



## RESEARCH ARTICLE

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# Moisture Dependence of an African Easterly Wave Within the West African Monsoon System

**Key Points:**

- More moisture narrows and shifts the African easterly jet poleward, reducing the kinetic energy available to the African easterly wave
- In a moister environment, more deep convection occurs but its phasing with the wave becomes sub-optimal for intensification
- Moisture reduces wave translation over land, leading to convection phase locking with the Guinea Highlands rather than with the wave itself

**Supporting Information:**

Supporting Information may be found in the online version of this article.

**Correspondence to:**

K. M. Núñez Ocasio,  
[knocasio@ucar.edu](mailto:knocasio@ucar.edu)

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**Author Contributions:**

**Conceptualization:** K. M. Núñez Ocasio, C. A. Davis, Z. L. Moon

**Data curation:** K. M. Núñez Ocasio

**Formal analysis:** K. M. Núñez Ocasio, Z. L. Moon

**Funding acquisition:** K. M. Núñez Ocasio

**Investigation:** K. M. Núñez Ocasio, C. A. Davis, Z. L. Moon

**Methodology:** K. M. Núñez Ocasio,

C. A. Davis, Z. L. Moon, Q. A. Lawton

**Project administration:** K. M. Núñez Ocasio

K. M. Núñez Ocasio<sup>1</sup> , C. A. Davis<sup>1</sup> , Z. L. Moon<sup>1,2</sup> , and Q. A. Lawton<sup>3</sup> 

<sup>1</sup>NSF National Center for Atmospheric Research, Boulder, CO, USA, <sup>2</sup>Earth Resources Technology (ERT), Inc., Laurel, MD, USA, <sup>3</sup>Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, FL, USA

**Abstract** The growth and propagation of African easterly waves (AEWs) remains an active area of research, especially for those that become tropical cyclones (TCs). This is partly due to the complex role of moisture, realized through AEW-convection interactions. The goal of this study is to understand how environmental moisture plays a role in influencing the growth and propagation of a case of an AEW-convection system, that became a TC and how that role relates to the West African Monsoon System. Moisture sensitivity experiments were performed in a regional and convection-permitting novel configuration. It is found that in a moister environment, diabatic heating associated with convection coupled to the wave is shallower, ultimately, weakening the wave amplitude. Energetics are reduced in a moister environment as the African easterly jet strengthens, yet narrows, and shifts northward limiting interaction with the monsoon and the wave-convection system. The more intense monsoonal flow in a moister environment can instigate the decoupling between convection and AEW as deep convection is more likely in the ridge rather than in the trough region. Over western Africa, more continuous rainfall over the Guinea Highlands can inhibit phase locking with the AEW. In a moister environment, the mean zonal flow is weaker and as a result, the westward translation speed of the wave due to mean flow advection is slower than in the other experiments. While the mean flow advection dominates the translation, further differences in phase speed arise from differences in convection within the wave.

**Plain Language Summary** African easterly waves (AEWs) which can serve as tropical cyclone (TC) precursors, remain an active area of research. This is in part due to the complicated interactions between the waves, clouds, and water vapor. Although we have learned that the further development of TC precursors coupled with cloud systems can benefit greatly from water vapor, we still have unanswered questions such as: would more water vapor in the atmosphere allow for more favorable interactions between the TC precursor and cloud systems that ultimately lead to a stronger and more efficient TC formation? A high-resolution weather and climate model was used to perform a set of moisture-varying experiments to evaluate the moisture dependency of a historic event of an AEW that became a TC. We found that more moisture can intensify the West African Monsoon system, but shifts the African easterly jet (the source of energy for AEWs) further north inhibiting wave growth over land. More moisture affects how fast the wave propagates both through the changes in the background flow and partly to those within the cloud-system structure. More moisture results in less favorable types of clouds close to the wave, which weakens the system.

## 1. Introduction

The interactions between moist convection and African easterly waves (AEWs) are relevant to the growth of the system (Cornforth et al., 2009; Núñez Ocasio & Rios-Berrios, 2023; Russell et al., 2020; Tomassini et al., 2017). Water vapor plays a crucial role in the tropical atmosphere because of its wide variability in space and in time consequently complicating its representation (Payra et al., 2016) and in the case of AEWs, influencing their predictability and the accuracy of regional weather forecasts (Davis et al., 2016; Elless & Torn, 2019; Núñez Ocasio & Rios-Berrios, 2023; Torn, 2010). Moreover, recent work has shown that AEWs that are potential candidates to undergo tropical cyclogenesis are likely to initiate and propagate in a more moisture-rich environment that favors a more intense West African monsoon (WAM), and more organized convection over topography in eastern Africa, further adding to that uncertainty in predictability (Núñez Ocasio et al., 2021).

In the need for a better understanding of how moisture modulates the AEW evolution, Núñez Ocasio and Rios-Berrios (2023) investigated the partly moisture-driven evolution of the AEW that became hurricane Helene (pre-Helene; 2006) using 15-km mesh-spacing global simulations. The growth and propagation of the wave were

**Resources:** K. M. Núñez Ocasio,  
Q. A. Lawton  
**Software:** K. M. Núñez Ocasio,  
Z. L. Moon  
**Supervision:** K. M. Núñez Ocasio,  
C. A. Davis  
**Validation:** K. M. Núñez Ocasio,  
C. A. Davis, Z. L. Moon  
**Visualization:** K. M. Núñez Ocasio,  
C. A. Davis, Z. L. Moon  
**Writing – original draft:** K. M. Núñez  
Ocasio  
**Writing – review & editing:** K. M. Núñez  
Ocasio, C. A. Davis, Q. A. Lawton

related to the position of the convection with respect to the center of the wave vortex. They found that the simulated waves were more intense and translated westward more slowly than in reanalysis, particularly for the wave that evolved in a more moisture-rich environment. It was not determined whether the differences in intensity and translation of the wave were due to more favorable growth caused by the more moisture-rich environment or due to other factors.

While early theories of AEWs emphasized a combination of baroclinic and barotropic instability of the African easterly jet, considerable work during the last two decades has emphasized deep moist convection as necessary to explain the observed growth rates of AEWs (i.e., Berry & Thorncroft, 2012; Fink & Reiner, 2003; Núñez Ocasio et al., 2020b; Russell & Aiyer, 2020; Russell et al., 2020; Tomassini et al., 2017), as well as the role of topographic features in modulating wave structure (Hamilton et al., 2017, 2020; Tompkins & Chiao, 2012). Yet, the precise role of moisture, realized through deep convection within AEWs, has proven somewhat elusive. Moisture mode has been used to explain growth, and to some extent, slower wave propagation, of convectively coupled equatorial waves (Adames, 2022; Ahmed et al., 2021; Fuchs & Raymond, 2002, 2005; Mayta et al., 2022; Núñez Ocasio & Rios-Berrios, 2023; Sobel, 2002; Sobel et al., 2001). Concerning moist waves relative to westward propagating AEWs, Sobel et al. (2001) showed that rotational moisture modes propagate slowly eastward, not westward as AEWs. However, they point out that the moisture-wave mechanism can be applied to AEWs as it can operate on the moisture gradient between the air masses advected from the Sahara and the moister landmass to its south. Recent highly idealized theoretical work has found slow moisture-mode-like westward-propagating disturbances similar to AEWs (i.e., Adames, 2022; Adames et al., 2019; Mayta et al., 2022). AEW observational and modeling work has supported these theoretical findings (Núñez Ocasio & Rios-Berrios, 2023; Núñez Ocasio et al., 2020b). Moreover, Núñez Ocasio and Rios-Berrios (2023) found pre-Helene to be a type of mixed moisture mode that was slowly propagating westward. As it relates to this work, these previous studies show the possibility that AEWs can behave as moisture modes and to some extent help explain their evolution. As it will be shown here, more moisture slows the pre-Helene wave. However, the focus here is to investigate whether more moisture ultimately favors growth and affects the wave's translation.

The goal of this study is to understand how environmental moisture plays a role in driving the growth and propagation of the AEW-convection system and how that role relates to the WAM system. Here, the WAM system includes the monsoon, the African easterly jet (AEJ), and interactions with AEWs and convection. To do this, moisture sensitivity experiments—using both increasing and decreasing relative humidity—were performed with a convection-permitting model to further evaluate the moisture dependency of the pre-Helene wave. This approach will be discussed further in the methods section; however, a few other modeling studies have used moisture and/or convection sensitivity experiments to understand AEW growth and its relationship to moisture and convection, and which are addressed next.

Using a baroclinic spectral model, Thorncroft and Hoskins (1994) tested different latent heating parameterization schemes in a set of experiments and found that baroclinic conversions increase due to the role of latent heating and are more relevant to AEW growth than barotropic conversions. Berry and Thorncroft (2012), examined how sensitive a simulated AEW is to moist convection by instantaneously removing convection by shutting off the convection parameterization halfway through the model run. They found that even though it propagated at a similar phase speed to the control simulation, the simulation with convection turned off mid-way had showed a decrease in net potential vorticity (PV) weakening the AEW. Supporting Berry and Thorncroft (2012), Russell et al. (2020), found that by either limiting convection or reducing the relative humidity in the atmospheric column in convection-permitting regional simulations, it reduced the anomalous PV production by latent heating, which can aid in the maintenance of the simulated AEW. Mesoscale convective systems ahead of the wave trough foster propagation, and those close to the trough contribute to further growth (Fink & Reiner, 2003; Núñez Ocasio et al., 2020a, 2020b; Russell et al., 2020). In fact, Núñez Ocasio et al. (2020b) found that the phasing between convective system and wave trough is essential as convective systems coupled to developing waves (those that undergo tropical cyclogenesis), are more likely moving at the same speed of wave and position with the trough.

A moisture-sensitivity study by Chen and Zhang (2019) was conducted using convection-permitting regional model simulations to study the MJO convective initiation. The mixing ratio of water vapor at all vertical levels was reduced, as well as hydrometeors at specific longitudes. They found that the moistening and heating through enhanced surface fluxes are not responsible for MJO convective initiation, rather it is the vertical motion associated with the global circumnavigating mode that humidifies the mid-troposphere and triggers convection. The

conclusions by Chen and Zhang (2019) support the representation of vertical mass flux as being forced by AEWs in this study.

More related to the goal of this study is work by Cornforth et al. (2009), where the causality of moistening the AEW-convection and the WAM systems is investigated, rather than just focusing primarily on the role of moist convection in the internal dynamics of AEW growth. In an idealized modeling framework, Cornforth et al. (2009) prescribed a meridional surface-temperature gradient to represent the Saharan conditions on a dry and a moist experiment with the only difference being that the moist experiment had a prescribed humidity profile. They found that, unlike their dry experiment, the moist experiment exhibited a stronger AEJ core that was more compact and further north. There were larger barotropic conversions in the moist experiment associated with a stronger negative meridional PV gradient that made the moist AEW stronger than the dry AEW. Another relevant study is that of Bercos-Hickey et al. (2020) which showed that wetter monsoonal climatological years with stronger meridional shear, are related to a more northward positioned AEJ compared to drier years.

Previous research has primarily focused on studying the mean state over Africa, particularly the WAM system, in relation to moist convection. Absent from this research is an exploration of water vapor sensitivity simultaneously of the WAM system that frames the AEW environment, and on the convection within the AEW that influences wave structure, propagation, and ultimate transition to a tropical cyclone (TC). In this study we introduce a novel model setup with convection-permitting capabilities, offering a multi-scale depiction of the WAM System and AEWs. Our research delves into how moisture influences the WAM System while simultaneously investigating the internal wave dynamics of a TC precursor with explicit convection.

This work investigates how environmental moisture modulates the AEW-convection and WAM systems. The period investigated in this study uses the case of pre-Helene (Núñez Ocasio & Rios-Berrios, 2023) when the wave was propagating over western Africa and the eastern Atlantic before tropical cyclogenesis. The study will focus primarily on the mean state and AEW evolution before TC genesis with some discussion on the implications of how moisture-caused changes may be linked to subsequent changes in the TC genesis process. The following two main questions will be addressed in this study.

- Q1: How do changes in moisture modulate the zonal mean state over Africa of the WAM system?
- Q2: How does environmental moisture affect the relationship between the AEW and convection, and how does that, in turn, affect wave amplitude and propagation?

Details of the convection-permitting model configuration, moisture-sensitivity experiments, and AEW tracking of pre-Helene are in Section 2. The AEW evolution of the moisture-sensitivity experiments is presented in Section 3.2 including a subsection discussing the evolution as it undergoes tropical cyclogenesis. The moisture sensitivity of the WAM system and its relation to the AEW is in Section 4 including an energetics analysis. Section 5 focuses on the moisture sensitivity of the AEW-convection system. Section 6 includes an analysis on the moisture sensitivity of the wave's translation on both the mean flow advection and propagation. The summary and conclusions are presented in Section 7.

## 2. Data and Methods

### 2.1. Model Configuration

The Model for Prediction Across Scales-Atmosphere (MPAS-A) version 7.3 with the Limited-Area configuration was used for this study (Núñez Ocasio, 2023; Skamarock et al., 2012) to simulate the pre-Helene case (1200 UTC 8 September–1800 UTC 13 September 2006) as in Núñez Ocasio and Rios-Berrios (2023) and the mean WAM system during that period. Figure 1 illustrates the Limited-Area domain encompassing 30°S to 51°N and 65°W to 59°E. A 15-km to 3-km variable-resolution mesh was used with the 3-km high-resolution refinement region elliptically shaped. The mesh was rotated 5° to ensure the track of pre-Helene remains within the refined region. The reason for using a combined Limited-Area and variable-resolution mesh is for computational efficiency by placing the convection-permitting mesh spacing only where it is needed, while transitioning to appropriately coarse resolution where the domain meets the lateral boundary data from the reanalysis.

The “convection permitting” physics suite was used where the scale-aware Grell-Freitas convection parameterization scheme (Grell & Freitas, 2014) is able to transition from parameterization at the hydrostatic scales (parameterized grid is at 15 km) to only parameterize shallow convection in the refined 3-km region. Thus, at

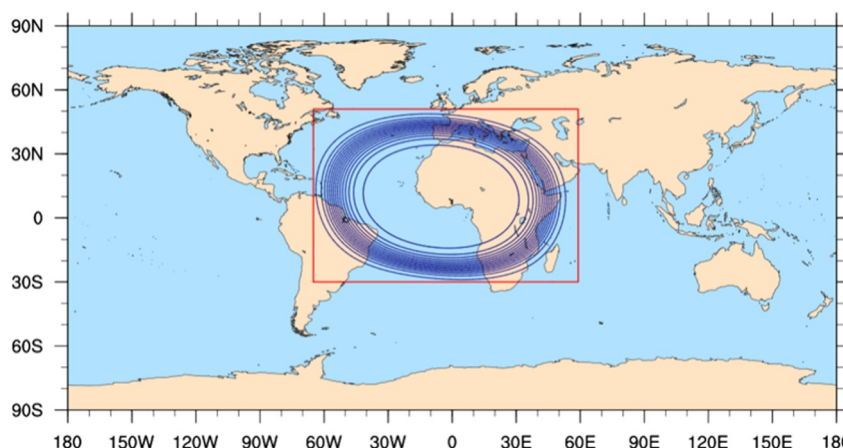


**Figure 1.** Illustration of the 15-km to 3-km variable resolution mesh and Limited-Area domain (red square) configuration produced using MPAS Tools (<https://github.com/MPAS-Dev/MPAS-Tools>). Contours are in  $1.6\text{--}7.2 \times 10^7$  km by  $0.4 \times 10^7$  km.

3 km, deep convection was explicitly resolved. The other schemes of the physics suite include RRTMG shortwave and longwave radiation (Iacono et al., 2008), Xu-Randall subgrid cloud fraction (Xu & Randall, 1996), MYNN boundary-layer and surface-layer schemes (Nakanishi & Niino, 2004), Noah land-surface scheme (Niu et al., 2011), and Thompson microphysics (Thompson et al., 2008).

The ECMWF reanalysis 5th Generation (ERA5; Hersbach et al., 2020) was used to initiate the model and provide lateral boundary conditions hourly as it captured the evolution of this historic case well (see Núñez Ocasio and Rios-Berrios (2023)). Note that the Helene case was highly predictable (i.e., Yang et al., 2023). The model was configured to run with 55 levels. Model outputs were hourly and isobaric variables used here were output with 27 isolevels. To the authors' knowledge, this is the first of its kind to use a combined Limited-Area and variable-resolution mesh configuration in MPAS. The limited-area option was employed to meet the need to prescribe moisture anomalies entering the computational domain of interest. The model output was interpolated to a latitude and longitude grid equivalent of a  $0.25^\circ \times 0.25^\circ$  horizontal resolution. The interpolation used a first-order conservative Gaussian grid (Jones, 1999) as done in Núñez Ocasio and Rios-Berrios (2022).

## 2.2. Moisture-Sensitivity Experiments

A total of nine sensitivity simulations were performed to understand how moisture content affects the growth and propagation of pre-Helene and the West African Monsoon System. It's important to acknowledge a limitation of this study, as the AEW component of the analysis is conducted for only one case; other AEWs undergoing TC genesis may exhibit different behavior. The simulations are divided into four main groups or experiments. The first is the control (hereafter referred to as CTRL/CONTROL) where initial and lateral boundary conditions were directly taken from ERA5 and moisture was not altered. The second group is labeled MOIST, where the relative humidity was increased by 20% everywhere and at all ERA5 pressure, levels yet capped at 100% relative humidity. The 20% experiment was chosen as a compromise where the spatial variation of relative humidity is largely retained even though portions of the domain reach saturation. A larger increase in relative humidity would result in saturation over the majority of the domain and thus, an unrealistic scenario. The last group is DRY0.5 in which the relative humidity was decreased everywhere at all pressure levels by 50%. Not having to cap like in the moist experiments, dry experiments can allow for more extreme modulations that can in turn, help understand the role of moisture and convection, and thus the selected percentage. Each group of experiments contains three simulations, two of which were initialized with random perturbations added to the 1,000-hPa temperature field, where the perturbations are Gaussian with a standard deviation of 0.6 K. Thus, for example, the MOIST group of experiments consists of simulations MOIST, MOIST\_pert, and MOIST\_pert2. The motivation to run several sensitivity simulations for each group of experiments is to add greater certainty that the conclusions being drawn are not simply from model stochasticity. Because results were very similar across the ensembles of the same group of experiments, either the reference group or the mean of the ensemble members will be shown from hereon.

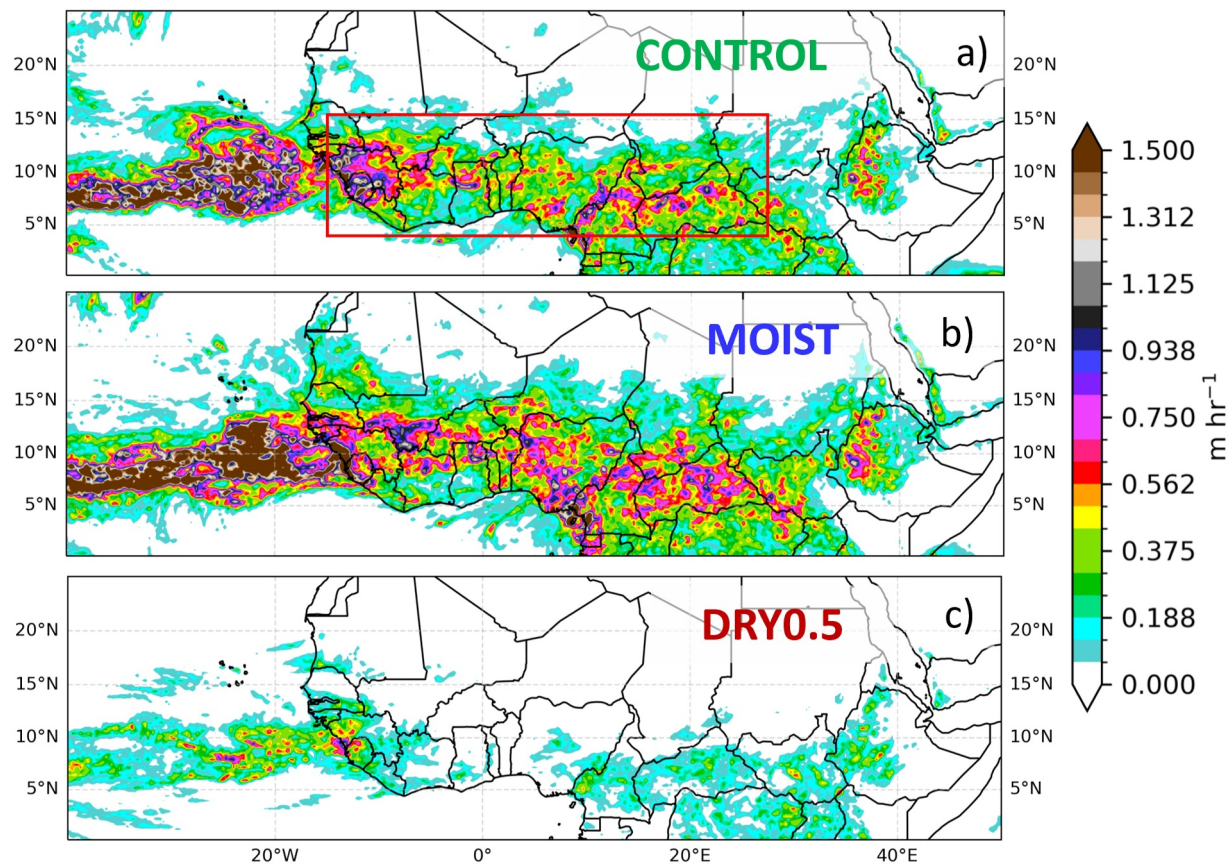


**Figure 2.** Reference group time means over the entire simulation period (5 days and 6 hr) of rain rate ( $\text{mm hr}^{-1}$ ) for (a) CTRL, (b) MOIST, and (c) DRY0.5. The red square denotes the region that will be named West African Monsoon box hereon from  $15^{\circ}\text{W}$  to  $25^{\circ}\text{E}$  and  $4^{\circ}\text{N}$  to  $15^{\circ}\text{N}$ .

Figure 2 shows the time mean precipitation rate for the period of the simulation for each reference member of each set of experiments (see Figures S1 and S2 in Supporting Information S1 for other simulations). Overall, MOIST is rainier than CTRL and DRY0.5. The greatest differences are evident over the WAM region over the African continent and ITCZ over the eastern Atlantic. MOIST shows more intense convection reflected by more regions of higher rain rates than the other experiments. This is especially true in regions of high topography such as the Guinea Highlands and the Cameroon Mountains.

### 2.3. AEW Tracking

Pre-Helene tracking in each experiment was performed objectively using the Lawton et al. (2022) AEW tracker. Radially averaged 600-km curvature vorticity was used to track the wave every six hours. ERA5 data was used initially to spin up the tracking algorithm. The curvature vorticity was calculated using 700-hPa spatially smoothed ( $1^{\circ} \times 1^{\circ}$  horizontal resolution) meridional wind fields interpolated to a latitude and longitude grid. The six-hourly tracks were temporally interpolated to obtain three-hourly positions of the wave and thus, positions were then used in the interpolated MPAS-A data to locate the wave and produce wave-relative plots. ERA5 pre-Helene was tracked as in Núñez Ocasio and Rios-Berrios (2023), by following the 700-hPa meridional wind minimum (inflection point) manually every 3 hr.

## 3. Overview of the AEW Evolution

### 3.1. AEW Evolution Over Land and Simulated Wave Validation

To study the evolution of the AEW and validate the model, Hovmöller diagrams for each reference member of each set of experiments (see Figures S3 and S4 in Supporting Information S1 for other simulations) for rain rate, 700-hPa relative humidity, and vorticity are shown in Figure 3. Corresponding rain rates from the NASA's

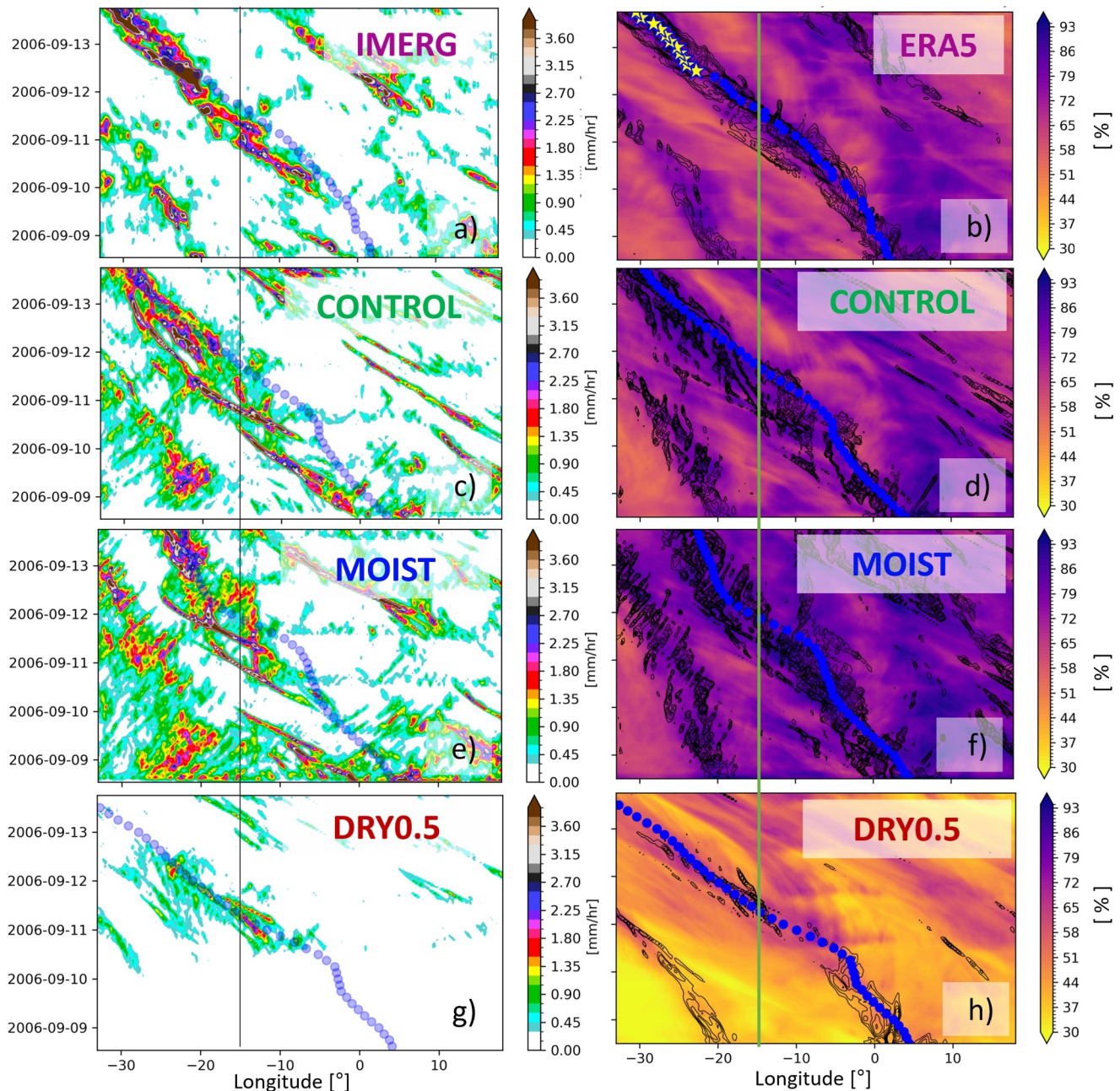


**Figure 3.** Hovmöller diagrams of latitude average from 5°N to 15°N of precipitation rate (left column) for (a) IMERG, (c) CTRL, (e) MOIST, and (g) DRY0.5. Hovmöller diagrams of latitude average from 5°N to 15°N of 700-hPa relative vorticity (right column black line contours;  $2$  to  $5 \times 10^{-5} \text{ s}^{-1}$  by  $0.4 \times 10^{-5} \text{ s}^{-1}$ ) and 700-hPa relative humidity (right column shade) for (b) ERA5, (d) CTRL, (f) MOIST, and (h) DRY0.5. Pre-Helene tracks for each data set are included. The vertical solid green and black lines indicate the approximate longitude of the western African coast. The star symbols in ERA5 depict when pre-Helene was categorized as a tropical cyclone on HURDAT2.

Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG; Huffman et al., 2019) and ERA5 Hovmöller diagrams are also included.

The translation of the pre-Helene toward the west is shown for IMERG and ERA5 in Figures 3a and 3b, respectively. The ERA5 700-hPa relative vorticity captures the wave signature even before the precipitation associated with convection couples to the wave. The highest observed precipitation rates are at or above  $4 \text{ mm hr}^{-1}$  between 12th and 13th of September, the period when pre-Helene undergoes TC formation. The highest 700-hPa relative humidity values are east of the observed wave (Figure 3b, shade).

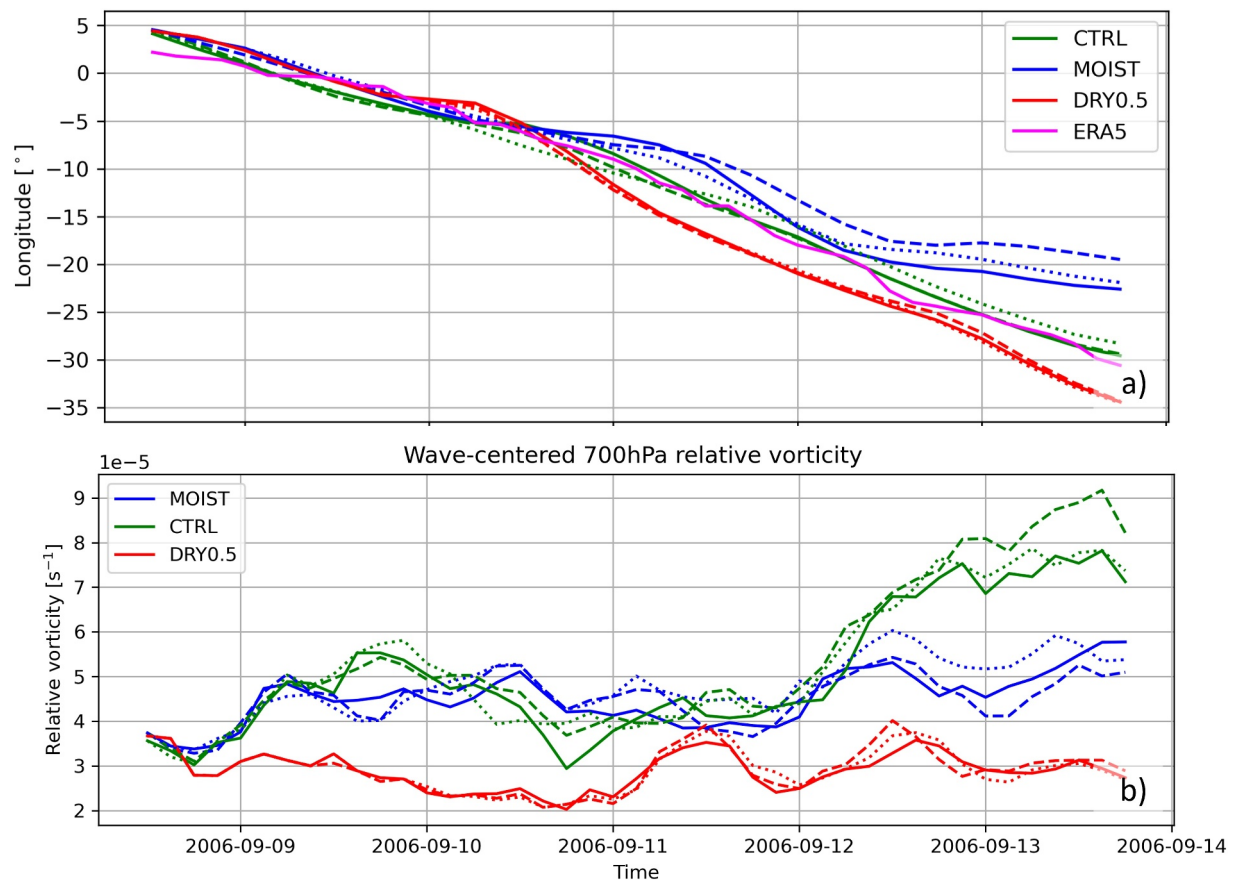


**Figure 4.** Time series of wave-centered (a) longitudinal position and (b) 700-hPa relative vorticity for the set of ERA5 (magenta solid line), CTRL simulations (green solid, dashed, and dotted lines), MOIST simulations (blue solid, dashed, and dotted lines), and DRY0.5 simulations (red solid, dashed, and dotted lines). For (b), the wave-centered value is the mean value of a  $6^\circ \times 6^\circ$  box centered ( $3^\circ$  on each side) on the trough.

At the wave scale, both the rainfall and vorticity signatures of pre-Helene in CTRL (Figures 3c and 3d, respectively) are well captured and comparable to the observed wave (Figures 3a and 3b). There are a few differences worth noting between how observations compare to the convection-permitting CTRL here and the 15-km global simulations of the same AEW case in Núñez Ocasio and Rios-Berrios (2023) (their Figure 4). Although all simulations here, in Núñez Ocasio and Rios-Berrios (2023), and IMERG are interpolated spatially to roughly the resolution of ERA5, convection-permitting simulations here still exhibit more high-resolution features as the simulations were spatially interpolated using a conservative method as discussed in Section 2. The rainfall footprint of pre-Helene in the 15-km global simulations (depicted in Figure 4 by Núñez Ocasio and Rios-Berrios (2023)) appears more continuous and less comparable to IMERG. In contrast, CTRL, shown here, exhibits a more realistic pattern with localized rainfall maxima comparable to those observed along the rainfall track. Overall, CTRL has a more filamentary structure in rainfall with a broader vorticity signal. This trend is similarly observed in 700-hPa relative humidity, vorticity, and wave track, where CTRL displays a much more comparable evolution to observations compared to the 15-km global simulations.

Compared to observations and CTRL, the MOIST wave moves the slowest (Figures 3f and 4a), yet deep convection appears to move at a similar speed to that in CTRL, thus resulting in convection being less in phase in MOIST with the wave trough (Figures 3e and 3f). This poor phasing can influence the strength and onset of the tropical cyclogenesis (Núñez Ocasio et al., 2020b), in this case, after 12 September (compare blue lines in Figure 4b with green lines). In CTRL where the wave propagates faster than in MOIST (but comparable to observations), the phasing between wave and convection (Figures 3c and 3d) supports a stronger wave before TC genesis and, ultimately, a more rapid TC genesis when compared to MOIST (Figure 4b). The DRY0.5 wave is generally the weakest across experiments and the fastest-moving, compared to observations. Although the

vorticity signature of DRY0.5 remains traceable even after crossing the coastline, convection initiates halfway through the simulation, inhibiting further growth and genesis. The wave-centered 700-hPa relative vorticity in Figure 4b is greater during the morning of September 12th for CTRL (green lines) than for MOIST (blue lines) and DRY0.5 (red lines). The differences across CTRL and MOIST experiments on the intensity of the wave once the system moves offshore and undergoes TC genesis are more evident than differences in the intensity over land (before the 12th of September in Figure 4b).

While the focus of this study will be on the evolution of the wave over the continent across experiments where differences are more subtle and complex, we will also provide a brief discussion on the differences in the translation of the CTRL and MOIST waves over water. This discussion will highlight how these differences are linked to the subsequent weaker TC genesis in MOIST compared to CTRL.

### 3.2. AEW Evolution Over Water (Tropical Cyclogenesis)

The time mean of rainfall associated with the WAM over the African continent and ITCZ in Figure 2 shows that MOIST has, on average, more intense rainfall and/or moderate rain more often. Compared to CTRL, MOIST experiences more continuous periods of heavy rainfall and maxima are farther south (south of 10°N) and over regions of high topography, such as the Guinea Highlands. During the time the MOIST wave trough approaches western Africa, it interacts with an anomalous stationary area of rainfall over the Guinea Highlands that initiated on the 10th September. This stationary convection is not present in CTRL (compare Figures 3e and 3c, over the vertical line denoting the coast). This suggests that the convection over the Guinea Highlands accelerates the wave westward initially, but when that convection persists after the trough passage, it slows the wave translation (Figures 3f and 4a). This convection is significant enough to alter the evolution of the AEW by first accelerating (when the convection is far west of the trough), and then decelerating the wave (when the convection is to the east of the trough axis). During the 12th of September, the sub-optimal phasing of the convection with the wave results in slower amplification compared with CTRL, where convection remains anchored to the same phase of the wave (not anchored to the terrain). Wave growth in general is presumably the result of the much stronger sustained convection coupled to the wave and not the terrain.

These results using convection-permitting simulations reveal the importance of the influence of the Guinea Highlands even when only moisture is modulated and not topography. The results support Hamilton et al. (2017, 2020) findings although the model does not reproduce the climatological offshore rainfall maximum described in Hamilton et al. (2020) due to the short period being simulated. Other past studies have suggested the relevance of the Guinea Highlands on wave amplitude due to topographic triggered mesoscale convective systems (i.e., Shen et al., 2010; Tompkins & Chiao, 2012). However, these studies are limited due to convection being parameterized. Here we show that this is indeed the case, but that moisture availability can determine whether that convection can remain coupled to the wave or the land, ultimately affecting further wave growth.

Finally, although with limited convection, pre-Helene in DRY0.5 is supported through dry dynamics (energetics analysis is in the following section) making it traceable up to the eastern Atlantic. This wave reaches beyond 40°W, farther than the other simulations. However, as in the land evolution, it remains the weakest simulated wave over water and it does not undergo TC genesis. The moisture sensitivity of the WAM system is explored next and a linkage to the moisture sensitivity of the pre-Helene AEW-convection system is drawn.

## 4. Moisture Sensitivity of the West African Monsoon System

The zonal mean state of the WAM system comprising of the monsoon, the AEJ, and associated AEW and convection activity for the simulated period of pre-Helene is compared across experiments and ERA5 (Figure 5). The basic circulations over the region are evident in all experiments with CTRL and MOIST having the most resemblance to ERA5. Contrary to the zonal wind cross-section time mean in the 15-km global simulations in Núñez Ocasio and Rios-Berrios (2023) (their Figure 2), here CTRL, exhibits slightly weaker AEJ, WAM, and Tropical easterly jet (TEJ) compared to ERA5. Note that the average longitude here differs slightly from theirs, and here, we've excluded the first day of the simulation period.

The TEJ core is around 200 hPa at 5°N. The TEJ is weaker and more spread out in DRY0.5 (Figure 5c) than in the CTRL (Figure 5a) and MOIST (Figure 5b). The same is the case for the AEJ located at about 650 hPa with MOIST exhibiting the strongest jet core of about  $13 \text{ m s}^{-1}$ . Compared to the AEJ in the other groups, the core of the AEJ in

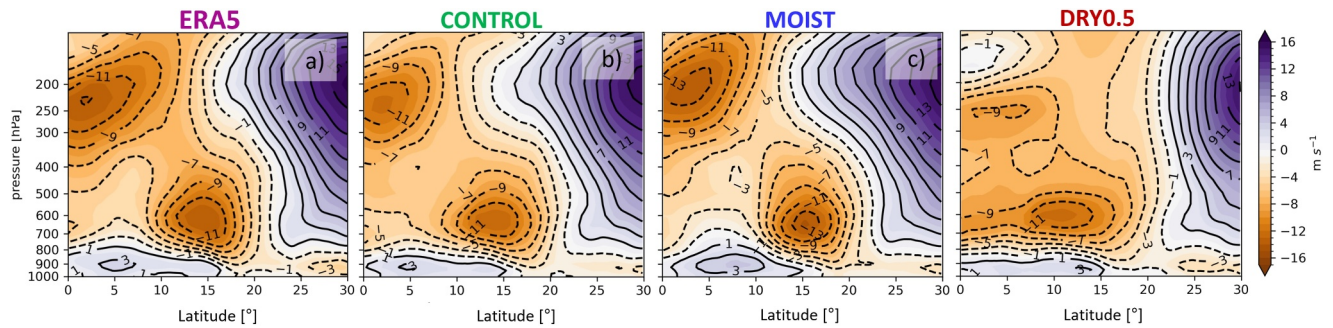


**Figure 5.** Vertical cross-section of the time mean zonal wind removing the first day of the simulation period for (a) ERA5, (b) CTRL, (c) MOIST, and (d) DRY0.5. Longitude average taken from 15°W to 25°E (West African Monsoon box in Figure 2). Y axis is in log scale.

MOIST is shifted slightly northward (core north of 15°N) and more compacted. These results are consistent with Cornforth et al. (2009) moist simulation in that the jet shifted northward and compacted. However, different from the jet here, the jet in their moist simulation was weaker than in their analogous dry simulation. The northward shift of the AEJ in MOIST results in a weakening of the low-to-mid-level easterly shear specifically over the WAM region. The northward shift of the MOIST AEJ can be explained by the more northward and stronger surface and low-level meridional potential temperature and equivalent potential temperature gradients when compared with the other groups (not shown). The more northward AEJ in MOIST is also supported by the stronger monsoonal flow (Figure 5c, near-surface westerlies between surface and 800 hPa and 0° to 15°N) having the capacity to transport additional moisture and associated shear toward the pole.

The low-level WAM westerly flow, with a core between 5° and 10°N and between 900 and 800 hPa, is deeper and stronger in MOIST when compared with the rest (Figure 5). The moisture associated with the monsoon is also greater in magnitude and the gradient is situated further north in MOIST than in CTRL (not shown). The weak monsoonal flow (surface to low-level westerlies) advances inland in DRY0.5 up to about 20°N; whereas in CTRL and MOIST, it is stronger, although it only reaches up to 16°N. Figure 6 shows vertical mean mass flux profiles (calculated as density times the vertical velocity following Raymond et al. (2011)). Although the IFS convective scheme parameterization is imprinted on the reanalysis, CTRL shows a comparable profile to ERA5 above 900 hPa. ERA5 below 900 hPa does not produce downdrafts. The more intense and vertically-

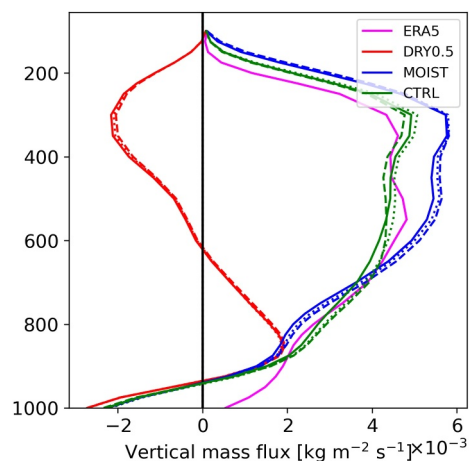


**Figure 6.** Time mean profile removing the first day of the simulation of vertical mass flux for the set of CTRL simulations (green solid, dashed, and dotted lines), MOIST simulations (blue solid, dashed, and dotted lines), DRY0.5 simulations (red solid, dashed, and dotted lines), and ERA5 (magenta line). Average is taken from 15°W to 25°E and 4°N to 15°N (West African Monsoon box in Figure 2).

#### 4.1. Energetics

To summarize thus far, it is shown that more moisture (MOIST) strengthens the AEJ and monsoonal flow, with the AEJ core compacting and shifting northward as in Cornforth et al. (2009). Relating the MOIST experiments to wetter monsoonal climatological years with stronger meridional shear, it has been shown that the AEJ is farther north than in drier years (Bercos-Hickey et al., 2020). It is hypothesized that although the AEJ in MOIST has more available zonal kinetic energy that can be converted to eddy kinetic energy, this north shift in the AEJ—while the wave remains in about the same position as in CTRL—reduces energy exchanges between southern-track AEW pre-Helene and the AEJ, ultimately decreasing energy conversions. This is evident from the shear of the zonal wind over the WAM box discussed further in Section 6 and from  $K_E$  ensemble mean vertical cross-sections in Figure 7 where  $K_E$  is defined as the eddy kinetic energy:

$$K_E = \frac{[u'^2 + v'^2]}{2}. \quad (1)$$

In Equation 1,  $u'$  and  $v'$  are the zonal and meridional wind anomalies, respectively, and anomalies are calculated relative to the zonal mean over the defined WAM region shown in Figure 2a. The  $[\overline{(\cdot)}]$  represents a zonal average of the zonal mean. At the AEJ level, between 700 and 600 hPa, the  $K_E$  CTRL ensemble mean (Figure 7a) shows values larger than  $28 \text{ m}^2 \text{ s}^{-2}$  in a deeper layer ( $28 \text{ m}^2 \text{ s}^{-2}$  contour completely close and wider in CTRL) compared with the ensemble mean of MOIST (Figure 7b) and DRY0.5 (Figure 7c) as hypothesized in the previous section.

To understand what types of energy conversions are related to  $K_E$  production, barotropic and baroclinic conversion of energy are analyzed (Figures 7d–7l). Following Hamilton et al. (2020) and Hsieh and Cook (2007), barotropic conversion of  $K_E$  via the interaction of the eddy momentum fluxes weighted by the horizontal and vertical shears of the zonal wind zonal are

$$C_{k1} = -[u'v'] \frac{\partial[u]}{\partial y} \quad (2)$$

$$C_{k2} = -[u'\omega'] \frac{\partial[u]}{\partial p}, \quad (3)$$

respectively. In Equation 2,  $\frac{\partial[u]}{\partial y}$  is the horizontal shear of the zonal wind, and in Equation 3,  $\frac{\partial[u]}{\partial p}$  is the vertical shear of the zonal wind. Shear produced by deep convection near the AEJ, in addition to the meridional gradient of base-state vorticity being negative, contribute to barotropic instability (Cornforth et al., 2009; Hsieh & Cook, 2007; Pytharoulis & Thorncroft, 1999). Baroclinic energy conversions are defined as:

$$C_{pk} = -\frac{R}{p} [\omega' T'] \quad (4)$$

and denote the conversion of eddy available potential energy to eddy kinetic energy through vertical overturning (Hamilton et al., 2020; Hsieh & Cook, 2007). In Equation 4,  $\omega'$  and  $T'$  are the vertical wind motion and temperature wind anomalies, respectively,  $R$  is the specific gas constant for dry air, and  $p$  is pressure. From the magnitudes in Figure 7, it is evident that baroclinic conversion of energy (Figures 7j–7l) dominates the  $C_{k1}$  (Figures 7d–7f) and  $C_{k2}$  (Figures 7g–7i) barotropic conversions. Regions of maximum  $C_{k1}$  are located near the AEJ associated with horizontal shear from the jet between 700 and 600 hPa and  $5^\circ$  and  $10^\circ\text{N}$ . MOIST and CTRL exhibit the largest magnitudes compared to DRY0.5. Between CTRL and MOIST, CTRL has slightly larger values of  $C_{k1}$  than MOIST, contributing to the larger values of  $K_E$  at the jet level. The larger magnitudes in  $C_{k2}$  (especially for CTRL and MOIST) are located below the AEJ, closer to 750 and 800 hPa (Figures 7g–7i) where large vertical shears are present. This low-to-mid-level production of  $K_E$  by  $C_{k2}$  especially in CTRL and MOIST, is a result of the downgradient transport of easterly momentum ( $[u'\omega']$ ) interacting with the vertical shear  $\left(\frac{\partial[u]}{\partial p}\right)$  and can also represent the importance of shallow cumulus convection (i.e., Hsieh & Cook, 2007).

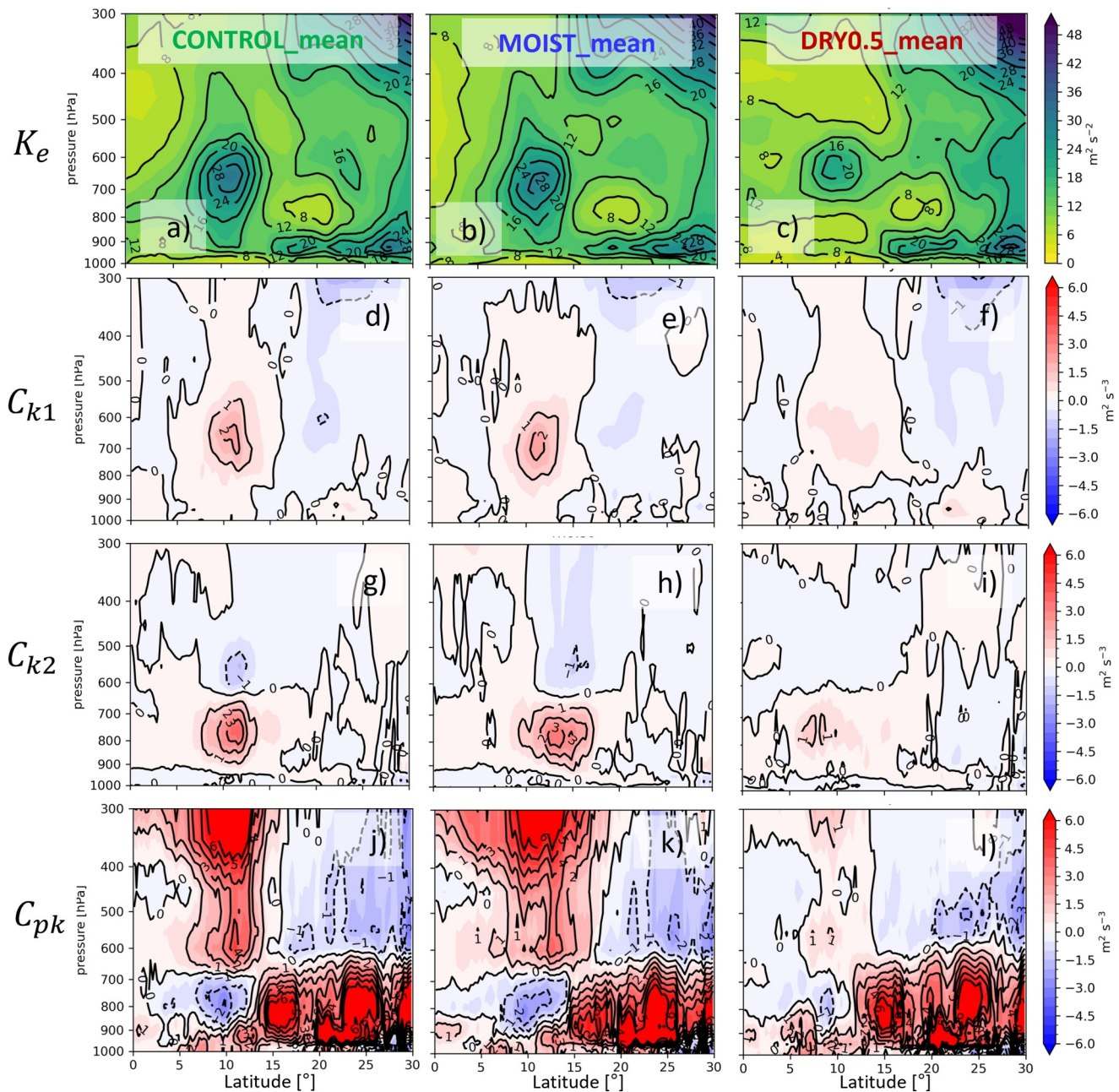


**Figure 7.** Ensemble mean vertical cross-sections for (a–c)  $K_E$ , (d–f)  $C_{k1}$ , (g–i)  $C_{k2}$ , and (j–l)  $C_{pk}$ . Longitude average taken from 15°W to 25°E (West African Monsoon box). Y axis is in log scale. Values of  $C_{k1}$ ,  $C_{k2}$ , and  $C_{pk}$  are multiplied by  $10^4$ .

Where there is higher production of  $K_E$  by  $C_{k2}$  around 750 hPa, there is negative  $C_{pk}$  conversion (destruction of eddy kinetic energy by baroclinic overturning; Figures 7j–7l). Past studies (i.e., Diedhiou et al., 2002; Hsieh & Cook, 2007; Norquist et al., 1977; Pytharoulis & Thorncroft, 1999) have tried to explain this region of negative  $C_{pk}$  conversion resulting from perturbed ascending cold air (descending warm air) converting the eddy kinetic energy to eddy available potential energy. This negative conversion is partly due to the overturning of relatively cooler air within the upward branch of the monsoon circulation over western Africa (Figure 8, west of 0°) where the ITCZ in combination with the WAM are deeper and extend farther north than over eastern Africa. East of 10°E this low-level negative  $C_{pk}$  conversion is due to warmer subsiding air. Compared to CTRL (Figure 8a) and DRY0.5 (Figure 8c), this temperature anomaly effect is muted in MOIST (Figure 8b). This is potentially because the soil and low levels are more homogeneously wetter and hence more of the heating disperses to evaporation

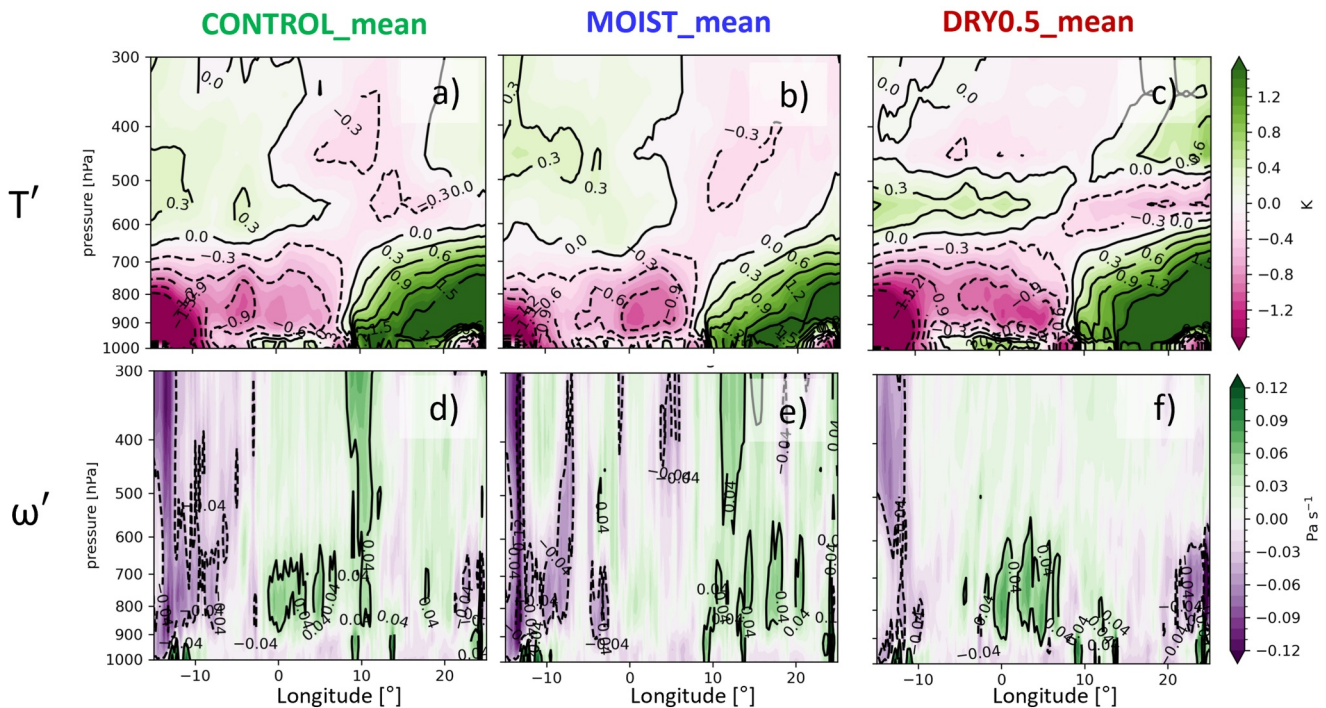


**Figure 8.** Ensemble mean vertical cross-sections for (a–c)  $T'$ , and (d–f)  $\omega'$ . Latitude average taken from  $9^{\circ}\text{N}$  to  $15^{\circ}\text{N}$  latitudes of large  $K_E$ . Y axis is in log scale.

rather than sensible heat. In the vicinity of  $10^{\circ}\text{E}$ , where the reversal in  $T'$  at the surface and low levels occurs, the Cameroon Mountains and Lake Chad are located. Past work has shown a relationship between the topography and the intensity of the meridional temperature gradient and the AEJ and how in that way, topography can alter the energetics of AEWs and their associated convection (i.e., Hamilton et al., 2017, 2020). Above 700 hPa, a  $T'$  quadrupole in the DRY0.5 may be causing negative  $C_{pk}$  conversion over and above this layer.

Large production of  $C_{pk}$  (positive  $C_{pk}$ ) in the mid-to-upper troposphere (600–300 hPa), between  $0^{\circ}$  and  $15^{\circ}\text{N}$ , in MOIST and CTRL (Figures 7j and 7k, respectively) is greatly reduced in DRY0.5 (Figure 7l). Between 650 and 400 hPa, positive  $C_{pk}$  is caused by presence of latent heat release by deep convection (especially in MOIST and CTRL) above the mid-troposphere related to warm ascending air (Figure 8,  $-\omega'T' > 0$ ) to the west of  $0^{\circ}$  and to a lesser extent, to cold air descending in convective downdrafts east of  $0^{\circ}$ . Evident is the larger region of upward motion in CTRL than in MOIST to the west of  $10^{\circ}\text{W}$  (Figures 8d vs. 8e). Over the Sahara, between  $15^{\circ}$  and  $30^{\circ}\text{N}$ , positive  $C_{pk}$  is due to the zonal gradient effects from the more active WAM and ITCZ to the west and is also due to the diurnal boundary layer evolution. Turbulence within the boundary layer evolution is the majority of the source of  $C_{pk}$  for DRY0.5 (Figure 7l).

The results here agree with Cornforth et al. (2009) in that baroclinic conversions dominate, although we demonstrate here that is true not only in DRY0.5, it is also true in MOIST. In addition, they agree that barotropic processes  $C_{k1}$  and  $C_{k2}$  in the lower-to-mid levels (Figure 7) are more relevant in moister conditions (CTRL and MOIST) associated with more intense WAM and ITCZ convection and horizontal shear. These results agree with Hsieh and Cook (2007) as barotropic instabilities are relevant for the further growth of the AEWs. Cornforth et al. (2009) found that the larger barotropic conversions in their moist experiment were associated with a stronger negative meridional PV gradient that made the moist AEW stronger than the dry AEW. In this study, MOIST has a stronger negative meridional PV gradient compared to CTRL and DRY0.5 (not shown) yet as seen from Figure 4, the wave in MOIST eventually is weaker than CTRL after crossing the coast. As will be shown in the next section, the overall amplitude of the MOIST wave was weaker over land than CTRL where the environment was relatively drier.

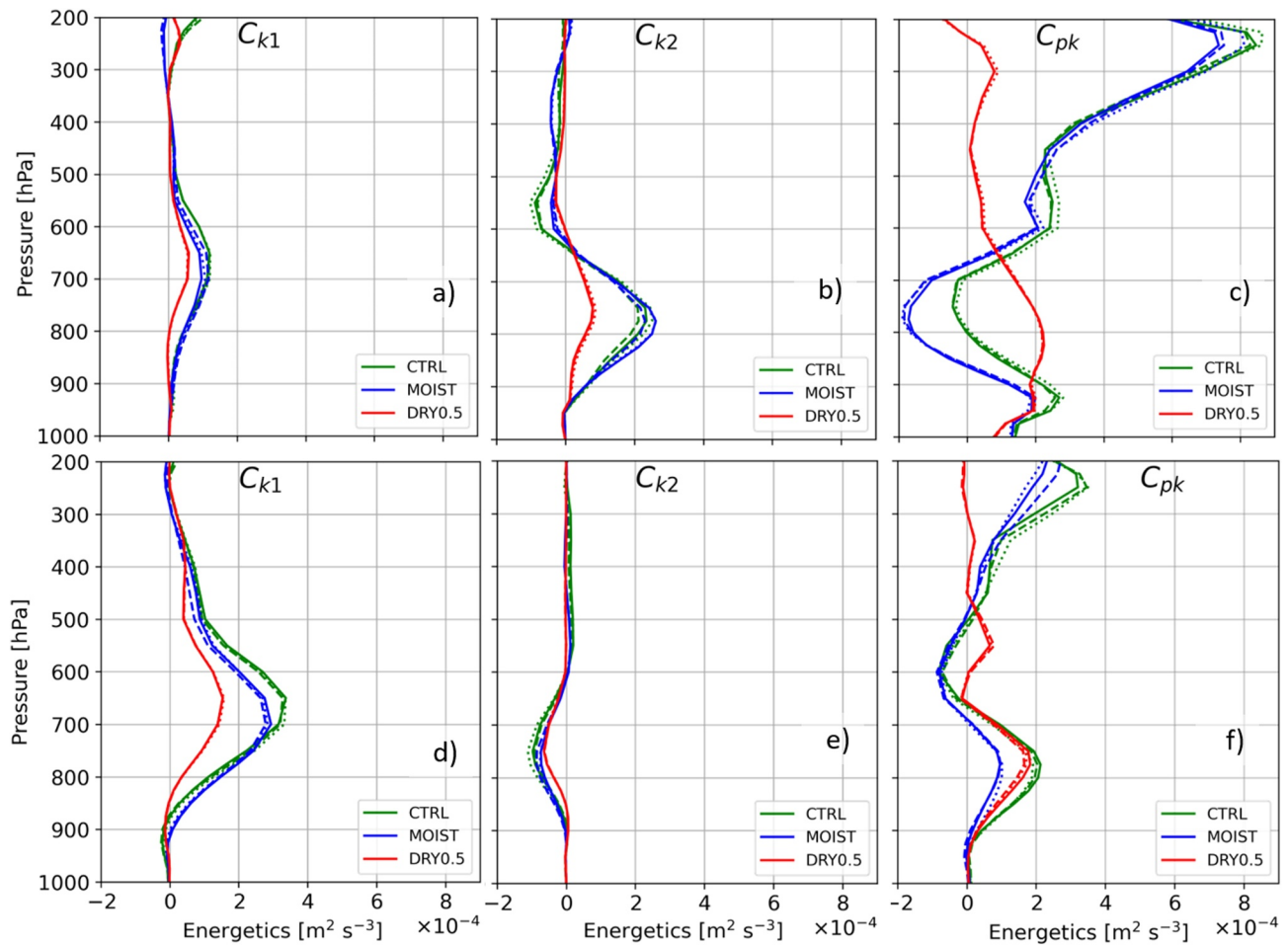


**Figure 9.** Ground-relative vertical profiles removing the first day of the simulation for (a)  $C_{k1}$ , (b)  $C_{k2}$ , and (c)  $C_{pk}$  with longitude average taken from  $15^{\circ}\text{W}$  to  $25^{\circ}\text{E}$  (West African Monsoon box) and latitude average from  $9^{\circ}$  to  $15^{\circ}\text{N}$ . Wave-centered vertical profiles for (d)  $C_{k1}$ , (e)  $C_{k2}$ , and (f)  $C_{pk}$ . The wave-centered domain is a  $24^{\circ} \times 6^{\circ}$  box ( $12^{\circ}$  on each side longitude and  $3^{\circ}$  on each side latitude) centered on the trough.

## 5. Moisture Sensitivity of the AEW-Convection System

Thus far, it has been shown that AEW growth depends both on sufficient AEW-AEJ and AEW-WAM interactions south of the AEJ.  $K_E$  is limited at the AEJ level in a moister environment as the AEJ shifts northward and the mean flow is reduced over the WAM region. It has also been shown that barotropic processes in the lower-to-mid levels are more relevant in moister conditions (CTRL and MOIST). Results from the previous section represent anomalies from a mixture of the zonally varying ITCZ, WAM, AEJ, and wave signals. In this section, the AEW-convection system is specifically investigated, and wave-relative energetics profiles are compared to the WAM/ground-relative energetics profiles.

Consistent with the results discussed in the previous section, the WAM/ground relative energetics vertical profiles in Figures 9a–9c reveal that  $C_{pk}$  is the dominant term and is especially true in moister environments (CTRL and MOIST in Figure 9c). The limited AEJ-WAM and AEJ-AEW interactions in MOIST, due to a more northward-positioned AEJ, results in a decrease in the energetic conversion, and it is evident in both ground (Figure 9c) and wave-relative  $C_{pk}$  profiles (Figure 9f) with CTRL exhibiting larger  $C_{pk}$  values than MOIST at and below the AEJ.

Wave-relative  $C_{k1}$  profiles (Figure 9d) are similar to WAM/ground-relative profiles (Figure 9a) but larger in magnitude and with wave-relative CTRL exhibiting the highest values between 800 and 600 hPa. This is consistent with the less constrained AEJ interacting with the monsoon and the AEW and thus, more conversion of zonal kinetic energy to  $K_E$ .  $C_{k1}$  is the dominant barotropic term in the wave-relative profiles.

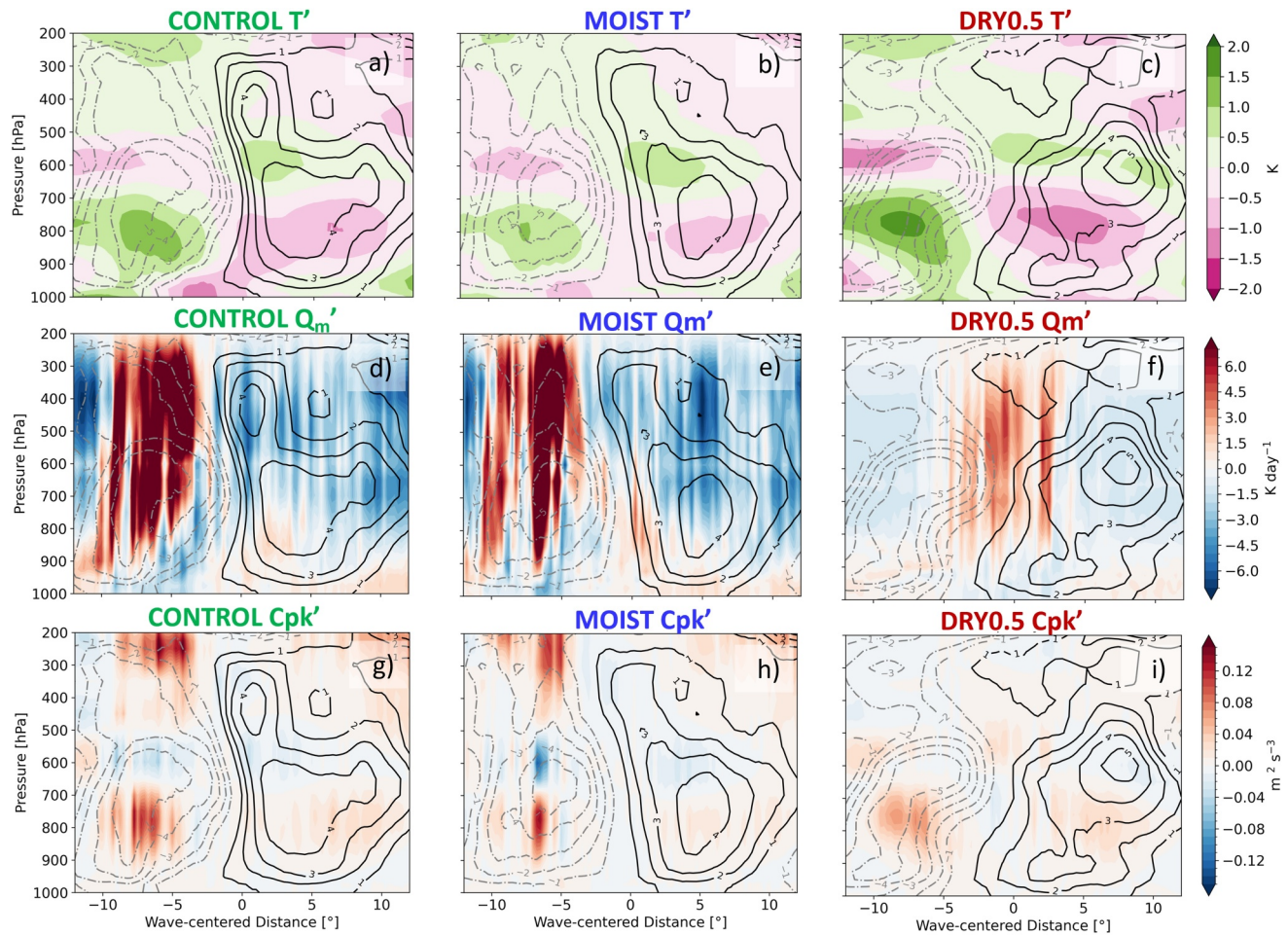


**Figure 10.** Reference group three-hourly wave-centered time mean anomalies over land of meridional wind (solid contours) and  $T'$  for (a–c) CTRL, MOIST, and DRY0.5, meridional wind (solid contours) and diabatic heating rates from microphysics scheme (shade) for (d–f) CTRL, MOIST, and DRY0.5, and meridional wind (solid contours) and  $C_{pk}'$  for (g–i) CTRL, MOIST, and DRY0.5. Anomalies are deviations from the zonal average over the wave wavelength for the time mean over land. Meridional wind contours are from  $-5$  to  $5 \text{ m s}^{-1}$  at  $1 \text{ m s}^{-1}$  intervals.

For  $C_{k2}$ , the lower troposphere shows opposite signs between wave and ground-relative reference frames. Wave-relative  $C_{k2}$  is negative for all simulations between 900 and 600 hPa with CTRL being the most negative (Figure 9e). This indicates weak upgradient momentum transport in the wave reference frame. The positive  $C_{k2}$  in the ground-relative energetics, with MOIST having the strongest magnitude, is due to downgradient momentum mixing that is slightly accentuated in MOIST, perhaps owing to more widespread convection relative to CTRL.

Above 600 hPa,  $C_{pk}$  for both wave and ground-relative profiles is largest for CTRL due to more top-heavy mass flux profiles and related warming in the upper troposphere (Figure 10). Below 600 hPa, the ground-relative energetics exhibit negative  $C_{pk}$ , consistent with the cooler (and more moist) air in the rising part of the monsoon overturning circulation. However, in the wave-relative frame, temperature anomalies are related to horizontal advection, hence the region of rising air is relatively warm in northerly flow, owing to the northward directed temperature gradient. Relative to the zonal average over the wave, the southerly flow region exhibits negative diabatic heating and subsidence in the presence of cooler air beneath 700 hPa. Thus,  $C_{pk}$  in the wave frame is positive, indicating an increase of  $K_E$ .

Figure 10 also shows that temperature anomalies are weaker in the MOIST experiment, hence the baroclinic conversion term is weaker as well. It appears that the temperature anomalies are partly offset by vertical motions within the wave that are more pronounced with more widespread convection. The temperature anomalies in the wave frame of reference here are different from those of Russell et al. (2020) model, adapted from Kuang (2008),

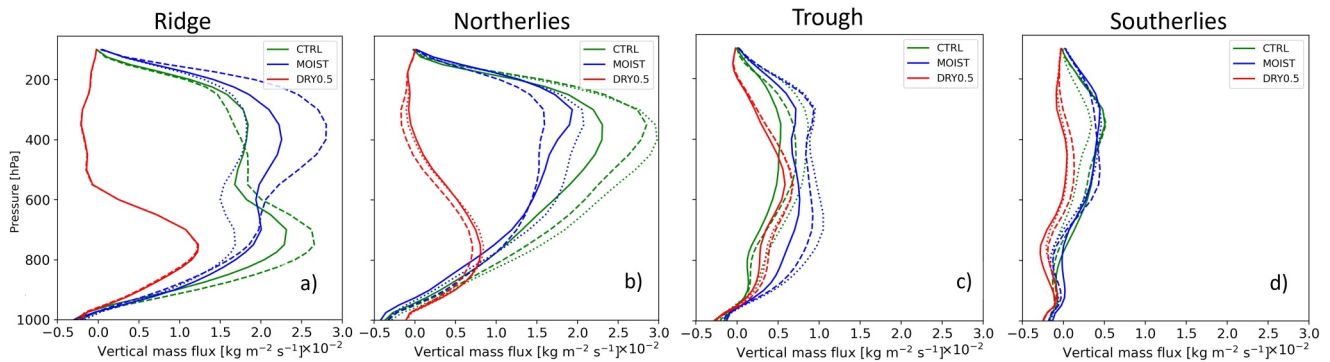


**Figure 11.** Three-hourly phase-centered time means over land of vertical mass flux profiles for the set of CTRL simulations (green solid, dashed, and dotted lines), MOIST simulations (blue solid, dashed, and dotted lines), and DRY0.5 simulations (red solid, dashed, and dotted lines). The phase-centered domain is a  $6^\circ \times 6^\circ$  box (extending  $3^\circ$  from the center of the phase in longitude and  $3^\circ$  from the wave track in latitude) at the same latitude and do not overlap.

as their temperature anomalies are in phase with the potential vorticity (their Figure 1). Their temperature anomalies would be nearly  $90^\circ$  out of phase with the temperature anomalies in the CTRL and MOIST experiments.

The wave-centered time mean anomalies of meridional wind and diabatic heating reveal that the AEW in CTRL experiments (Figure 10d) exhibit stronger coupled convection than MOIST (Figure 10e) and DRY0.5 (Figure 10f). This means that there is more deep convection closer to the trough in CTRL related to the stronger wave amplitude in CTRL (meridional wind contours). The AEW-convection system in CTRL and MOIST also shows a deeper structure than that in DRY0.5 (Figure 10f, shallower wave). In addition to the changes in the amplitude of the wave through the anomalous winds, the main differences are found in the intensity of the diabatic heating from deep and/or stratiform convection. CTRL simulations favor a larger fraction of deep moist convection and/or stratiform heating ahead of the vortex when compared to MOIST and DRY0.5. This can also be seen by the more top-heavy vertical mass flux profiles in the northerlies in Figure 11b for CTRL (green lines) compared to the rest. This diabatic heating from deep convection ahead of the trough results in anomalous PV production from diabatic heating at the low and mid levels supporting propagation (Núñez Ocasio et al., 2020b; Russell et al., 2020; Tomassini et al., 2017). Thus, CTRL has more PV production than MOIST ahead of the wave, contributing to (slightly) faster westward propagation, as will be shown in the next section.

For both MOIST and CTRL, diabatic heating is weaker over the wave-trough region than in the northerly wave phase. Toward the wave trough in CTRL, there is a reduction of deep-layer diabatic heating, with the structure being more confined to higher levels (500–200 hPa), signifying a mix of deep convection and stratiform clouds. The more top-heavy diabatic heating results in mid-level PV production supporting wave growth at the mid-levels agreeing with previous studies (i.e., Janiga & Thorncroft, 2013; Russell et al., 2020).

There are key differences, however, in these results that are not discussed in previous studies: a moister atmosphere (MOIST simulations) favors a bottom-heavy mass-flux profile near the wave trough, which is interpreted here as a greater fraction of shallow convection (congestus). The resulting detrainment in the mid-troposphere weakens the mid-tropospheric AEW vorticity. This detrainment in MOIST ultimately leads to an AEW-convection system that is weaker by the time it reaches the coast, and therefore delays the spin up of a TC and/or results in a weaker TC relative to CTRL (i.e., Figures 4b and 4c). Why the AEW environment in MOIST hinders deeper updrafts and/or deeper convection (more top-heavy vertical mass fluxes) is related in part to the more statically stable background state conditioned by a continuously stronger monsoon circulation.

In the region between the trough and the southerlies, there is anomalous cooling above 500 hPa occurring across simulations. This structure is also in agreement with the trailing stratiform cloud structure exhibiting heating above cooling type of vertical profile in the southerlies (Janiga & Thorncroft, 2013; Russell et al., 2020; Schumacher et al., 2007). This cooling may simply indicate absence of anomalous heating. However, this structure corresponds to the negative-to-positive vertical mass flux profiles in the southerlies (Figure 11d). The weaker AEW-convection system in MOIST when compared to CTRL is also associated with the more concentrated and deeper cooling at the higher levels in the southerlies (behind the wave center in Figure 10e).

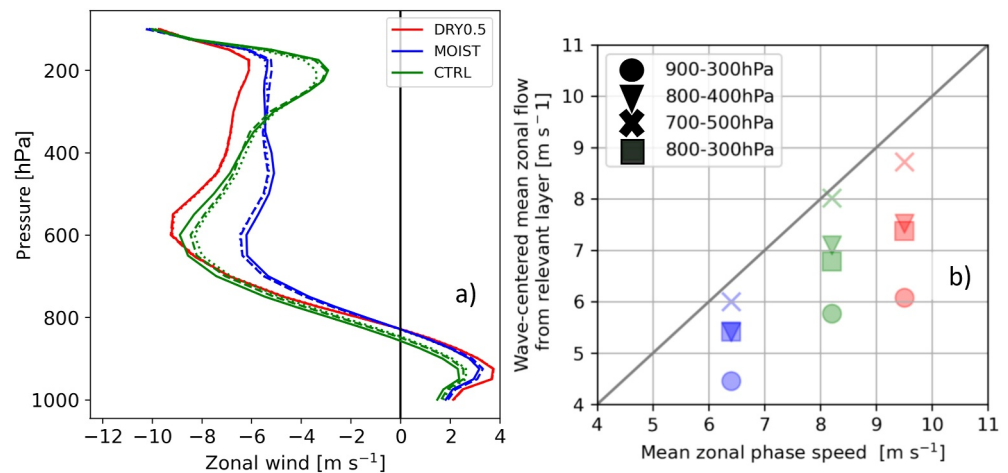


**Figure 12.** Mean zonal wind profile for the wave-centered domain in Figure 10 in panel (a). Scatter plot of mass-weighted wave-centered mean relevant zonal layer flow versus average zonal phase speed taken from 3-hourly centers in panel (b). Values are magnitudes. Each symbol represents the ensemble mean.

Dry simulations exhibit temperature anomalies consistent with meridional temperature advection. Temperature anomalies are out of phase with the meridional wind below the AEJ, and in phase above it. However, there is somewhat of a weak diabatic heating anomaly signature at the center of DRY0.5 (Figure 10f) related to anomalous higher values of vertical mass flux at the mid-levels (Figure 11b). With less cloud cover everywhere, dry simulations exhibit more surface heat flux from solar radiation and a deeper boundary layer, and this, in turn, may also be reflected as intense dry convection in the boundary layer scheme.

From these results, it is evident that a more saturated AEW-convection environment does not necessarily relate to a higher likelihood of more intense convection aligning with the wave trough. In a moister environment, although there is increased convection, less lifting is required. Consequently, this results in less intense convection supporting the wave growth. While temperature remains a primary factor, moisture, in a secondary role, modulates the CTRL wave more than the MOIST wave by facilitating increased phasing between the trough and deep convection. The last section analyzes the moisture sensitivity of wave translation through mean flow advection and propagation.

## 6. The Role of Moisture in the Mean Flow Advection and Propagation

To this point, we have shown that changes in moisture modulate the zonal mean state of the WAM system. We have also shown how moisture affects deep convection within the AEW and its phase relationship which can alter the wave's propagation and growth. In this section we expand upon Q2: How does environmental moisture affect wave propagation?

We first assess the mean zonal flow in relation to wave phase speed by computing profiles of the zonal wind averaged over the wave centered domain as in Figure 10. The vertical shear of the AEJ results in layer-dependent average zonal wind speeds; several reasonable choices are shown in Figure 12. For all choices, the trend across simulations is roughly the same, and the layer-averaged mean flow bears a similar quantitative relationship to the computed zonal phase speed. The waves move with nearly the maximum speed of the AEJ, and this speed varies according to the influence of moisture on the basic state. While the AEJ is strongest in MOIST, the jet is shifted poleward relative to the latitude of wave propagation; hence the zonal wind averaged relative to the wave is weaker (less easterly) than in the other simulations (Figure 12).

If one views the moist waves as potential vorticity anomalies, it may be more appropriate to use a deeper layer mean flow to describe the westward translation. In Figure 10, temperature anomalies within the waves are out of phase with the relative vorticity, thus implying that the PV anomaly of the wave is governed by the relative vorticity anomaly. Because relative vorticity is appreciable between 900 and 300 hPa, we consider several layer choices within this interval.

Results in Figure 12b show that, while the mean flow advection dominates the translation, further, smaller differences in phase speed arise. Except for the shallowest layer, the wave propagation (wave translation speed minus mean flow advection), is about  $0.5 \text{ m s}^{-1}$  greater in CTRL than MOIST. In other words, there is an additional contribution of westward propagation needed in CTRL to account for its full westward translation speed.

To investigate what gives rise to different propagation speeds of the wave in the CTRL and MOIST simulation, we provide a semi-quantitative analysis using a simplified (quasi-geostrophic) form of the vorticity equation:

$$\frac{\partial \zeta}{\partial t} + \bar{u} \frac{\partial \zeta}{\partial x} = -v \frac{\partial \bar{\eta}}{\partial y} + f_0 \frac{\partial \omega}{\partial p}. \quad (5)$$

In Equation 5,  $\zeta$  is the vertical component of the vorticity of the AEW (i.e., a perturbation quantity),  $\bar{\eta}$  is the zonal mean absolute vorticity, and  $\omega$  is the vertical velocity (also a perturbation quantity). Assuming wavelike solutions for a streamfunction  $\psi = A \exp i(kx + ly - kct)$ , where  $\nabla^2 \psi = \zeta$ , and  $(u, v) = \left( \frac{\partial \psi}{\partial y}, \frac{\partial \psi}{\partial x} \right)$ ,

$$ik(k^2 + l^2)c\psi = ik(k^2 + l^2)\bar{u}\psi - ik \frac{\partial \bar{\eta}}{\partial y} \psi + f_0 \frac{\partial \omega}{\partial p} \quad (6)$$

Further assuming that the horizontal structure of  $\omega$  is set by the wave such that the upward vertical mass flux occurs in the northerly phase, as seen in CTRL (Figure 11), the vertical motion is taken to be proportional to  $-v$ . Hence,  $\omega = -H(p)ik\psi$ . Solving for the phase speed  $c$ ,

$$c = \bar{u} - \frac{\frac{\partial \bar{\eta}}{\partial y}}{k^2 + l^2} - \frac{f_0 \frac{dH}{dp}}{k^2 + l^2}. \quad (7)$$

Here,  $H(p)$  is a structure function for the vertical motion. For simplicity,  $\frac{dH}{dp}$  is taken to be a constant, representing the average behavior of  $H$  over the bulk of the troposphere where vertical motion increases with height over convecting regions up to 400 hPa. By making the vertical motion proportional to  $-v$ , the dispersion relation adds an additional term that acts like an effective restoring force for the wave and directly influences its propagation. A larger positive vertical gradient of vertical motion (proportional to  $\frac{dH}{dp}$ ) will move the wave more rapidly to the west.

Our goal is to explain the differences between simulations. Assuming that the wavelength of the easterly wave in each simulation is identical (which is supported by Figure 3), then the difference in the phase speed between simulations can be expressed:

$$\Delta c = \Delta \bar{u} - \frac{\Delta \frac{\partial \bar{\eta}}{\partial y}}{k^2 + l^2} - \frac{f_0 \left( \Delta \frac{dH}{dp} \right)}{k^2 + l^2}. \quad (8)$$

Apart from the difference in zonal mean flow that arises from changes in moisture, Equation 8 indicates two other possible contributions to differences in phase speed: differences in the absolute vorticity gradient and differences in the vertical velocity profile. For the difference between simulations CTRL and MOIST, this can be understood from the last term in Equation 8. From Figure 11, it is noted that the difference in the upward perturbation mass flux in the northerly flow quadrant of the wave is roughly  $1 \text{ kg m}^{-2} \text{ s}^{-1}$ . In the southerly phase, the differences between simulations CTRL and MOIST are small. This is because there is little convection in the southerly phase, so the total mass fluxes are nearly zero—hence, negative in a perturbation sense. The function  $H$  scales as  $\omega$  divided by the scale for the meridional velocity  $v$ . From Figure 10 a scale of  $3 \text{ m s}^{-1}$  for  $v$ , and a scale for the change in  $\omega$  of  $0.05 \text{ Pa s}^{-1}$  is assumed, where the difference in  $\omega$  between CTRL and MOIST in the northerly phase has been divided by two in order to roughly account for the fact that the differences in mass flux are mainly confined to the northerly wave phase. Assuming a zonal and meridional wavelength of 2,000 km and  $f_0 = 5 \times 10^{-5} \text{ s}^{-1}$  yields a difference in phase speed of about  $0.5 \text{ m s}^{-1}$ . This is roughly consistent with the propagation difference between MOIST and CTRL seen in Figure 12.

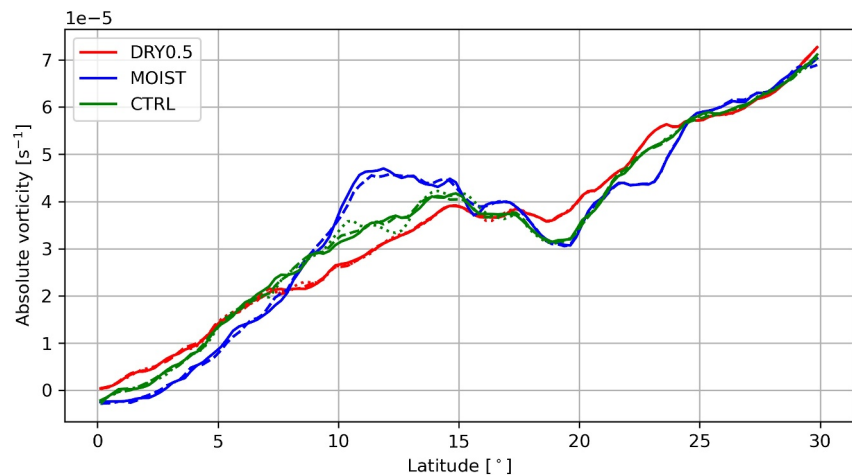


**Figure 13.** Zonal mean absolute vorticity ( $\bar{\eta}$ ) removing the first day of the simulation as a function of latitude, vertical averaged from 900 to 400 hPa for CTRL simulations (green solid, dashed, and dotted lines), MOIST simulations (blue solid, dashed, and dotted lines), and DRY0.5 simulations (red solid, dashed, and dotted lines). Longitude average is taken from 15°W to 25°E (West African Monsoon box in Figure 2).

The zonal mean meridional vorticity gradient (i.e. effective  $\beta$ ) is locally altered by the effects of moisture on the strengthening of the monsoon circulation (Figure 13), but averaged over the meridional scale of the wave, say, from 4°N to 15°N, there is little systematic difference in this gradient. Over a narrower meridional interval, such as 11°N to 15°N, there are obvious differences in the absolute vorticity gradient between CTRL and MOIST, but it is not clear how the locally larger absolute vorticity in MOIST near 15°N would affect wave propagation. Hence, the difference in effective  $\beta$  does not appear to explain the propagation difference between simulations MOIST and CTRL.

For a given layer used to define the zonal mean flow, the wave in DRY0.5 translates faster relative to that flow than in the CTRL and MOIST simulations (Figure 12). As seen in Figure 7, the wave amplitude in DRY0.5 is confined to a shallower layer than in MOIST or CTRL, implying that a shallower layer should be used to define the mean flow. If we choose the layer from 700 to 500 hPa to define the mean flow for the wave in DRY0.5, we see that it is less than  $1 \text{ m s}^{-1}$  slower than the translation speed. Because we do not expect much contribution from diabatic heating in this experiment, the additional westward phase speed must come from effective  $\beta$ . Given the absolute vorticity gradient of  $3 \times 10^{-5} \text{ s}^{-1}$  over the latitude range of 4°N to 15°N (Figure 13), the propagation from effective  $\beta$  is about  $1 \text{ m s}^{-1}$ . Thus, the modest contribution to wave propagation from the  $\beta$  effect adds to the advection by the mean flow to approximately account for the wave translation in DRY0.5.

## 7. Conclusions

This work was motivated by a recent study that investigated pre-Helene's partly moisture-driven growth (Núñez Ocasio & Rios-Berrios, 2023). Questions remained unresolved on the evolution and associated convection including whether a more moisture-rich environment results in a mean state and in moisture feedbacks that favor further wave growth. The goal of this study was to understand how environmental moisture plays a role in driving the growth and propagation of the AEW-convection system in the pre-Helene case and how that role relates to the WAM system. A total of nine moisture sensitivity experiments are performed introducing a novel MPAS-A setup with convection-permitting capabilities, offering a more realistic depiction of the WAM system and AEWs. Additionally, our research delves into how moisture influences the WAM system while simultaneously investigating the internal wave dynamics of a TC precursor with explicit convection. Based on the results presented here, we offer answers to the main questions of this study.

Q1: How do changes in moisture modulate the zonal mean state over Africa and of the WAM system?

A moister atmosphere results in more intense AEJ, WAM, and vertical mass flux profiles from more convection. The AEJ core compacts and shifts northward as in Cornforth et al. (2009). The northward shift of the jet results in fewer interactions between the AEJ-WAM system and weaker mid-level easterly background flow over the

WAM region. AEW-AEJ interactions are also limited in a moister environment as the AEJ shifts northward yet the wave continues propagating in about the same latitudes across experiments. This results in the MOIST waves extracting less energy from the AEJ and thus, having less  $K_E$ . When analyzing the energy conversion terms it is found that the more  $K_E$  in CTRL is due to larger barotropic conversion from more shear produced by deep convection near the AEJ (more AEJ-WAM and AEW-AEJ interactions) and greater positive feedbacks between invigorating vertical circulations, the AEJ, and the wave ( $C_{pk}$ ). Drier conditions, on the other hand, weaken the zonal mean state, diluting and spreading out both the AEJ and WAM.

Q2: How does environmental moisture affect the relationship between the AEW and convection, and how does that, in turn, affect wave amplitude and propagation?

The CTRL simulations shows the fastest attaining tropical cyclogenesis events across experiments as well as the most optimal phasing between wave center and convection. This motivated the focus of this study to further explore this optimal phasing and land evolution of the AEW-convection system. It is evident that although moister waves move slower, the associated convection is out of phase with the center of the wave, ultimately weakening and/or delaying the moister TC genesis. In addition, the stronger southwesterly low-level shear in the moister atmosphere may contribute to the out-of-phasing between AEW and convection. The changes in back-ground flow by changes in moisture content also affect the translation of the AEW. In a moister environment, the mean flow is reduced over the WAM region resulting in moister waves being the slowest and dry waves the fastest. The changes in mean flow over the WAM region explain most of the phase speed of the waves. Still, a small but non-negligible contribution to the translation is due to propagation which is explained by the changes in AEW-convection propagation (wave translation speed minus mean flow advection) across experiments.

In terms of new insights gained from this work, we can confirm the changes in the WAM system within a more realistic simulation setup when altering moisture. This allows us to compare and differentiate from past studies. Notably, previous studies have not used such a comprehensive set of diagnostic calculations nor have they linked the WAM system to a specific TC genesis precursor.

Concerning the AEW-convection system case that evolves into a TC, a notable and perhaps unexpected finding from this work is that increased moisture results in weaker and slower tropical cyclogenesis. Throughout the paper, we establish how this weakening is intricately linked to both the internal dynamics within the AEW-convection system and the overall mean state. More convection occurs in a moister environment, but phasing of deep convection and the wave becomes sub-optimal by additional moisture. This study also shows how moisture affects wave translation both through alteration of the mean zonal state and through the phase relationship of convection relative to the wave structure.

Another relevant contribution of this work is that although previous studies have suggested a significant role of topography on AEW growth through coupling with convection, this study further suggests how localized convective organization forced by topography can substantially change the wave speed and amplitude.

Our results agree with Tomassini et al. (2017), Russell et al. (2020), Núñez Ocasio et al. (2020b) and Núñez Ocasio and Rios-Berrios (2023) that convection at the wave center helps maintain the wave. However, wave temperature anomalies by the northward temperature gradient over Africa still appear to play a major role in the amplitude and energetics of the wave. Our results somewhat provide a shift in relative importance about PV production from clouds (diabatic heating) playing a major role in the propagation of an AEW in more favorable environments. Here we find that the majority of the changes in translation due to changes in moisture can be explained by the resulting differences in the magnitude of the easterly mean flow over Africa associated with the AEJ (weaker mean flow in MOIST results in a slower wave). Albeit a secondary role in using a semi-quantitative analysis that accounts for the background vorticity gradient, the PV production from diabatic heating ahead of the wave that is favored in a not-so-moist environment can help explain the unaccounted small difference in propagation relative to the mean flow between CTRL and MOIST.

One caveat in this work is the short period of the simulation. Cornforth et al. (2009) proposed that a weaker jet can result in a greater delay of AEW growth. Here, we can also relate this proposal to the timing of when the wave undergoes the process of TC genesis. We cannot confirm whether or not the delayed TC genesis process from a weaker AEW in MOIST would later become a slower-growing, but stronger TC. The evolution of the system after TC genesis, however, is out of the scope of this study. Another caveat is the fact that although here we are using nine simulations, they are for one AEW case, other AEWs may behave differently.

Finally, it is worth noting that moisture-sensitivity experiments like these cannot be directly related to climate studies (e.g., the role of temperature and anthropogenic sources are not being considered here), but could inform potential differences in future, more moist climate states. The results are instead meant to help elucidate the role of moisture and convection in the African mean state, AEW growth, and TC genesis to enable better evaluation of weather and climate models in the tropics.

## Data Availability Statement

Post-processed model outputs and the namelists for the 12 MPAS-A simulations can be accessed at <https://doi.org/10.5065/gry9-7q56> (Núñez Ocasio, 2023). The modified MPAS-A code to output isobaric variables following MPAS developers can be found in the first author's Github: <https://github.com/knubez/MPAS-Model>. Please reference this paper that uses this code and/or the one mentioned on the Github. The ERA5 data for initial and boundary conditions for CTRL were accessed via NSF NCAR Research Data Archive (<https://rda.ucar.edu/datasets/ds633.0/>) through the Computational and Information Systems Laboratory (CISL). IMERG was provided by NASA's Goddard Earth Sciences Data and Information Services Center (<https://disc.gsfc.nasa.gov/>).

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## References

- Adames, A. F. (2022). The basic equations under weak temperature gradient balance: Formulation, scaling, and types of convectively coupled motions. *Journal of the Atmospheric Sciences*, 79(8), 2087–2108. <https://doi.org/10.1175/JAS-D-21-0215.1>
- Adames, A. F., Kim, D., Clark, S. K., Ming, Y., & Inoue, K. (2019). Scale analysis of moist thermodynamics in a simple model and the relationship between moisture modes and gravity waves. *Journal of the Atmospheric Sciences*, 76(12), 3863–3881. <https://doi.org/10.1175/JAS-D-19-0121.1>
- Ahmed, F., Neelin, J. D., & Ángel, F. A. (2021). Quasi-equilibrium and weak temperature gradient balances in an equatorial beta-plane model. *Journal of the Atmospheric Sciences*, 78(1), 209–227. <https://doi.org/10.1175/JAS-D-20-0184.1>
- Bercos-Hickey, E., Nathan, T. R., & Chen, S.-H. (2020). On the relationship between the African easterly Jet, Saharan Mineral dust Aerosols, and West African precipitation. *Journal of Climate*, 33(9), 3533–3546. <https://doi.org/10.1175/JCLI-D-18-0661.1>
- Berry, G. J., & Thorncroft, C. D. (2012). African easterly wave dynamics in a mesoscale numerical model: The upscale role of convection. *Journal of the Atmospheric Sciences*, 69(4), 1267–1283. <https://doi.org/10.1175/JAS-D-11-099.1>
- Chen, X., & Zhang, F. (2019). Relative roles of preconditioning moistening and global circumnavigating mode on the MJO convective initiation during DYNAMO. *Geophysical Research Letters*, 46(2), 1079–1087. <https://doi.org/10.1029/2018GL080987>
- Cornforth, R. J., Hoskins, B. J., & Thorncroft, C. D. (2009). The impact of moist processes on the African easterly Jet–African easterly wave system. *Quarterly Journal of the Royal Meteorological Society*, 135(641), 894–913. <https://doi.org/10.1002/qj.414>
- Davis, C. A., Ahijevych, D. A., Wang, W., & Skamarock, W. C. (2016). Evaluating medium-range tropical cyclone forecasts in uniform- and variable-resolution global models. *Monthly Weather Review*, 144(11), 4141–4160. <https://doi.org/10.1175/mwr-d-16-0021.1>
- Diedhiou, A., Janicot, S., Viltard, A., & De Felice, P. (2002). Energetics of easterly wave disturbances over West Africa and the tropical Atlantic: A climatology from the 1979–1995 NCEP/NCAR reanalyses. *Climate Dynamics*, 18(6), 487–500. <https://doi.org/10.1007/s00382-001-0195-7>
- Elles, T. J., & Torn, R. D. (2019). Investigating the factors that contribute to African easterly wave intensity forecast uncertainty in the ECMWF ensemble prediction system. *Monthly Weather Review*, 147(5), 1679–1698. <https://doi.org/10.1175/MWR-D-18-0071.1>
- Fink, A. H., & Reiner, A. (2003). Spatiotemporal variability of the relation between African easterly waves and West African squall lines in 1998 and 1999. *Journal of Geophysical Research*, 108(D11), 4332. <https://doi.org/10.1029/2002JD002816>
- Fuchs, Z., & Raymond, D. J. (2002). Large-scale modes of a nonrotating atmosphere with water Vapor and cloud–radiation feedbacks. *Journal of the Atmospheric Sciences*, 59(10), 1669–1679. [https://doi.org/10.1175/1520-0469\(2002\)059<1669:LSMOAN>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<1669:LSMOAN>2.0.CO;2)
- Fuchs, Z., & Raymond, D. J. (2005). Large-scale modes in a rotating atmosphere with radiative–convective instability and WISHE. *Journal of the Atmospheric Sciences*, 62(11), 4084–4094. <https://doi.org/10.1175/JAS3582.1>
- Grell, G. A., & Freitas, S. R. (2014). A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. *Atmospheric Chemistry and Physics*, 14(10), 5233–5250. <https://doi.org/10.5194/acp-14-5233-2014>
- Hamilton, H. L., Núñez Ocasio, K. M., Evans, J. L., Young, G. S., & Fuentes, J. D. (2020). Topographic influence on the African easterly Jet and African easterly wave energetics. *Journal of Geophysical Research: Atmospheres*, 125(8), e2019JD032138. <https://doi.org/10.1029/2019JD032138>
- Hamilton, H. L., Young, G. S., Evans, J. L., Fuentes, J. D., & Núñez Ocasio, K. M. (2017). The relationship between the Guinea Highlands and the West African offshore rainfall maximum. *Geophysical Research Letters*, 44(2), 1158–1166. <https://doi.org/10.1002/2016GL071170>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hsieh, J.-S., & Cook, K. H. (2007). A study of the energetics of African easterly waves using a regional climate model. *Journal of the Atmospheric Sciences*, 64(2), 421–440. <https://doi.org/10.1175/JAS3851.1>
- Huffman, G. J., Bolvin, D. T., Nelkin, E. J., & Tan, J. (2019). Integrated multi-satellite Retrievals for GPM (IMERG) technical documentation. *Technical Reports Series*. Retrieved from [https://docsserver.gesdisc.eosdis.nasa.gov/public/project/GPM/IMERG\\_doc.06.pdf](https://docsserver.gesdisc.eosdis.nasa.gov/public/project/GPM/IMERG_doc.06.pdf)
- Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., & Collins, W. D. (2008). Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *Journal of Geophysical Research*, 113(D13), D13103. <https://doi.org/10.1029/2008JD009944>
- Janiga, M. A., & Thorncroft, C. D. (2013). Regional differences in the kinematic and thermodynamic structure of African Easterly Waves. *Quarterly Journal of the Royal Meteorological Society*, 139(675), 1598–1614. <https://doi.org/10.1002/qj.2047>
- Jones, P. W. (1999). First- and second-order conservative Remapping schemes for grids in spherical coordinates. *Monthly Weather Review*, 127(9), 2204–2210. [https://doi.org/10.1175/1520-0493\(1999\)127<2204:FASOCR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<2204:FASOCR>2.0.CO;2)
- Kuang, Z. (2008). A moisture-stratiform instability for convectively coupled waves. *Journal of the Atmospheric Sciences*, 65(3), 834–854. <https://doi.org/10.1175/2007JAS2444.1>

- Lawton, Q. A., Majumdar, S. J., Dotterer, K., Thorncroft, C., & Schreck, C. J. (2022). The influence of convectively coupled kelvin waves on African easterly waves in a wave-following framework. *Monthly Weather Review*, 150(8), 2055–2072. <https://doi.org/10.1175/MWR-D-21-0321.1>
- Mayta, V. C., Adames, A. F., & Ahmed, F. (2022). Westward-propagating moisture mode over the tropical Western Hemisphere. *Geophysical Research Letters*, 49(6), e2022GL097799. <https://doi.org/10.1029/2022GL097799>
- Nakanishi, M., & Niino, H. (2004). An improved Mellor–Yamada level-3 model with condensation physics: Its design and verification. *Boundary-Layer Meteorology*, 112, 1–31. <https://doi.org/10.1023/B:BOUN.0000020164.04146.98>
- Niu, G.-Y., Yang, Z.-L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., et al. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research*, 116(D12), D12109. <https://doi.org/10.1029/2010JD015139>
- Norquist, D. C., Recker, E. E., & Reed, R. J. (1977). The energetics of African wave disturbances as observed during phase III of GATE. *Monthly Weather Review*, 105(3), 334–342. [https://doi.org/10.1175/1520-0493\(1977\)105<0334:TEOAWD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1977)105<0334:TEOAWD>2.0.CO;2)
- Núñez Ocasio, K. M. (2023). *MPAS-A moisture-sensitivity simulations with convection-permitting resolution and regional configuration using the Model for Prediction Across Scales (MPAS) version 7.3*. NCAR/UCAR - GDEX. <https://doi.org/10.5065/gry9-7q56>
- Núñez Ocasio, K. M., Brammer, A., Evans, J. L., Young, G. S., & Moon, Z. L. (2021). Favorable monsoon environment over Eastern Africa for subsequent tropical cyclogenesis of African easterly waves. *Journal of the Atmospheric Sciences*, 78(9), 2911–2925. <https://doi.org/10.1175/JAS-D-20-0339.1>
- Núñez Ocasio, K. M., Evans, J. L., & Young, G. S. (2020a). Tracking mesoscale convective systems that are potential candidates for tropical cyclogenesis. *Monthly Weather Review*, 148(2), 655–669. <https://doi.org/10.1175/MWR-D-19-0070.1>
- Núñez Ocasio, K. M., Evans, J. L., & Young, G. S. (2020b). A wave-relative framework analysis of AEW–MCS interactions leading to tropical cyclogenesis. *Monthly Weather Review*, 148(11), 4657–4671. <https://doi.org/10.1175/MWR-D-20-0152.1>
- Núñez Ocasio, K. M., & Rios-Berrios, R. (2022). AEW hindcast using the Model for Prediction across Scales–Atmosphere (MPAS–A) version 7.1 [Dataset]. *National center for atmospheric research*. NCAR/UCAR - GDEX. <https://doi.org/10.5065/t224-6s94>
- Núñez Ocasio, K. M., & Rios-Berrios, R. (2023). African easterly wave evolution and tropical cyclogenesis in a pre-Helene (2006) Hindcast using the Model for Prediction Across Scales–Atmosphere (MPAS–A). *Journal of Advances in Modeling Earth Systems*, 15(2), e2022MS003181. <https://doi.org/10.1029/2022MS003181>
- Payra, S., Ricaud, P., Abida, R., El Amraoui, L., Attié, J.-L., Rivière, E., et al. (2016). Evaluation of water vapour assimilation in the tropical upper troposphere and lower stratosphere by a chemical transport model. *Atmospheric Measurement Techniques*, 9(9), 4355–4373. <https://doi.org/10.5194/amt-9-4355-2016>
- Pytharoulis, I., & Thorncroft, C. (1999). The low-level structure of African easterly waves in 1995. *Monthly Weather Review*, 127(10), 2266–2280. [https://doi.org/10.1175/1520-0493\(1999\)127<2266:TLLSOA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<2266:TLLSOA>2.0.CO;2)
- Raymond, D. J., Sessions, S. L., & López Carrillo, C. (2011). Thermodynamics of tropical cyclogenesis in the Northwest Pacific. *Journal of Geophysical Research*, 116(D18), D18101. <https://doi.org/10.1029/2011JD015624>
- Russell, J. O. H., & Ayyer, A. (2020). The potential vorticity structure and dynamics of African easterly waves. *Journal of the Atmospheric Sciences*, 77(3), 871–890. <https://doi.org/10.1175/JAS-D-19-0019.1>
- Russell, J. O. H., Ayyer, A., & Dylan White, J. (2020). African easterly wave dynamics in convection-permitting simulations: Rotational straitform instability as a Conceptual model. *Journal of Advances in Modeling Earth Systems*, 12(1), e2019MS001706. <https://doi.org/10.1029/2019MS001706>
- Schumacher, C., Zhang, M. H., & Ciesielski, P. E. (2007). Heating structures of the TRMM field campaigns. *Journal of the Atmospheric Sciences*, 64(7), 2593–2610. <https://doi.org/10.1175/JAS3938.1>
- Shen, B.-W., Tao, W.-K., & Wu, M.-L. C. (2010). African easterly waves in 30-day high-resolution global simulations: A case study during the 2006 NAMMA period. *Geophysical Research Letters*, 37(18), L18803. <https://doi.org/10.1029/2010GL044355>
- Skamarock, W. C., Klemp, J. B., Duda, M. G., Fowler, L. D., Park, S.-H., & Ringler, T. D. (2012). A Multiscale Nonhydrostatic atmospheric model using Centroidal Voronoi Tessellations and C-Grid staggering. *Monthly Weather Review*, 140(9), 3090–3105. <https://doi.org/10.1175/MWR-D-11-00215.1>
- Sobel, A. H. (2002). Water vapor as an active scalar in tropical atmospheric dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 12(2), 451–459. <https://doi.org/10.1063/1.1480795>
- Sobel, A. H., Nilsson, J., & Polvani, L. M. (2001). The weak temperature gradient approximation and balanced tropical moisture waves. *Journal of the Atmospheric Sciences*, 58(23), 3650–3665. [https://doi.org/10.1175/1520-0469\(2001\)058<3650:TWTGAA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<3650:TWTGAA>2.0.CO;2)
- Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Monthly Weather Review*, 136(12), 5095–5115. <https://doi.org/10.1175/2008MWR2387.1>
- Thorncroft, C. D., & Hoskins, B. J. (1994). An idealized study of African easterly waves. I: A linear view. *Quarterly Journal of the Royal Meteorological Society*, 120(518), 953–982. <https://doi.org/10.1002/qj.49712051809>
- Tomassini, L., Parker, D. J., Stirling, A., Bain, C., Senior, C., & Milton, S. (2017). The interaction between moist diabatic processes and the atmospheric circulation in African Easterly Wave propagation. *Quarterly Journal of the Royal Meteorological Society*, 143(709), 3207–3227. <https://doi.org/10.1002/qj.3173>
- Tompkins, C. F., & Chiao, S. (2012). Modeling studies of impacts from the Guinea Highlands in relation to tropical cyclogenesis along the West African coast. *Meteorology and Atmospheric Physics*, 115(1–2), 57–72. <https://doi.org/10.1007/s00703-011-0167-3>
- Torn, R. D. (2010). Ensemble-based sensitivity analysis applied to African easterly waves. *Weather and Forecasting*, 25(1), 61–78. <https://doi.org/10.1175/2009WAF222255.1>
- Xu, K.-M., & Randall, D. A. (1996). A Semiempirical cloudiness parameterization for use in climate models. *Journal of the Atmospheric Sciences*, 53(21), 3084–3102. [https://doi.org/10.1175/1520-0469\(1996\)053<3084:ASCPFU>2.0.CO;2](https://doi.org/10.1175/1520-0469(1996)053<3084:ASCPFU>2.0.CO;2)
- Yang, S.-C., Chen, S.-H., & Chang, C.-C. (2023). Understanding the impact of assimilating FORMOSAT-7/COSMIC-2 radio occultation refractivity on tropical cyclone genesis: Observing system simulation experiments using Hurricane Gordon (2006) as a case study. *Quarterly Journal of the Royal Meteorological Society*, 149(753), 1293–1318. <https://doi.org/10.1002/qj.4455>