show 20 perturbation composites for horizontal and vertical structures of several dynamical and thermodynamical variables, namely: OLR, total precipitation, wind, horizontal divergence, relative humidity, total cloud condensate, temperature and moist static energy.

The OLR and precipitation composites (Fig. 3.17) show a coherent region of strong zonal anomalies associated with the Kelvin wave. The meridional spread of the signal is larger for OLR values. Also, the rain region is shifted eastward by about 800 km of the OLR region (which, because of the methodology used, is exactly collocated with the CCKW axis). For both variables there are 2 regions of strong anomalies with the opposite sign: the closest is behind the wave axis and the other is ahead by ~10,000 km. OLR perturbations range from -40 to 10 W/m2 (the scales for these and the remaining variables have been chosen to be useful for all 7 simulations).

In terms of the vertical structure of the zonal wind field (Fig. 3.18c), there is a strong core of easterly anomalies associated with the CCKW, which is centered at the equator and extends for about 4000 km in the zonal direction, and in the vertical is located at 13-15 km height, with a strong gradient in the tropopause (~16 km), and slow decay into the mid-levels. It is a triangle-shaped feature, deeper ahead of the wave than behind (positively tilted isolines with height in high levels and negatively tilted in low levels). Below, also collocated with the CCKW axis, there is a core of westerly anomalies that
extends to the surface, and is tilted westward with height. Ahead of the wave, there is another significant regions of westerly anomalies that extends from mid to high levels, and for over 15,000 km in the zonal direction.

More details of the three dimensional structure of the zonal wind can be appreciated by looking at the horizontal plots for low and high levels. At 200 mb (Fig. 3.18b), the easterly core extends meridionally 2,000 km over both hemispheres, beyond which there are 2 elongated westerly anomalies, which connect at the equator 5,000 km ahead of the CCKW axis. The other shown composite was computed within the boundary layer (Fig. 3.18a): the region of strong equatorial westerly anomalies decays, but then strengthens towards 2 lobules off the equator, by 8,000 km behind the wave axis.

The vertical velocity structure at 700 m (Fig. 3.19a): height is well correlated with the total precipitation structure, that is, the ascent region ahead of the CCKW axis. By about 5,000 m height (Fig. 3.19b), it is slightly shifted westward, but the peak is still ahead by about 700 km. The strongest upward anomaly (~5cm/s) is at about 9-10 km height (Fig. 3.19c), approximately the same height for the strongest zonal mean (~3.3 cm/s), yielding a total composited CCKW ascent of ~ 8 cm/s. Note that the composite is computed as a mean in the [-2°:2°] equatorial band; stronger values would arise by computing it right at the equator (zonal mean of $w$ has a peak value of 4.5 cm/s as shown in Fig. 3.3c).

The strong CCKW convergence in low levels along ITCZ (Fig. 3.20b) is dynamically balanced by a divergent outflow aloft (Fig. 3.20c). The perturbation composite for meridional wind at 200 hPa (Fig. 3.20a) shows 2 clear regions of anomalies of opposite sign, being their maximum amplitude located at the CCKW axis. By additionally considering the zonal flow, the resulting pattern is a pair of anticyclonic vortices, one on
each hemisphere, as depicted by the overlapped arrows (perturbation wind vectors): the centers of these circulations are about 2,500 km ahead of the wave axis. The zero divergence level is approximately at 7.5 km height (Fig. 3.20d). The convergence region at 700 m is well correlated with the updraft (at the same level), as well as with the precipitation region.

The perturbation composite for relative humidity at the equator (Fig. 3.21b) shows positive anomalies of up to 25% at about 6 km, which added to the zonal mean yields a value of ~75%. Notice that this clear CCKW signal completely disappears between 1 and 3 km height (i.e.: nearly homogeneous RH values for the entire domain in that layer), but it is again present below, in the surface layer. The meridional structure within the boundary layer (Fig. 3.21a) shows that the relative humidity in the extratropics at the wave axis is smaller than its zonal average; however, lagging behind (about 6,000 km) there is a lobule of positive anomalies on each hemisphere.

In terms of actual humidity (including liquid water content), not only do the positive anomalies extend downward to the surface, but also ahead of the wave, with the moistened region extending over a significant section of the domain, 15,000 km (Fig. 3.21d). The moisture peak is about 5 km height, and extends vertically for about 4,000 km and meridionally around 3,000 km (Fig. 3.21c).

The Kelvin wave is also characterized by an axis of cold anomalies (about -1 K), both meridionally and vertically, as can be seen in Fig. 3.22a,b. In mid-levels, there is a zonally extended region of warm anomalies ahead of the wave (collocated with the aforementioned dry anomalies); however, behind the wave there are two warm anomalies outside the equatorial region (between 2,000 and 5,000 km), with weak cold
perturbations along the equator. For the 850 mb level, similar coherent patterns are present (not shown) but in the 200 mb level, there is a sequence of regions of alternating anomalies, with amplitudes that greatly exceed the positive (negative) perturbations ahead (behind) of the CCKW axis along the equator (not shown). Between 8 and 12 km height the regions of cold anomalies extends backwards, but above that layer, it bends forward, nearly horizontal around the tropopause, giving an overall boomerang-like shape to the vertical temperature structure.

Moist static energy structure (Fig. 3.22c,d) is similar to that of temperature, except in low levels due to the humidity component. While for temperature the strong east-west anomalies are present in mid and high levels, they extend through the whole vertical for \( mse \).

### 3.4.2 Simulations comparison

Figs 3.23 through 3.31 show the intercomparisons among the 7 WRF simulations for a reduced set of variables: these plots are representative of the CCKW structure, which was shown with more detail for the CTRL Aquaplanet simulation. The top half of each figure shows the CTRL and OBS Aquachannel cases, and the bottom half the 5 remaining Aquapatch simulations (the bottom row contains the 2 nested cases).

The greatest overall difference is the small amplitude of CCKW signals for the OBS HR Aquapatch (panel e on each figure), compared to the 6 other simulations. As already mentioned in section 3.1 for the zonal mean profiles, this is undoubtedly linked to the double ITCZ nature of this case: the broader convective area produces (and is affected
by weaker dynamics. In the case of composites of vertical structure, the replacement of the averaging [-2°:2°] band by a broader one does not counteract this effect (not shown).

The second comparison is between Aquachannel (panels a and b) and Aquapatch (panels c through g) simulations: how does the overall structure change by reducing the domain to one third of the original? Those signals localized at/near the CCKW axis do not significantly change their zonal widths; examples can be seen in most of the composites. In contrast, the patterns that extend upstream and downstream of the wave, are much reduced and actually converge into a compact structure at the $x=0=Lx$ position. In other words, the zonally slow decay (or transition region) disappears, as is the case for $mse$ (Fig. 3.25) zonal wind (Figs. 3.26 and 3.27), and $q_{total}$ (Figs. 3.31). Therefore, this might represent a clear disadvantage while trying to analyze the structures of the leading and the trailing part of the CCKW.

The CTRL versus OBS simulations for the aquachannel domain show one distinctive feature: the “wavenumber 2” persistence on the latter, which is indicated by a region of anomalies centered at about 7,000 km west of the “main” CCKW axis (clear on Figs. 3.23b, 3.26b, 3.27b, 3.28b and 3.30b). Individual cases of $k=2$ were actually observed in both simulations, typically characterized by a new wave forming ahead of a pre-existent decaying one. Nonetheless, the overall effect through the entire integration period prevails only on the OBS case. In turn, the CTRL versus OBS comparison for the nested Aquapatch setting is dominated by an overall weaker signal for the latter case, and this is due to a much broader ITCZ (although differences are not striking like in the double ITCZ case).
Finally, a cloud-resolving vs convection-parameterized comparison can be addressed for the CTRL case (panels c, d and f), since differences in mean ITCZ structure are much smaller than for the OBS simulations. Signals are strongest for the Nested Aquapatch (and overall, the CTRL nested has the strongest among the 7 simulations) than for the HR and LR Aquapatches (the perturbations of the latter are the smallest of the 3). The most important finding is that despite the magnitudes, the structure for all variables is remarkably similar in the 3 cases.

3.4.3 Comparison with APE simulations

Horizontal composites were generated using the APE transient dataset and the same methodology than for the WRF simulations (CCKW tracking via OLR sequences). Structures for OLR, precipitation, mid-level vertical velocity and upper-level winds are shown in Figs. 3.32 through 3.36. The scales are the same as used for the WRF simulations, allowing a better comparison of magnitudes. In all figures it is evident that the double ITCZ case (OBS ECM-CY29) has the weakest signal, just like the OBS HR Aquapatch in the WRF composites.

The OLR fields (Fig. 3.32) show significantly smaller amplitudes of anomalies compared with the Aquachannel cases (Fig.3.23). Two other differences are readily discernible: the Aquaplanet CCKW signal extends deeper towards midlatitudes, and also, the regions of positive anomalies both ahead and behind the wave are closer to the CCKW axis than in the Aquachannel cases.
Both structure of intensity of composited precipitation are strikingly similar between CTRL Aquaplanets (Fig. 3.33) and both CTRL and OBS Aquachannels (Fig. 3.24). The amplitude of rain perturbation is somewhat smaller for the OBS DWD case, while the structure and magnitude of the OBS ECM-CY29 case resemblances that of the OBS HR Aquapatch.

Vertical velocity fields (Fig. 3.34) were actually estimated from omega, using a constant reference density value of 0.690 kg/m$^3$ at 500 mb. This variable is well correlated with precipitation; again, anomalies are greater for the CTRL cases. In particular, for the CTRL DWD case (Fig. 3.34a), the magnitude (and not just its structure) is very similar to that from the CTRL Aquachannel case (Fig.3.19b).

Composites for zonal wind at high levels show an overall agreement in their structure for the 4 Aquaplanet cases (Fig. 3.35): the most coherent pattern is a quadrupole signal in midlatitudes, with positive (negative) values ahead of (behind) the CCKW axis. However, the biggest difference arises when comparing with Aquachannel cases: the dominating signal for the latter is a core of strong easterly anomalies centered at the equator that extends considerably both zonally and meridionally (Fig. 4.27a,b). This signal is weak for DWD, and strong for CTRL ECM-CY29, but for the 3 cases it is ahead of the CCKW axis, with westerly anomalies behind.

From the point of view of the total composited zonal wind (adding the values of zonal means and anomalies), the discrepancies between Aquachannels and Aquaplanets are reduced: recall that the flow for the WRF simulations is superrorational in the tropics, unlike in the Aquaplanets (Fig. 3.5c). Therefore, the equatorial core of strong anomalies at the equator associated with the CCKWs counteracts such westerly background flow.
Interestingly, some of the Aquapatch cases represent “intermediate cases”, in which both signals are present, (peaks of anomalies at both the equator and midlatitudes). In particular, the magnitude at the CCKW region of the CTRL ECM-CY29 case (Fig. 3.35b) does not differ much from the CTRL LR and HR Aquapatches (Fig. 3.27c,d).

Upper-level meridional wind for DWD and ECM-CY29 simulations is shown in Fig. 3.36, and can be compared with the WRF composites shown in Fig. 3.29. The quadrupole structure around the CCKW axis is also found in the Aquaplanet cases. However, a clear difference between the Aquachannels and the 2 CTRL Aquaplanets, is that in the latter there is a series of regions of alternating equatorward and poleward anomalies along the midlatitudes, with magnitudes somewhat smaller than those of the quadrupole.

Since composites of vertical structures cannot be computed due to the lacking of vertical dependence of the transients, we consider first APE references. Nakajima et al (2013) show some composites of CCKW structure for several of the APE models, and the results are discussed (there are no additional CCKW composites in the APE ATLAS). However, differences in the methodology of calculation are worth mentioning: the filtering region is much broader (red polygons in Fig. 3.12), and was applied to power spectra of precipitation rather than OLR, and for a narrower band: [-5º:5º] instead of [-15º:15º]. The composite technique uses a regression analysis, rather than a CCKW tracking algorithm. Furthermore, only the CTRL case is analyzed by the Nakajima et al, and DWD is not part of the model selection. The horizontal composites shown are total rain and wind vectors at 925 mb, geopotential height and wind vectors at 850 mb and 250 mb, and the vertical composites shown are for temperature and mixing ratio, together with wind vectors. Except for wind vectors and geopotential, variables shown are zonal
perturbations. The zonal extension of these plots is reduced to the 10,000 km comprising the CCKW axis, (i.e.: only ¼ of the domain) and also for the horizontal plots, only the [-15º:15º] band is shown. Finally, in all composites values are normalized, so magnitudes cannot be compared, only spatial patterns.

The only 2 vertical structure composites from the CTRL ECM-CY29 model are reproduced here for a qualitatively comparison with the CTRL Aquachannel simulation. Fig. 3.37a shows the CTRL ECM-CY29 composited temperature, and the corresponding CTRL Aquachannel simulation is additionally shown in Fig. 3.37b, for the same section of the domain. There is an overall agreement between both models. Mid-level cold anomalies nearly aligned with the CCKW axis, and above that, a warm anomaly intrusion between 200 and 400 hPa, that extends eastward for over 5,000 km, and downward. On top, near the tropopause there is another tongue of cold anomalies.

An analogous comparison is presented in Fig. 3.37c,d for humidity. Both models show a well-extended region of positive moisture anomalies, collocated with the CCKW axis by mid-levels, where it is strongest. One difference is that for the Aquaplanet case, it is negatively tilted with height, being the peak at the boundary layer about 2,000 km ahead. Instead, in the Aquachannel case, it is nearly zonally oriented, but there is a secondary tongue between surface and mid-levels, which is positively tilted with height.

Lastly we compared the composites of temperature, humidity and zonal wind anomalies from 2 other aquaplanet experiments to better assess differences in vertical structures against our WRF simulations. The first set corresponds to Frierson (2007), whose model uses a simplified Betts-Miller cumulus scheme, and composites were obtained following a filtering technique, with pressure velocity at 500 mb as a CCKW
tracker. The second is taken from Lee et al (2003): their model uses a simplified Arakawa-Schubert scheme, and composites were obtained without filtering, being convergence at 850 mb the tracking variable. There are some noticeable differences in location and extension of the strongest signals for temperature anomalies (not shown). On the other hand, the slantwise structure of moisture anomalies is remarkably coherent in all simulations (not shown). Finally, the zonal wind composites for both aquaplanet simulations show a very similar structure than those seen for the WRF simulations, despite differences in the latitudinal averaging region. Qualitatively, the first baroclinic mode is the most prominent feature (not shown).
Table 3.1: True and relative (respect to the mean barotropic flow) CCKW speeds (in m/s) for all the simulations. Maximum and minimum of each set are highlighted. Mean barotropic flow computed in the [-15°:15°] band, integrated from 1000 mb to 100 mb.

<table>
<thead>
<tr>
<th></th>
<th>AQUACHANNEL</th>
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<th>AQUAPATCH</th>
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<td>OBS</td>
<td>CTRL</td>
<td>HR</td>
<td>OBS</td>
<td>CTRL</td>
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<td>16.76</td>
<td>15.33</td>
<td>11.12</td>
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<td>MEAN FLOW</td>
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<td>7.29</td>
<td>6.24</td>
<td>-0.43</td>
<td>7.22</td>
</tr>
<tr>
<td>RELATIVE SPEED</td>
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<td>9.47</td>
<td>9.09</td>
<td>11.55</td>
<td>10.36</td>
</tr>
</tbody>
</table>

Table 3.2: As in Table 3.1, extended to the Aquaplanet simulations.

<table>
<thead>
<tr>
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<th>WRF PATCH</th>
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<th>PLANET</th>
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<tbody>
<tr>
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<td>OBS</td>
<td>CTRL</td>
<td>HR</td>
<td>OBS</td>
<td>CTRL</td>
</tr>
<tr>
<td>MEAN FLOW</td>
<td>9.19</td>
<td>6.25</td>
<td>7.29</td>
<td>6.24</td>
<td>-0.43</td>
<td>7.22</td>
</tr>
</tbody>
</table>

Table 3.3: As in Table 3.2, but considering a low-level background flow (vertically integrated up to 700 mb).
Figure 3.1: Time and zonal mean meridional profiles of precipitation (a), $q_{total}$ [water vapor + total cloud condensate (precipitating and non-precipitating)] at 500 mb (b) and relative humidity at 500 mb (c). Time and zonal mean vertical profiles of relative humidity at the equator (d) and mean [-15º:15º] vertical profiles of $q_{total}$ (e) and relative humidity (f).
Figure 3.2: Time and zonal mean meridional profiles of zonal (a) and meridional (b) wind at 200 mb, and meridional wind at 850 mb (d). Time and zonal mean vertical profiles of zonal wind at the equator (c), and mean in the [-15°:15°] band (e), and meridional wind at 5°N (f).
Figure 3.3: Time and zonal mean meridional profiles of vertical velocity at 500 mb (a) and moist static energy at 200 mb (b) and 850 mb (d). Time and zonal mean vertical profiles (mean in the [-15°:15°] band) of vertical velocity (e), and moist static energy (f).
Figure 3.4: Time and zonal mean meridional profiles of precipitation (a) and relative humidity at 850 mb (b). Time and zonal mean vertical profiles of relative humidity at the equator (c).
Figure 3.5: Time and zonal mean meridional profiles of zonal (a) and meridional (b) wind at 200 mb. Time and zonal mean vertical profiles of vertical zonal wind at the equator (c) and meridional wind at 5°N (d).
Figure 3.6. Normalized Power spectra of OLR-S for a) CTRL Aquachannel, b) OBS Aquachannel, and c) CTRL LR Aquapatch simulations. Red polygon indicates CCKW-filtering region.
Figure 3.7. Normalized Power spectra of OLR-S for a) CTRL and b) OBS HR Aquapatch simulations and for c) CTRL and d) OBS Nested Aquapatch simulations. Red polygon indicates CCKW-filtering region.
Figure 3.8: Speed distributions as computed from the CCKW tracking algorithm. Speed categories are number of grid points advanced by the CCKW axis between 2 consecutive time steps. Also indicated is the frequency of “jumps” from one wave to another (in a different region of the domain).
Figure 3.9: As in Figure 3.6 but for OLR-A. Notice the different scales.
Figure 3.10: As in Figure 3.7 but for OLR-A. Notice the different scales.
Figure 3.11: CCKW-filtered (a) and MJO-filtered (b) Hovmoller diagrams in the [-15º:15º] band for the OBS Nested Aquapatch simulation.
Figure 3.12: Normalized Power spectra of OLR-S for the Aquaplanet simulations. a) CTRL DWD, b) OBS DWD, c) CTRL ECMCY29 and d) OBS ECMCY29. The red polygon corresponds to the CCKW-filtering region used in APE (the filtering region for the WRF simulations is also shown in dashed lines). Notice the different scales.
Figure 3.13: As in Figure 3.12 but of OLR-A.
Figure 3.14: As in Figure 3.8 but for the 4 Aquaplanet simulations. Notice that due to the course resolution of the model output (2 degrees), the CCKW axis might remain at the same grid point within a 6-hour interval.
Figure 3.15: Meridional profiles of Standard Deviation for precipitation and OLR
Figure 3.16: OLR Variance at the ITCZ for all simulations: total (a), CCKW component (b), and ratio CCKW/total (c).
Figure 3.17: Perturbation composites of OLR and precipitation, for the CTRL Aquachannel simulation. Overlapped on the left, the mean meridional profile.
Figure 3.18: Horizontal and vertical structures of zonal wind perturbation composites, for the CTRL Aquachannel simulation. Vertical level (width of tropical band) is indicated on each horizontal (vertical) composite. Overlapped on the left, the mean meridional (vertical) profile.
Figure 3.19: As in Figure 3.18 for vertical velocity.
Figure 3.20: As in Figure 3.18 for meridional velocity and horizontal divergence
Figure 3.21: As in Figure 3.18 for relative humidity and $q_{total}$.
Figure 3.22: As in Figure 3.18 for potential temperature and moist static energy.
Figure 3.23: WRF perturbation composites of OLR. First 2 rows correspond to CTRL (a) and OBS (b) Aquachannel simulations. Third row corresponds to CTRL LR (c), CTRL HR (d) and OBS HR (d) Aquapatch cases, respectively. Last row corresponds to CTRL (f) and OBS (g) Nested Aquapatch simulations. Scale is fixed for all cases.
Figure 3.24: As in Figure 3.23 but for precipitation
Figure 3.25: As in Figure 3.23 but for moist static energy at the equator.
Figure 3.26: As in Figure 3.23 but for zonal wind at 200 mb
Figure 3.27: As in Figure 3.23 but for zonal wind at the equator
Figure 3.28: As in Figure 3.23 but for vertical velocity at the equator
Figure 3.29: As in Figure 3.23 but for meridional wind at 200 mb
Figure 3.30: As in Figure 3.23 but for horizontal divergence at the equator
Figure 3.31: As in Figure 3.23 but for $q_{total}$ at the equator
Figure 3.32: Aquaplanet composites for perturbations of OLR. The corresponding models are (a) CTRL DWD, (b) CTRL ECMCY29, (c), OBS DWD and (d) CTRL ECMCY29. Scale is fixed for all cases.
Figure 3.33: As in Figure 3.32 but for precipitation
Figure 3.34: As in Figure 3.32 but for vertical velocity at 500 mb
Figure 3.35: As in Figure 3.32 but for zonal wind at 250 mb
Figure 3.36: As in Figure 3.32 but for meridional wind at 250 mb
Figure 3.37: Qualitative comparison of temperature (a and b) and humidity (c and d) perturbation composites at the equator, between the CTRL ECM-CY29 simulation (a and c, adapted from Nakajima et al 2013), and the CTRL Aquachannel simulation (b and d). Only ¼ of the zonal domain is shown.
CHAPTER 4. ANALYSIS OF CCKW LIFE CYCLES

Why do CCKWs strengthen and decay? This is a topic that has not previously been addressed. One of the aims of this thesis is to analyze different phases of the lifecycles of CCKWs, and seek an answer to that question. For this purpose we extend the composite and phase speed analysis by subdividing the data in 3 groups, each of them containing a selection of cases of the early, mature and decaying stages of the CCKW. Details of the subjective methodology used are presented in Section 1. Section 2 addresses the mean phase speeds of each stage of the CCKW and their relation with the zonal wind, while Section 3 shows some of the composited horizontal and vertical structure for each of the stages. Finally, and based on these results, an analysis of the coupling and decoupling processes involved in the CCKW dynamics is performed (section 4). As stated before, since the LR aquapatch simulation was intended as a transition case, it was excluded for this stage analysis.

4.1 Stages of the CCKW life cycle

Initially the possibility of applying the tracking algorithm method with some modifications was evaluated. A straightforward approach would be to assign the entire length of the simulations (1440 output intervals for the single-grid simulations) into the 3 categories, one for each stage. However, one of the shortcomings of this algorithm is that it picks locations for the CCKWs even when there is no such wave, when the last has
already dissipated and the new one has not yet formed. Since this occurred frequently, some of the stages would be corrupted by the inappropriate data.

To more accurately identify each of the stages, a subjective selection process is applied instead. The method consists of a direct visual inspection on a CCKW-filtered Hovmoller diagram. Only well-defined, “ideal” CCKWs are selected. By ideal, we mean that not only are cases of too weak or non-existent CCKWs eliminated, but also cases in which the OLR gradient is too weak (i.e.: a CCKW that takes an anomalously high number or days to either strengthen or decay), and cases where there is a splitting of 2 waves (i.e., different phase speeds) at a given point during the weakening stage, or merging during the strengthening phase. Since this restriction would eliminate most of the observed waves leaving just a small sample for the analysis in some of the simulations, stages from each wave are used even if the other stages are not satisfactory (“ideal stages” instead of “ideal waves”).

The rest of the process is applied subjectively as well. Once a case is selected for one of the stages, the zonal location of the CCKW axis for each of the times for that case has to be assigned. For all of the $N$ consecutive output intervals comprised in each case, only one of them is assigned a position, and the location of the remaining is assigned automatically, using a constant phase speed that varies from case to case, and which is also determined subjectively. A trial-and-error procedure is applied several times with corrections on the starting grid point and phase speed, until the $N$ points are well aligned with the OLR signal on the CCKW-filtered Hovmoller diagram.

Some details about the application of this method are listed next:
1. The number of time intervals per wave is set to $N=10$ (i.e., 60 hours) for 10 of the 18 sets of selections (3 stages x 6 simulations); in 8 times it was lowered to 8 (48 hours) due to rapid transitions, i.e., strong OLR gradients (this was the case for the 6 sets comprising the nested simulations, and for the early and mature stages of the HR CTRL aquapatch).

2. For the early stage selection, the location assignment is the starting point, and the computation of the remaining $N-1$ positions with the phase speed is forward in time; for the decay stage, the final point is selected and the process is backwards in time, while for the mature stage, a point in the middle is used with 2 forward and backward estimations, using 5 and 4 time intervals respectively (4 and 3 if $N=8$), and independent phase speeds.

3. The number of selected cases $M$, varies from set to set depending of the number of “ideal stages” that follow the criteria described above.

4. The total number of cases multiplied by the total number of time intervals used for each case gives the size of the sample ($M \times N$), and is indicated in the heading of the composites of this chapter. The number for the nested aquapatch simulations varies within the range of 40 to 88, about 5-10% of the simulation period (720), while for all the others it is in the range of 72 to 150, also ~5-10% of the 1440 output intervals of the simulation.

After a preliminary analysis of composites obtained for the different stages, it was found that in particular for the aquachannel cases there was a significant wavenumber 2 component in the OLR and other variables. Most of the times it is due to the coexistence for several times of strengthening and dissipating CCKWs: the new wave was developing
downstream (eastward) of the old wave. This phenomenon was present 2-3 times in a sample of 8-10 cases, generating a significant signal of a weakening (strengthening) wave projected on the early (decay) stage composite (Fig. 4.1a). In order to avoid such effect, cases with a clear k=2 signal (a second wave present) were excluded from the selections, regardless of the stage of the intervening waves (Fig 4.1b, and Fig. 4.2). This consideration was not applied if the OLR amplitude of the second wave was much weaker than the wave of interest. An example of the result of the subjective process for one of the simulations is shown in in Fig. 4.2. For comparison, the automatic identification of the CCKW axis by the algorithm is shown too.

The number of selected CCKW cases for each of the 18 sets is shown in Table 4.1. 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 fraction of the sample used for the combined stages of each simulation relative to the simulation length is between 18% and 33%. This means that a substantial period of time on each simulation did not meet the criteria for the stage analysis.

### 4.2 Propagation Speeds of each CCKW stage

Table 4.2 shows the mean phase speed for each set. There are two major results that immediately arise. First, the mean phase speed from the algorithm for the entire integration period is less than the computed speed for any of the stages. In other words, the “ideal CCKWs” propagate slightly faster than the “mean CCKWs”, and this can be
interpreted as a correction to the algorithm calculation, that computes speeds for every
time step (unless there is a jump from a wave to another) and regardless of the wave
intensity. The departures range from 0.47 m/s for the OBS Aquaplanet case to 2.47 m/s
for the CTRL Nested Aquapatch case. In relative terms, the increased speed ranges from
2.8% for the OBS Aquaplanet case, to 16.0% for the OBS HR Aquapatch.

Second, the phase speed at the dissipating stage is slightly greater than for the other 2
stages. The difference ranges from 0.06 m/s to 1.98 m/s, and the mean over the 12
departures is 1.06 m/s. In relative terms, the weakening CCKW moves 6.77% faster than
at the early or mature stages. Comparing decay versus mature stages, these results are not
surprising since 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.

However, the fact the decaying CCKW is faster than the strengthening CCKW has no
immediate explanation and required more analysis: specifically, an analysis of the mean
equatorial zonal flow for each of the stages. Figure 4.3 depicts the vertical profiles of $u$
for the CTRL and OBS Aquachannel simulations. Since there are no significant
differences when considering zonal means (light dotted curves), mean $u$ was computed in
2 other ways: namely, at the CCKW axis (solid curves), and as a zonal mean but
restricted to a 4,000 km width containing the axis (dashed curves). For either case, it can
be seen that the equatorial flow is stronger at the decay stage than at the strengthening
phase in two vertical layers: above 17 km height and below 6 km. On the other hand, the
westerly flow above that level and up to the upper level jet is actually stronger for the
early stage than the decaying stage, suggesting that the intensity of the low-to-mid-level
flow might be more intimately related to the CCKW phase speed than the flow integrated
over the entire column. Similar results were found in the remaining simulations (not
shown), although these relationships are lost if a broader ITCZ mean is considered
instead of the flow at the equator (not shown).

Also notice from Fig. 4.3 that the magnitude of the zonal wind of the mature stage is
not too different from that at the decay stage, and even larger when considering the
CCKW axis. The fact that the CCKW propagates slower at the mature stage could be
then explained by the reduction in static stability due to the enhanced convective
processes, which seems to be an important factor in the modulation of the CCKW phase
speeds.

The result that the low-to-mid level equatorial flow embedded in the CCKW region
has the largest correlation with the CCKW phase speed propagation would support the
use of a low level barotropic flow rather than the mean barotropic flow as defined by
Diaz and Kiladis (2014), not just for the sake of a model intercomparisons of relative
CCKW phase speeds (as used in the previous chapter), but in term of their dynamics: i.e.:
understanding the different phase speeds of CCKWs along their lifecycle.

In fact, Fig 4.3 shows an interesting zonal flow evolution as it interacts with the
CCKW. The zonal mean values are nearly identical for the 3 stages, and could be
considered as the representation of the zero/fourth stage, i.e. both before the CCKW
forms and after it has dissipated. As a CCKW develops, the equatorial flow changes
progressively towards a significantly less sheared structure: westerlies becoming
easterlies in low levels, while in higher levels the westerly flow diminishes its intensity.
Finally, the shear (from surface up to the tropopause) reverses its sign by the mature/decay stage.

4.3 Composited structure of each CCKW stage

Figures 4.4 through 4.19 show the composited structure of the different stages along the CCKW lifecycle for the different simulations, and for a reduced set of variables: OLR, total condensate, zonal wind, and pressure. For each case, 3 plots are shown corresponding to the strengthening, mature, and dissipating stages respectively. Additionally, the plot at the top of each page shows the composited variable obtained from the objective algorithm throughout the entire simulation (hereinafter “full” composite), to facilitate comparisons. This analysis was performed for all the composited variables shown in Chapter 3, but only those figures showing significant differences among the stages’ composites and/or the full composite are included here.

Overall, it is found that extreme values for the mature stage are typically around 80-100% in excess of those in the full composites (even over 200% for vertical velocity at 850 mb in some simulations, not shown). For early and decaying stages, the increase is mostly in the range 60-90%, although it was found for some variables in some simulations that the strongest signal occurs for the early/decaying stage (surface pressure, moist static energy in 200 mb, not shown). This general pattern is not surprising since the algorithm from which full composites are obtained includes every time step throughout the simulation, some of which have much weaker convective activity (compared to the “ideal” CCKWs selected for the stages analysis).
OLR (Figs. 4.4 through 4.7) is of particular interest since the subjective selection of CCKW stages was performed using OLR Hovmöller diagrams. Only one well-defined region of convection appears at the middle of the domain, but for the OBS aquachannel simulation (Figs. 4.5) there are weak signals of convection (negative perturbations) near $x=0.75 \times 10^4$ km and $x=1.4 \times 10^4$ km in the early and $x=1.2 \times 10^4$ km in the mature stages. Recalling the discussion of section 1, an attempt was made to minimize this “wavenumber 2 effect” as much as possible, and indeed a significant improvement was achieved over the resulting OLR perturbation composites produced by the first analysis (not shown).

The other distinctive feature on the OLR field appears in the decay stage and to a lesser degree, the other 2 stages and the full composite. It is a pair of negative anomalies located off the equator (centered at about $y=\pm 3000$ km), about 6,000 km ahead of the CCKW axis (in both the aquachannels and the aquapatches), and with a diameter of around 1,000 km. These lobules already appear on the full composites (though very weakly) but their relative importance increases when strong CCKWs are isolated. They are associated with surface vortices, as depicted by the perturbation wind vectors overlapped on the OLR plots, and also to anomalies in $q_{\text{total}}$ at 500 mb (Figs.4.8 through 4.10), $w$ at 850 mb (not shown), and RH at 530 mb (not shown), and divergence at 200 mb (not shown).

The zonal wind field presents a remarkable feature at the strengthening phase (Figs.4.11 through 4.16). The high-level core of easterly anomalies is now lagging behind the CCKW axis by about 5,000-7,000 km in the case of the aquachannel simulations, and also it is slightly weaker (about -11 m/s versus -15 m/s for the other 2 stages). For the
aquapatch cases, the biggest change is in the core intensity (notice that in some plots the
color saturates at -15 m/s but there can be more contours within that core), and to a lesser
degree, there is a ~200-500 km lag of this signal with respect to the CCKW axis.

This delay on the position of the core of easterly anomalies might simply be due to a
late response (~2-3 days) of the dynamics in high levels to convection associated to the
synoptic-scale CCKW, (as shown in the transition early-mature-decay stages in Fig. 4.3).
However, there is no such effect for the upper-level divergence, (not shown, but
schematically depicted with wind vectors): the core of divergence is collocated with the
CCKW axis, and it is mainly produced by the \( v \) component. Other thermodynamic
variables like \( \theta \) or \( mse \) are also well correlated in upper levels with divergence and OLR
(not shown).

Finally, the last variable of interest is pressure. For the surface perturbations for any
of the stages, the equatorial signal is weak compared to the extratropical trains of
cyclones and anticyclones (not shown). Since these midlatitude systems propagate
zonally with different speeds than that of the CCKW, compositing does not show any
coherent structure.

The vertical structure of pressure anomaly at the equator illustrates its evolution with
the CCKW. In the aquapatch simulations, there are no significant differences among the
stages or full composite (Fig. 4.17 through 4.20). For the CTRL aquachannel case (Fig.
4.17), the length of the positive and negative anomalies regions for each stage varies but
are overall shorter than in the full composite. The peak negative anomalies also change
location (\( x=2.45 \times 10^4 \) km for the full composite and mature stage, \( x=2.35 \times 10^4 \) km at the
early stage, and $x=2.80 \times 10^4$ km at the decay stage). Even clearer is the existence of a secondary peak within the positive anomalies region for the early stage, located about 5,000 km behind the peak closer to the CCKW axis. This secondary peak does not appear to be associated with a “wavenumber 2 effect”, due to the absence of any signals at such locations for the other variables.

The OBS aquachannel case (Fig. 4.18) shows the biggest differences among the 4 plots. The positive anomaly region changes location, spread, and position of peak within it, and position of the secondary peak, if it exists; to a lesser degree the same occurs for the negative anomaly region. In particular for the strengthening phase, not only the gradient in the transition from positive to negative anomalies is much weaker, but also it is shifted westward, unlike the other 3 plots and the 4 from the CTRL aquachannel case, where it is strong and is almost aligned with the CCKW axis. To assess these differences, the same plots were compared to corresponding ones from the preliminary version of the aquachannel stage analysis (with a moderate wavenumber 2 signal, as described in section 1; not shown): several changes were found in terms of location of peak and spread and location of the anomaly regions. This additional evidence suggests that pressure is a problematic variable for the analysis of CCKW structure, at least when compositing and using OLR as a tracker.

The fact that this behavior for pressure greatly reduced in the 4 remaining aquapatch simulations (only shown for the 2 CTRL cases in Fig. 4.19) may be explained by their significantly shorter domains, which potentially reduces the spread of anomalies in the zonal direction.
4.4 Coupling of convection and dynamics: SCCs and pressure wave interactions

The implications of the findings of the previous section are further developed here. To better understand why composites of pressure differ among the different stages and full composite, we investigate how well correlated the peaks of pressure are with the peaks of OLR, the latter being the variable used as the CCKW tracker for the compositing. Therefore, the CCKW-tracking algorithm was performed again using minimum of PSFC instead of minimum of OLR; some other variables were additionally tested for comparison: minimum divergence at 850 mb (DIV850), maximum total cloud condensate at 500 mb (Q500), and minimum zonal wind at 200 mb (U200).

Fig. 4.20a,b shows the propagation of the axis of the strongest CCKW for the 5 trackers, overlapped onto a single longitude-time diagram. These two images, selected from the OBS Aquaplanet simulation, provide 2 clear examples of faster propagation of the wave when the tracking variable is PSFC: each is indicated by a large ellipse.

Additionally, we present in Fig. 4.20c,d similar diagrams that highlight the late response of the zonal wind to the CCKW convective activity. In these 2 cases it is clear how the U200 algorithm identifies the strongest wave about 3 days later than the other algorithms, which coincidently identify it nearly at the same time and location. This represents another way to analyze this late response, as described before from the composites of Figs. 4.11 through 4.16, and also from the vertical profiles of Fig. 4.3.

To better assess the phase speed propagation for the entire simulation period, for all trackers and for all simulations, the mean phase speeds were computed and results are
shown in Table 4.3. Clearly, the CCKW wave moves significantly faster when using PSFC as a tracker instead of OLR, with an overall excess of ~ 3 m/s. On the other extreme, the moisture wave is the slowest, with a mean speed of 11.59 m/s, representing a deficit of ~ 4 m/s with respect to the OLR wave. The tracking variable with the smallest discrepancy versus OLR is low level horizontal convergence.

Notice from Fig. 4.20 that the PSFC wave leads the others, which is consistent with the signals shown in the composites. It is worth mentioning that if the maximum of PSFC were used as the wave tracker instead of its minimum, the pressure wave would be lagging behind the other waves initially, and later they would merge due to the faster speed of the former. Also notice that different algorithms do not necessarily follow the same CCKW: this is due to differences in the time at which each of the variables reaches its peak, and to the relative strengths of the peaks in case of coexisting CCKWs.

The fact that different algorithms might follow different waves means that the algorithms are independent one from another. However, it is of interest to analyze relative east-west displacements in the peak of a given variable relative to the OLR peak, but for the same OLR wave. This can be performed by adding constraints to the location of the axis: that is, restricted to a narrow range around the OLR wave axis, the location of the peak is found for all other trackers (where in this case that peak is not necessarily the strongest peak in the domain at a given time). The “control” tracking algorithm is for OLR, and therefore it remains unchanged. The benefit of this approach is to assess the positive or negative lag for each of the variables versus OLR.

Fig. 4.21 depicts the results of this procedure, for the CTRL Aquachannel and nested simulations, for the first 180 days. Positive zonal displacements for each tracker with
respect to OLR indicate that the peak for that variable is ahead (eastward) of the OLR peak. Notice that the maximum possible displacement is less or equal than half of the zonal extension of the domain. The generally small lag between OLR and Q500 indicates that these 2 variables are highly correlated along the CCKW life cycle. On the other hand, and consistent with results from Figs. 4.20, PSFC is significantly biased, although not exclusively eastward.

To quantify the distribution of the lag for each tracker with respect to OLR, box plots were computed and are shown in Fig. 4.22. As expected, the most significant displacements are for PSFC, followed by U200. This behavior explains the strong sensitivity of PFSC composites obtained with OLR as a tracker to different averaging periods. Therefore, the full composite for the entire simulation period (Figs. 4.17a and 4.18a) could be representative of the average pressure structure to a certain degree, but not for the composites for each of the stages. Despite the biases for upper-level wind, the composites shown in Figs. 4.11 through 4.16 are robust and representative of each of the stages.

In light of this discussion, one might expect that if pressure at any level or zonal wind at high levels is used as the tracker of CCKWs, 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 the case for the preliminary work of Blanco et al (2014) that used PFSC as the “best tracker”.

We show normalized power spectra for upper level wind and surface pressure for some of the simulations. The upper level wind spectra are shown in Fig. 4.23 for both
Aquachannel simulations as well as the CTRL HR and Nested Aquapatches: the only spectral peak corresponds to the CCKW.

However, besides the dominant CCKW signal there are some spectral peaks in the normalized symmetric PSFC spectra (Fig. 4.24): for the 2 aquachannel cases, there are eastward wavenumber 1 signals for high frequencies, in particular at ~0.65 cpd (period of ~36 hours). More interestingly perhaps, is the power associated with westward propagation, in particular at the periods of 160 hours (0.15 cpd) and 80 hours (0.3 cpd). The last result is robust (present in all simulations) and hence provide important information about the hierarchy of coexisting pressure waves in the tropics. An immediate question is whether these waves are inherent of tropical dynamics and independent of CCKWs, or whether they exist as a consequence of the dominant Kelvin mode.

To further analyze the interaction of the “convective wave” (or “super cloud cluster”, hereinafter SCC, as defined by Nakazawa 1988) and the pressure wave, both OLR and PSFC anomalies are plotted together on a single Hovmoller diagram (Fig.4.25). This representation is advantageous compared with Fig. 4.20, because it shows raw data, and hence sensitivities due to algorithms are removed. Also, they provide more detail about the evolving structures along their eastward propagation, that were not seen when analyzing CCKW-filtered OLR diagrams, as was done for the subjective selection of cases.

These diagrams suggest an answer to the question of why the convective envelopes decay. As mentioned earlier, not only does convection lag behind the pressure wave, but it also propagates at a slower speed. From Fig.4.25a,b it is evident that when the
separation is sufficiently large, the SCCs simply dissipate. Additionally, new clusters form ahead, initially approximately collocated within the peak of minimum surface pressure. 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.

Notice that the pressure wave is exclusively wavenumber 1, while this is not the case for the convective envelopes, since sometimes 2 or more coexist in time, at different stages of their lifecycles. In fact this discretization of the number of coexisting SCCs is not straightforward when considering 2 adjacent ones (i.e.: the strengthening wave right ahead of the decaying wave), due to the hierarchy of scales of convection. For example, in some cases the corresponding pair of SCCs could be referred to as a single (synoptic-scale) SCC with 2 coherent mesoscale features, one dissipating and the other one intensifying ahead. The smaller-scale features (convective to meso-scale) generally propagate eastward at a speed much slower than the SCCs, and their lifespans are generally in the range of 2-5 days. The approximate mean speed values of both pressure and SCC waves are in agreement with the results obtained using the tracking algorithms (OLR vs PSFC on Table 4.3). However, these velocity differences are not discernible comparing the signals of the normalized power spectra for OLR (Figs. 3.12-13) and PSFC (Fig. 4.24). Usually when the pressure wave decays, the embedded SCCs dissipate as well, and if the pressure signal is weak, cumulus activity is less organized (meso-scale at most) and scattered. For instance Fig. 4.25c shows a period where an absence of organized convective activity corresponded with the absence of pressure signal during days 5-15, for the CTRL HR Aquapatch case.
The evolution throughout the entire integration period was carefully analyzed for all the simulations. Even when the aforementioned characteristics remain as the dominant ones, some other details were observed. Interestingly, for the CTRL Nested Aquapatch simulation (Fig. 4.25d), there are cases with enhanced convection but absence of pressure anomalies (days 120-125 and 143-146 and 173-180) as well as the opposite case, i.e.: strong pressure signal with scattered or inexistente convection (days 168-170 at x=8,000-12,000 km). The MJO-like event of the OBS Nested Aquapatch described in chapter 3 (Fig. 3.11) is separately shown in Fig. 4.26. The very slow-moving convective envelope during days 65-105 is characterized by the lack of a significant pressure signal (except for days ~80-90). Also for the CTRL Aquachannel case, a few wavenumber 2 events were observed on the pressure wave due to splitting, with the resulting pair persisting for 2-3 weeks (not shown). Finally, despite the wider range of propagating speeds of the SCC which differs from the nearly-constant-speed pressure waves, occasionally both waves propagate at the same speeds although they remain out of phase (not shown).

Notice that for this discussion of the pressure and SCC waves regarding Fig. 4.25 the term CCKW has been left aside. The CCKWs are neither the SCCs nor the pressure wave alone, but the system as a whole. By addressing the characteristics of the pressure wave and the SCC wave, we are giving more insight in the properties of the CCKWs, and in particular, the nature of their coupling\(^1\), which appears sometimes intermittent or unstable. The modulation of the convective envelopes by the pressure (Kelvin) wave is clear from Fig. 4.25, but it is not the net effect of the former onto the latter. Some

\(^1\) We use here the term “coupling” referring particularly to interactions between convection and the pressure wave. In the original definition by WK99, the coupling of the CCKWs refers to the correspondence of OLR power and the Matsuno modes. Additionally, the convection is “well-coupled” to many dynamical variables like vertical wind, horizontal convergence, mse, etc., as shown by the clear signatures on their composited horizontal and vertical structures.
questions that arise are to what degree the SCC activity slows down the pressure wave, and to what degree the intensity of the SCC activity can affect the magnitude of the pressure wave.

Considering the work by Seo et al (2012) described in the introduction, it would be of interest to further analyze the results obtained for their EXP1 and EXP2. Even when convection was not suppressed as a whole but instead removing one of its processes alone (shallow convection or cloud-top convective detrainment, respectively), the SCC activity was greatly diminished as seen by OLR normalized spectra (their Fig. 2). The pressure wave is not analyzed, at least independently of the cumulus activity: they show in their Fig. 3 longitude-time diagrams of OLR anomalies overlapped to 1000 mb geopotential anomalies, being the latter regressed to CCKW-filtered OLR (the disadvantage of this procedure is analogous to the compositing of pressure using CCKW-filtered OLR as a tracker, as shown in our Figs. 4.17 through 4.19). Therefore, it could be possible that a coherent pressure wave is present in those simulations, perhaps with faster speeds than typical observed, due to the suppressed SCC activity.

The consideration of the pressure wave separately from the SCCs was addressed by Nasuno et al (2008). For the 40-day period of their aquaplanet explicit convection simulation, they analyzed the composited structure of pressure waves (k=1, cx~23 m/s) and compared them with the corresponding structure of the SCC mode (k=3-5, cx~17 m/s). Not only does their compositing technique consists of a time average following the wave axis at its corresponding speed, but also filtering for the wavenumbers of interest. They found significant differences in the composite structures between the SCC and the pressure wave, and then analyzed the interaction of the 2 modes, concluding that it is
bidirectional. 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. However, 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 last pattern in Nasuno et al, which represents a “case study”, is repeatedly observed in our 1-year and 6-month aquachannel and aquapatch simulations, and with the aforementioned particularities. 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. And again, the interpretation of the “CCKW” term is not unique: Nasuno et al (2008) treat the waves independently as 2 convectively coupled modes (i.e.: the coupling is for each mode, between the dynamics and convection) and provided that, the interaction between them can be then analyzed. Instead, our perspective is that the interaction is itself the coupling of those 2 “modes”, which are perhaps equally important elements of the CCKWs.

In light of this discussion, the concept of “horizontal and vertical structures of CCKWs” applied in this and the previous chapters, corresponds strictly to “horizontal and vertical structures of SCCs”, because composites were obtained by tracking the OLR (SCC) wave. However, both denominations are used interchangeably in the literature, not only because OLR and precipitation are the most used variables to track CCKW, but also because all structures are coherently coupled (even pressure to a first order
approximation). But as shown in this section, when the pressure and SCC waves are analyzed in detail, a distinction becomes necessary.

The results presented in this chapter are important for the understanding of the life cycles of CCKWs. As we have seen, the strengthening and decay of SCCs along a self-sustained pressure wave represent a different phenomenon than the intensification and dissipation of the CCKWs as a whole (SCCs and pressure altogether). The correlation found between the dissipation of SCCs and their lag behind the pressure wave is a significant result that suggests an answer to the question formulated at the beginning of this chapter. More research is needed however, to explain the dynamics of the strengthening and decay of CCKWs.
Table 4.1: Number of CCKW cases selected for each of the 18 sets, organized by stage and simulation. Values in red indicate that the number of time intervals per wave is 8 (otherwise 10). Below, the number of cases for the 3 stages combined, also expressed in terms of number of time intervals, and percentage of these to the total number of intervals (simulation length).

<table>
<thead>
<tr>
<th></th>
<th>AQUACHANNEL</th>
<th>HR AQUAPATCH</th>
<th>NESTED AQUAPATCH</th>
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<td>CTRL</td>
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<tr>
<td>STAGE DECAY</td>
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<tr>
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<td>ΔT Δs Ratio (%)</td>
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<td>23.61</td>
<td>18.06</td>
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</table>

Table 4.2: Mean propagation speed (in m/s) of CCKWs at each of the stages for different simulations

<table>
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<th>NESTED AQUAPATCH</th>
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<tr>
<td>MEAN OVER 3 STAGES</td>
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<td>17.05</td>
<td>17.18</td>
</tr>
<tr>
<td></td>
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<td>HR AQUAPATCH</td>
<td>NESTED AQUAPATCH</td>
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</tr>
<tr>
<td></td>
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<td>10.75</td>
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<td>17.33</td>
<td>12.88</td>
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<td>19.68</td>
<td>17.25</td>
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Table 4.3: Mean propagation speed (in m/s) of CCKWs for different trackers.
Figure 4.1: Example of results (OLR composite for the early stage of the CTRL Aquachannel simulation) obtained after modification of the subjective method. Top, original case. Bottom, updated method. Notice that although not fully removed, the wavenumber-2 effect (at x~1.25x10^5 km) was significantly diminished.
Figure 4.2: Example of a CCKW-filtered Hovmoller diagram for the first 60 days of the CTRL aquachannel simulation. Overlapped circles indicate location of the CCKW axis (a) calculated by the tracking algorithm, and (b) assigned by the subjective method for the CCKW stage analysis (early and decay stages indicated with white circles and mature stage with white crosses). Notice that 1) for the algorithm there is a cross for each output interval of the simulation, while for the subjective method there are crosses only for selected times. 2) the location assigned by the subjective method does not necessarily coincide with the location calculated by the algorithm. 3) by days 7-12, there is coexistence of a decaying CCKW and a strengthening CCKW downstream, and hence the 2 were excluded of the analysis.
Figure 4.3. Zonal wind vertical profiles (m/s) for early (red), mature (blue) and decay (red) stages, and for zonal mean (light dotted lines), zonal mean in a 4,000 km width around the CCKW axis (dashed lines) and at the CCKW axis (heavy lines). Profiles are evaluated at the equator, and they correspond to the CTRL (a) and OBS (b) Aquachannel simulations.
Figure 4.4: Perturbation composites of OLR for the early (b), mature (c) and decay (d) stages of the CCKW lifecycle, and for the entire simulation (a, "full" composite), for the CTRL Aquachannel simulation.
Figure 4.5: As in Figure 4.4 but for the OBS Aquachannel simulation.
Figure 4.6: As in Figure 4.4 but for the CTRL HR Aquapatch (a, b, c and d) and for the CTRL Nested Aquapatch (e, f, g and h) simulations.
Figure 4.7: As in Figure 4.4 but for the OBS HR Aquapatch (a, b, c and d) and for the OBS Nested Aquapatch (e, f, g and h) simulations.
Figure 4.8: Perturbation composites of total cloud condensate at 500 mb for the early (b), mature (c) and decay (d) stages of the CCKW lifecycle, and for the entire simulation (a), for the CTRL Aquachannel simulation.
Figure 4.9: As in Figure 4.8 but for the OBS Aquachannel simulation.
Figure 4.10: As in Figure 4.8 but for the CTRL HR Aquapatch (a, b, c and d) and for the CTRL Nested Aquapatch (e, f, g and h) simulations.
Figure 4.11: Perturbation composites of zonal wind at 200 mb for the early (b), mature (c) and decay (d) stages of the CCKW lifecycle, and for the entire simulation (a), for the CTRL Aquachannel simulation.
Figure 4.12: As in Figure 4.11 but for the OBS Aquachannel simulation.
Figure 4.13: As in Figure 4.11 but for the CTRL HR Aquapatch (a, b, c and d) and for the CTRL Nested Aquapatch (e, f, g and h) simulations.
Figure 4.14: Perturbation composites of zonal wind at the equator for the early (b), mature (c) and decay (d) stages of the CCKW lifecycle, and for the entire simulation (a), for the CTRL Aquachannel simulation.
Figure 4.15: As in Figure 4.14 but for the OBS Aquachannel simulation.
Figure 4.16: As in Figure 4.14 but for the CTRL HR Aquapatch (a, b, c and d) and for the CTRL Nested Aquapatch (e, f, g and h) simulations.
Figure 4.17: Perturbation composites of pressure at the equator for the early (b), mature (c) and decay (d) stages of the CCKW lifecycle, and for the entire simulation (a), for the CTRL Aquachannel simulation.
Figure 4.18: As in Figure 4.17 but for the OBS Aquachannel simulation.
Figure 4.19: As in Figure 4.17 but for the CTRL HR Aquapatch (a, b, c and d) and for the CTRL Nested Aquapatch (e, f, g and h) simulations.
Figure 4.20. Hovmoller diagrams of the CCKW axis evolution, using different variables as trackers. Top panels for the OBS Aquachannel simulation, for days 240-300 (a) and 300-360 (b). Bottom panels for the CTRL Aquachannel simulation, for days 180-240 (c) and 300-360 (d).
Figure 4.21: Longitude lag for each of the wave trackers with respect to the OLR wave, as a function of time, for CTRL Aquachannel (top) and nested (bottom) simulations. Negative values correspond to the peak of the variable behind (westward of) the OLR axis.
Figure 4.22: Box plots with distribution of zonal lagging VAR-OLR for all simulations. The edges on the box correspond to the 25th and 75th percentiles; median is represented by the central line, and the mean value, by a circle. Red crosses represent values beyond 2.7 standard deviations.
Figure 4.23: Normalized spectra of symmetric zonal wind at 200 mb, for a) CTRL and b) OBS Aquachannel simulations, and for CTRL c) HR and d) Nested Aquapatch simulations.
Figure 4.24: Normalized spectra of symmetric PSFC, for CTRL (a,c,e) and OBS (b,d,f) cases of Aquachannel (a,b), HR Aquapatch (c,d) and Nested Aquapatch (e,f) simulations.
Figure 4.25: 60-day Hovmoller diagrams of OLR (black) and PSFC (pink) negative anomalies averaged in the [15°S:15°N] band, for the CTRL (a) and OBS (b) Aquachannel simulation, and the CTRL HR (c) and Nested (d) Aquapatch simulations.
Figure 4.26: As in Figure 4.25 for the entire integration period of the OBS Nested Aquapatch simulation.
CHAPTER 5. SUMMARY AND CONCLUSIONS

This thesis has studied idealized Convectively Coupled Kelvin Waves, i.e., envelopes of enhanced convection that propagate eastward within the ITCZ. Since Matusno’s theoretical work on linear modes in the tropics in 1966, research has significantly advanced our understanding of both observed and simulated CCKWs, particularly in the last two decades with the increased availability of datasets and computational resources. Structural patterns of CCKWs are well-known, and several theories have been hypothesized to explain their dynamics. The first objective of this work was to analyze the structure and variability of CCKWs and the ITCZ with changes in model domain, resolution and forcing. The second objective was to learn about properties of the waves at different stages of their lifecycle, a topic that has not been previously addressed, to help understand why CCKWs strengthen and decay.

A series of 7 idealized simulations were conducted using the WRF model to analyze sensitivities to a shortening of the domain by using aquachannel and aquapatch configurations instead of the more traditional aquaplanets. Moreover, for the aquapatch case, sensitivity to resolution was tested via 3 different grids: 139km, 46km and a double-nested case with 46km, 15km and 5km spacing, respectively, with explicit convection in the innermost grid. Using the Aquaplanet Experiment as a benchmark, the CTRL and OBS meridional profiles of SST were selected. Our results were compared with those from 2 of the APE models, namely, DWD and ECM-CY29 (also for both CTRL and OBS SSTs), selected because they use the same cumulus parameterization as our WRF simulations: the Tiedtke scheme.
The model intercomparison was carried out throughout diverse methods and metrics such as time and zonal means of precipitation, zonal wind, etc., normalized OLR power spectra, total OLR variance and its CCKW component, mean CCKW phase speeds and composited horizontal and vertical structures for different variables. The Wheeler and Kiladis (1999) filtering technique was used to extract the CCKW signal over the symmetric component of the OLR field and additionally an algorithm was applied to track the propagation of CCKWs along the tropics.

The OBS High Resolution (HR) Aquapatch simulation exhibits the largest difference from the other 6 WRF runs: it is a clear “double ITCZ” case, in which precipitation spreads meridionally with maxima off the equator, characterized by a weaker and broader mean circulation, and furthermore, the CCKW signal in the composited structures is the weakest. A similar double ITCZ case was found in the OBS ECM-CY29 simulation. The dominant signal in the OLR-S power spectra corresponds to the CCKWs, which overall is aligned with faster equivalent depth curves on the CTRL cases, compared to the OBS ones; this was verified by the computation of the mean CCKW phase speed. The typical structure of the CCKW wave is well-represented by the aquachannel simulations: the horizontal and vertical composites are in overall agreement to those shown here for the APE cases, and other idealized simulations.

Comparison of aquachannel versus aquapatch results requires a separate discussion. For the composite CCKW, the structures surrounding the wave axis are similar, but the leading and trailing parts for moisture, zonal wind, and other variables get distorted by the reduction of the domain to one third of its original length. More important is the fact that CCKWs tend to organize in the largest possible scale, i.e., that determined by the
domain length. Hence, wavenumber 1 for the aquapatch simulations represents a scale of only 13,300 km and the length of the convective envelope is somewhat shorter than in the aquachannel cases (not shown). In turn, this shorter CCKW structure might be connected with the slower CCKW propagation relative to the low-level background flow compared to aquachannel relative speeds (third row of Table 3.3). More generally, changes in domain length and resolution can be accompanied by great changes in the ITCZ structure even when the model physics and dynamics remains the same. This was the case for the OBS SST profile, shown in Fig 3.1a: while there is a single ITCZ case for the aquachannel, there is double ITCZ for the HR aquapatch. However, while these considerations might support dismissal of the aquapatch as a useful modeling framework, on the other hand this setup proves beneficial because it enables us to use explicit convection with nested grids.

The second part of this thesis (chapter 4) introduced a new approach for the understanding of the CCKWs dynamics. Several theories have been proposed to explain them, such as wave-CISK, WISHE and stratiform instability feedback mechanisms (Fig. 1.5). Instead of analyzing its mean properties, usually corresponding to the self-sustaining stage, here the focus was placed on the different phases along its lifecycle, in terms of composited structures and propagation speeds, to try to understand why CCKWs originate, strengthen, and dissipate.

Overall, minor differences were found among the stages for most of the analyzed composited variables, but with a few exceptions. The upper level zonal wind exhibited a different structure in the early stage composite, as compared to composites for decay, mature stages and full simulation (Fig. 4.12 through 4.14). This late dynamical response
to the organized cumulus activity was consistently found when the CCKW tracking algorithm was modified by replacing OLR by U200 as the tracking variable in the CCKW-filtered Hovmoller diagrams, with a clear delay in the appearance of the axis of a new wave (Fig. 4.18). Additionally, a clear correlation was found between the low level mean barotropic flow (LLMBF, defined as a weighted-mass integral between 1000 mb and 700 mb), and the phase speed of the CCKWs. In turn, the use of the LLMBF instead of the MBF as defined by Dias and Kiladis (2014), minimized differences in relative propagation speeds among the 11 simulations considered in chapter 3 (5 aquapatch, 2 aquachannel, and 4 aquaplanet).

When this stage analysis was applied to the pressure field, the structures exhibited as many different patterns as different samples of the simulation were considered (Figs. 4.15 and 4.16). The CCKW tracking algorithm with surface pressure as variable showed that the pressure wave leads the SCC wave and it also travels faster (Fig. 4.18). In particular, when raw Hovmoller diagrams of OLR and surface pressure were overlapped (Fig. 4.23), it was found that SCCs decay when they lag too far behind the pressure wave. More specifically, they dissipate when they fall behind the region of strongest negative pressure anomalies (with a zonal extension of the order of $\sim 10^4$ km). Typically when the old SCC dies, a new one forms ahead, nearly collocated with the pressure wave axis.

These results question the concept of a truly “coupled” CCKW as introduced by Wheeler and Kiladis (1999) after seeing that observed OLR signals on a normalized power spectra overlap with the linear Matsuno modes. The “coupling” term also applies to the coherence of OLR structures with many other dynamical and thermodynamical variables, i.e.: comparing their vertical and horizontal composites. Despite the fact that
under a quick comparison negative pressure anomalies are correlated with the CCKW, when looking more in detail it is clear that this variable is not “well-coupled” to convection. As a matter of fact, the “de-coupling”, i.e.: the increasing separation with time between the pressure wave and the SCCs, causes the dissipation of the latter. The pressure wave is typically wavenumber 1 and long-lasting, although it occasionally dissipates as well (altogether with the embedded SCCs). Further research is needed to understand why CCKWs as a whole (SCC and pressure waves) originate and decay.

The life cycle of CCKWs found in our WRF simulations is similar to results obtained with other idealized simulations. For example, Fig. 16 of Blackburn et al (2013) shows 30-day Hovmoller diagrams of precipitation in the [-5°:5°] band for 16 models of the APE experiment (including DWD and ECM-CY29), for the CTRL case. The eastward propagating signal with speeds of ~ 15m/s is the dominant feature for most of the models. Moreover, the intensity of these CCKW varies in time, with clear cases of strengthening and decay phases, an occasionally periods of weak and/or disorganized convection in the synoptic scale. More examples of evolution of CCKWs are provided in Fig. 4 of Khouider and Han (2013), who also used WRF model and performed sensitivity tests to nesting and to explicit convection, and in Fig. 2 of Frierson (2007), obtained with the simplified Betts-Miller cumulus scheme.

In turn, realistic simulations as well as observational studies also show similar evolution of CCKWs, with the particularity that the Pacific and Indian Oceans are preferred locations of enhanced Kelvin wave activity (Fig.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 Figs. 8 and 9b from WK99, and Figs. 5 and 15
from Roundy and Frank (2004), indicating that topography presumably plays a significant role in CCKW activity. However, as shown by the aforementioned results of idealized simulations, episodic strengthening and decay are intrinsic to CCKW dynamics.
References


