Mean Climate and Tropical Rainfall Variability in Aquaplanet Simulations Using the Model for Prediction Across Scales-Atmosphere

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Abstract Aquaplanet experiments are important tools for understanding and improving physical processes simulated by global models; yet, previous aquaplanet experiments largely differ in their representation of subseasonal tropical rainfall variability. This study presents results from aquaplanet experiments produced with the Model for Prediction Across Scales-Atmosphere (MPAS-A)—a community model specifically designed to study weather and climate in a common framework. The mean climate and tropical rainfall variability simulated by MPAS-A with varying horizontal resolution were compared against results from a recent suite of aquaplanet experiments. This comparison shows that, regardless of horizontal resolution, MPAS-A produces the expected mean climate of an aquaplanet framework with zonally symmetric but meridionally varying sea-surface temperature. MPAS-A, however, has a stronger signal of tropical rainfall variability driven by convectively coupled equatorial waves. Sensitivity experiments with different cumulus parameterizations, physics packages, and vertical grids consistently show the presence of those waves, especially equatorial Kelvin waves, in phase with lower-tropospheric convergence. Other models do not capture such rainfall-kinematics phasing. These results suggest that simulated tropical rainfall variability depends not only on the cumulus parameterization (as suggested by previous studies) but also on the coupling between physics and dynamics of climate and weather prediction models.

Plain Language Summary Continuous improvements of weather and climate models are necessary to advance both our understanding and ability to predict high-impact weather under present and future climates. One particular area requiring model improvements is the representation of tropical rainfall variability happening at subseasonal timescales. With this issue in mind, we produced experiments using a simplified version of a global model called an aquaplanet—an Earth-like water-covered surface devoid of land, topography, sea-ice, or seasons. We first demonstrate that the model used in this study, which was specifically designed to study weather and climate, simulates a mean climate that is consistent with other aquaplanet experiments. We also demonstrate that the model is able to capture tropical rainfall variability driven by phenomena called convectively coupled Kelvin waves. Because other models do not capture this variability, we show experiments changing various components of the model to explore the influence of those components on the representation of Kelvin waves. Those experiments demonstrate that, contrary to previous perceptions, the component that approximates deep cumulus clouds is not the only responsible component. Instead, the ability to produce a certain phasing between winds and rainfall appears to explain whether a model can capture Kelvin waves.

1. Introduction

Weather and climate phenomena are traditionally simulated by different tools—numerical weather prediction (NWP) models or climate models. In the tropical atmosphere, however, rainfall variability is driven by phenomena happening at the intersection of weather and climate timescales. Planetary-scale phenomena, known as convectively coupled equatorial waves (Kiladis et al., 2009), circumnavigate the world while influencing clouds, precipitation, and circulation patterns both within and outside the tropics. Despite their important influence, convectively coupled equatorial waves are not well captured by neither NWP nor climate models (e.g., Dias et al., 2018; Lin et al., 2006; Nakajima et al., 2013) even under simplified configurations (e.g., Nakajima et al., 2013). This limitation demands continuous model improvements to better capture atmospheric phenomena happening at the intersection of weather and climate timescales. The
present study examines the ability of a global model to capture weather-to-climate phenomena, with an emphasis on tropical rainfall variability, in a simplified yet realistic framework: an aquaplanet.

The aquaplanet framework offers many opportunities for improving both the representation and understanding of atmospheric phenomena in global models. An aquaplanet is an idealized representation of Earth without complexities associated with land, topography, sea-ice, and seasons. Despite those simplifications, aquaplanet experiments generate climate and weather systems that resemble those of real Earth (e.g., Blackburn et al., 2013; Medeiros et al., 2015; Medeiros & Stevens, 2011). As such, aquaplanet experiments fit into a modeling hierarchy that has been used for many purposes, including fundamental understanding of atmospheric dynamics and identification of model biases (Hayashi & Sumi, 1986; Held & Suarez, 1994; Hess et al., 1993; Maher et al., 2019; Möbis & Stevens, 2012; Sumi, 1992; Williamson, 2008; Williamson & Olson, 2003). The long integration time (months to years) has also allowed for statistical studies of weather phenomena, such as middle latitude cyclones (Pfahl et al., 2015), tropical cyclones (Merlis & Held, 2019, and references therein), and atmospheric rivers (Swenson et al., 2018). Unlike other types of idealized studies where a disturbance of interest is specified in the initial conditions and the integration is limited to a single case, aquaplanet experiments spontaneously produce multiple weather phenomena under similar background conditions to the real world. All these features make aquaplanet experiments attractive tools for studying the weather-to-climate continuum.

Some aquaplanet experiments exhibit tropical rainfall variability associated with convectively coupled equatorial waves. For example, the Aqua-Planet Experiment (Blackburn et al., 2013) compared solutions from over a dozen models. One of the most striking results was the diversity of tropical rainfall variability among models. Some models exhibited rainfall variability associated with convectively coupled equatorial waves, including Kelvin waves and inertio-gravity waves. Other models, however, only developed stationary features in the tropics or westward-propagating “advective disturbances” that did not exhibit characteristics of convectively coupled equatorial waves. A follow-up study attributed the diversity of solutions to differences in the diabatic heating profiles produced by the cumulus parameterization schemes (Nakajima et al., 2013). Whether other aspects of the models contribute, however, remains unclear because the comparison was based on solutions from models with different dynamical cores, physics packages, horizontal and vertical grid spacing, and so forth.

Other studies have also examined the representation of convectively coupled equatorial waves—particularly Kelvin waves—in general circulation and limited-area models (e.g., Blanco, Nolan, & Mapes, 2016; Blanco, Nolan, & Tulich, 2016; Dias et al., 2018; Frierson, 2007; Frierson et al., 2011; Lin et al., 2006; Peatman et al., 2018; Seo et al., 2012; Straub et al., 2010). Most of those studies also emphasize the influence of deep cumulus schemes on the structure and variability of Kelvin waves. A comparison of real-world climate simulations, for example, revealed that five out of 20 models were able to capture Kelvin wave activity comparable to observations (Straub et al., 2010). On the other hand, a comparison of two global weather prediction models suggested that one of the models had superior skill at predicting wave propagation due to a more accurate coupling between dynamics and physics, such that rainfall associated with the waves followed after lower-tropospheric convergence (Dias et al., 2018). Other studies have performed sensitivity experiments with the same model and have found that Kelvin wave activity is sensitive to mid-tropospheric entrainment or changes in the base state due to entrainment coefficients (e.g., Frierson et al., 2011; Peatman et al., 2018; Seo et al., 2012). Despite these efforts, there is still a clear need for improving the representation of tropical rainfall variability in climate and weather models.

The main purpose of this study is twofold: (1) to document the aquaplanet configuration in a model specifically designed to study weather and climate and (2) to use this aquaplanet configuration to investigate the sensitivity of tropical rainfall variability to various aspects of the model. To this end, a series of aquaplanet experiments, described in section 2, was produced with the Model for Prediction Across Scales-Atmosphere (MPAS-A Skamarock et al., 2012). Because there is no true aquaplanet reference, results from MPAS-A were compared against a suite of aquaplanet experiments recently produced with other global models. Other studies have used aquaplanet experiments with MPAS-A (e.g., Hagos et al., 2013; Martini et al., 2015; Rauscher & Ringler, 2014; Rauscher et al., 2013; Swenson et al., 2018); however, those studies have neither used grid spacing characteristic of numerical weather prediction models nor have they documented the mean climate and tropical rainfall variability of MPAS-A in comparison to other models.
We demonstrate in section 3 that, regardless of horizontal resolution, MPAS-A produces a mean climate that is largely consistent with the mean climate of other aquaplanet experiments. MPAS-A, however, stands out from other models in its ability to produce tropical rainfall variability associated with convectively coupled equatorial waves. Sensitivity experiments presented in section 4 suggest that such skill is not only attributable to the cumulus scheme but also seems related to the coupling between dynamics and physics in a model. Altogether, this study demonstrates that MPAS-A is well suited for fundamental studies of the weather-to-climate continuum in a simplified yet realistic framework. Future plans and opportunities with the MPAS-A aquaplanet configuration are discussed in section 5.

2. Methods

We conducted aquaplanet experiments with MPAS-A (Rios-Berrios et al., 2020; Skamarock et al., 2012), version 6.2. MPAS-A is a global, nonhydrostatic atmosphere model that was designed to seamlessly resolve weather and climate phenomena of different spatiotemporal scales. This model employs C-grid discretization on an unstructured Voronoi mesh, which allows for either a global mesh with quasi-uniform cells or for a variable mesh with smaller cells (i.e., higher horizontal resolution) in a region of interest transitioning to larger cells elsewhere on the globe. MPAS-A has been used predominantly for real-data applications (i.e., numerical weather prediction) (e.g., Davis et al., 2016; Schwartz, 2019; Wong & Skamarock, 2016), but its unique features make this model also suitable for fundamental studies of weather-to-climate phenomena.

The experimental setup largely followed the protocol of the Aqua-Planet Experiment (Blackburn et al., 2013), with only minor modifications needed in MPAS-A. The entire globe was configured as a water-covered surface with a time-invariant, zonally symmetric sea-surface temperature (SST) profile given by

\[
\text{SST}(\phi) = \begin{cases} 
27 \times & \left[1 - \frac{1}{2} \left(\sin^4 \left(\frac{3}{2} \phi\right) \right) \right. \\
0, & \text{if } |\phi| \leq \frac{\pi}{3} \\
\text{otherwise}.
\end{cases}
\]

This profile, known as the “QOBS” profile (Neale & Hoskins, 2001), is an idealized approximation to the time-averaged, zonally averaged surface temperature of Earth. The SST peaks at the equator with a maximum of 27°C and drops off to 0°C at 60° latitude. A perpetual equinox was specified by fixing the declination angle at 0° and fixing the solar constant at 1,365 W m⁻² in the radiation driver of MPAS-A. As in the Aqua-Planet Experiment, a hemispheric-symmetric, zonally symmetric ozone distribution was used and interactions between aerosols and radiation were neglected. Gas concentrations were left as the default values in MPAS-A, but this choice does not affect the results presented herein.

Aquaplanet experiments are typically integrated for several months to many years, depending on computational constrains and other factors. Most experiments use climate models, which employ horizontal and vertical diffusion that allows numerically stable integration for many years and decades. Given that MPAS-A has been mostly used for integration times of up to several months, a second-order diffusion was added to the horizontal wind at the top five model levels (k) at each cell (i). The second-order diffusion coefficient (K) was given by

\[
K(k, i) = 2.0 \text{ m}^2 \text{s}^{-2} \frac{|k - (N - 6)|}{6} \Delta x, \text{ for } k = (N - 5, N),
\]

where \(\Delta x\) is the horizontal cell spacing and \(N\) is the total number of vertical levels. Sensitivity experiments demonstrated that MPAS-A remained stable without the extra diffusion, but the winds at the model top reached substantially stronger magnitudes than those produced by other models (not shown). The second-order diffusion was applied in addition to the default filters in MPAS-A, consisting of Smagorinsky second-order diffusion (Smagorinsky, 1963) with a length scale equal to the mesh spacing of each experiment and Rayleigh w-damping beginning at 30-km height with a 0.2 coefficient.

Three main experiments were produced with variations only to the horizontal cell spacing. The primary experiment discussed here (120-km MPAS-A hereafter) used 120-km cell spacing, which is comparable to the horizontal grid spacing of most previous aquaplanet experiments (i.e., 1°). Two additional experiments were produced with horizontal cell spacing chosen to mimic high-resolution climate models (30-km cell
spacing) and operational NWP global models (15-km cell spacing). All three experiments used quasi-uniform meshes and 75 vertical levels with a model top at 40 km. The vertical spacing between levels increased from approximately 90 m near the surface to approximately 800 m at the uppermost layer. These experiments also used the same physics packages consisting of the “mesoscale reference” suite in MPAS—-a combination of physics packages that have been thoroughly tested for simulations of mesoscale weather. These packages include the new Tiedtke cumulus parameterization (Zhang & Wang, 2017), RRTMG shortwave and longwave radiation (Iacono et al., 2008), Xu-Randall subgrid cloud fraction (Xu & Randall, 1996), WSM6 microphysics (Hong et al., 2004), and YSU boundary layer (Hong et al., 2006). Additional sensitivity experiments were produced with variations in the physics packages or the vertical grid. Details of those experiments will be provided in section 4.

All experiments were initialized with a resting atmosphere and a globally uniform sounding. The initial sounding was obtained from a separate simulation initialized with an isothermal atmosphere \( T = 300 \) K and 50% relative humidity below 500 hPa at every grid point. After running this experiment for 3 years, globally averaged temperature, pressure, and water vapor mixing ratio were obtained and used to initialize the experiments discussed here. This method ensured that the solution of each experiment was spontaneously generated by the experiment itself and not by the imposed initial three-dimensional structure.

The 120-km MPAS-A experiment was integrated for 3 years and 2 months. A statistical equilibrium was evident after 30 days as estimated from two globally averaged metrics: water vapor path (Figure 1a) and daily precipitation rate (Figure 1b). The 30-km and 15-km experiments were integrated for 2 years and 2 months due to large data storage demands; however, Medeiros et al. (2016) demonstrated that 2 years should be sufficient to obtain robust statistics from aquaplanet experiments. Figure 1 shows that these experiments also reached equilibrium after approximately 30 days. For consistency across experiments, the first 60 days (or 2 months) from each experiment were considered model spin up and were not included in any analysis.

To evaluate the experimental setup of the MPAS-A aquaplanet experiments, the 120-km experiment was compared against aquaplanet experiments from the Cloud Feedback Model Intercomparison Project, Phase 3 (CFMIP-3; Webb et al., 2017). Their “aqua-control” experiment was used because it employs the same SST profile and general configuration as the experiments conducted here. Output from four CFMIP-3 contributing models was available as of the time of this project: NCAR CESM2 (Danabasoglu, 2019), GFDL-CM4 (Silvers, 2018), CNRM-CM6 (Voldoire, 2019), IPSL-CM6A-LR (Boucher et al., 2018). We also examined output from CFMIP-2 and included results from three models (MIROC5, MRI, MPI-ESM-LR) in the assessment of tropical rainfall variability (more details in sections 3–4). The horizontal grid spacing varies between contributing models, with most of the models using 1–2.5° horizontal grid spacing. The vertical grid spacing also varies between models—from 32 levels in CESM2 to 79 levels in GFDL with a model top above the stratopause (see https://explore.es-doc.org/cmip6/models for more details about each participating model). All output variables—including those from MPAS-A—were
bilinearly interpolated to the same 1° × 1° grid and the same 17 isobaric levels. Although this interpolation is not necessarily conservative, using the same grid was intended to yield a fair comparison between models and experiments. CFMIP-3 models were integrated for 10 years, but only the first 3 years were used for comparison with the same integration period of the 120-km MPAS-A experiment. Additionally, rainfall statistics from MPAS-A and CFMIP-3 aquaplanet experiments were compared against satellite-based observations to assess the realism of precipitation extremes produced by the aquaplanet experiments. Observed precipitation rates were obtained from NASA’s Integrated Multi-satelliteE Retrievals for GPM (IMERG; Huffman et al., 2019). IMERG combines infrared and radar measurements from low-orbit satellites to produce rainfall estimates on a 0.1° × 0.1° grid between 60°S to 60°N. Here, we only considered the tropical East and Central Pacific oceans (from 10°N to 10°S and from the dateline to 90°W)—where the aquaplanet framework is most similar to real Earth—during the months of March and September from 2000 to 2018. For a consistent comparison, both IMERG and model output were interpolated to a 1° × 1° grid between 10°S and 10°N.

3. Comparison Against Other Aquaplanet Experiments
3.1. Mean Climate

MPAS-A aquaplanet experiments develop a general circulation that is largely consistent with the circulation of other aquaplanet experiments. This result is evident in time-averaged, zonally averaged (a, b) temperature (shading, every 5 K) and zonal wind (contours, every 2.5 m s⁻¹) and (c, d) relative humidity (shading, every 5%) and meridional circulations (streamlines). Left panels show the CFMIP-3 multi-model mean; right panels shown the 120-km MPAS-A experiment. Solid lines in panels (a, b) represent westerlies, dashed lines represent easterlies, and the thick solid line represents the zero contour.

Figure 2. Pressure-latitude analyses of time-averaged, zonally averaged (a, b) temperature (shading, every 5 K) and zonal wind (contours, every 2.5 m s⁻¹) and (c, d) relative humidity (shading, every 5%) and meridional circulations (streamlines). Left panels show the CFMIP-3 multi-model mean; right panels shown the 120-km MPAS-A experiment. Solid lines in panels (a, b) represent westerlies, dashed lines represent easterlies, and the thick solid line represents the zero contour.
strong meridional temperature gradient exists between 20° and 60°. Consistent with that gradient, westerly tropospheric jets appear equatorward of 40° in both hemispheres. A narrow Hadley circulation is evident with the ascending branch centered on the equator and the descending branch located just poleward of 25° latitude (Figures 2c and 2d). Moist air exists within the ascending branch, while the driest tropospheric air is co-located with the descending branch in the subtropics.

There are, however, several noteworthy differences between the time-averaged circulation from MPAS-A and the CFMIP-3 models. While tropospheric easterly winds appear within the tropics in both cases, MPAS-A exhibits stronger lower-tropospheric easterlies as indicated by the −10 m s⁻¹ contour extending to higher altitudes than in the CFMIP-3 multi-model mean (Figures 2a and 2b). The upper-tropospheric and lower-stratospheric zonal winds also differ in the tropics: MPAS-A depicts westerlies at nearly all levels above 200 hPa, whereas the CFMIP-3 multi-model mean is associated with easterlies above 100 hPa (Figures 2a and 2b). Likewise, the ascending branch of the Hadley circulation extends to 200 hPa in MPAS-A but beyond that altitude in the CFMIP-3 multi-model mean (Figures 2c and 2d). Other noteworthy differences include ~2 m s⁻¹ stronger midlatitude tropospheric jets, ~2 K cooler polar stratosphere, stronger stratospheric meridional temperature gradients, and ~17 m s⁻¹ stronger stratospheric winds in MPAS-A than in the CFMIP-3 multi-model mean.

Table 1

| Experiment                  | Period       | $u_{\text{max}}$ | $\phi_{\text{max}}$ | $\Psi_{\text{max}}$ | $\phi_{\text{rev}}$ | $\langle pr \rangle$ |
|-----------------------------|--------------|------------------|----------------------|---------------------|---------------------|---------------------|
| CFMIP-3 multi-model mean    | 3 years      | 47.2             | 31.0                 | 1.84                | 9.75                | 28.75               |
| NCAR CESM2                  | 3 years      | 43.6             | 30.5                 | 1.98                | 7.5                 | 27.5                |
| GFDL-CM4                    | 3 years      | 45.8             | 32.5                 | 2.11                | 8.5                 | 26.5                |
| CNRM-CM6                    | 3 years      | 51.1             | 30.5                 | 1.79                | 10.5                | 26.5                |
| IPSL-CM6A-LR                | 3 years      | 48.3             | 30.5                 | 1.49                | 12.5                | 34.5                |
| 120-km MPAS-A               | 3 years      | 49.9             | 30.5                 | 1.97                | 8.5                 | 26.5                |
| 120-km MPAS-A               | 2 years      | 50.5             | 30.5                 | 1.96                | 7.5                 | 26.5                |
| 30-km MPAS-A                | 2 years      | 49.7             | 31.5                 | 2.22                | 7.5                 | 26.5                |
| 15-km MPAS-A                | 2 years      | 50.8             | 31.5                 | 2.21                | 7.5                 | 26.5                |
| 120-km MPAS-A, Grell-Freitas| 3 years      | 50.1             | 31.5                 | 2.01                | 5.5                 | 26.5                |
| 120-km MPAS-A, Kain-Fritsch | 3 years      | 49.4             | 30.5                 | 2.30                | 6.5                 | 25                  |
| 120-km MPAS-A, convection-permitting suite | 3 years | 45.0             | 29.5                 | 1.72                | 6.5                 | 26.5                |
| 120-km MPAS-A, 33 levels    | 3 years      | 45.0             | 29.5                 | 2.18                | 6.5                 | 26.5                |

Note. Columns show (from left to right) experiment name, averaging period, maximum time-averaged, zonally averaged zonal wind ($u_{\text{max}}$; m s⁻¹), jet latitude ($\phi_{\text{max}}$; degrees), maximum streamfunction ($\Psi_{\text{max}}$; $10^{12}$ kg s⁻¹), latitude of maximum streamfunction ($\phi_{\text{rev}}$; degrees), latitude of streamfunction sign reversal ($\phi_{\text{rev}}$; degrees), and time-averaged, globally averaged precipitation rate ($\langle pr \rangle$; mm day⁻¹).

Properties of the simulated general circulation are summarized in Table 1 with statistics obtained from hemispherically averaged fields. The tropospheric jets are slightly stronger and equatorward in MPAS-A than in most CFMIP-3 models: MPAS-A develops zonal jets with maximum time-averaged zonally averaged zonal wind of 49.9 m s⁻¹ at 30.5° latitude, which is stronger than all but one CFMIP-3 model (CNRM). The strength and width of the Hadley circulation was quantified with a mass streamfunction, defined as

$$\Psi(\phi, p) = \frac{2\pi a \cos(\phi)}{g} \int_{p_0}^{p} |p| dp,$$

where $a$ is Earth’s radius, $\phi$ is latitude, $g$ is gravitational acceleration, and $|p|$ is the time-averaged, zonally averaged meridional wind. The maximum value of $\Psi$ gives a proxy for the Hadley cell strength, whereas the smallest latitude at which $\Psi$ reverses sign serves as a proxy for the Hadley cell width. As done by Medeiros et al. (2016), the streamfunction was first averaged between 300 and 700 hPa before obtaining its statistics. Based on these diagnostics, the Hadley circulation in MPAS-A is stronger and peaks closer to the equator than in most CFMIP-3 models (Table 1). On average, $\Psi$ reaches a maximum of $1.97 \times 10^{12}$ kg s⁻¹ at 8.5° latitude and switches sign at 26° latitude in MPAS-A.

MPAS-A experiments with different horizontal resolution show generally consistent results with only minor discrepancies, hinting at a possible convergence with the same dynamical core and model physics (Figure 3).
Two-year averages show roughly the same general circulation in all experiments: warm and ascending air in the tropics, dry and descending air in the subtropics, and westerly jets located with the strong meridional temperature gradient just equatorward of 40° (Figures 3a, 3c, and 3e). The tropospheric jets are approximately 1° further poleward in the 30-km and 15-km experiments than in the 120-km experiment; however, the strength of the tropospheric jets varies with resolution without a clear relationship between increasing resolution and maximum jet speed (Table 1). MPAS-A experiments also differ in their simulated tropical circulations: the 30-km and 15-km experiments depict ascent up to higher altitudes than the 120-km experiment (Figures 3b, 3d, and 3f). The simulated Hadley circulation strengthens with increasing resolution, but its peak and width happen at similar latitudes regardless of resolution (Table 1). Additionally, the 30-km and 15-km experiments also have stratospheric easterlies in the tropics, whereas the 120-km experiment has westerlies.

Past aquaplanet experiments with multiple models differ the most in the tropics (Blackburn et al., 2013). This result still holds true with the latest start-of-the-art global models, including MPAS-A. Figures 4a and 4b show the simulated precipitation pattern from MPAS-A and available CFMIP-3 models through an analysis of the time-averaged zonally averaged daily precipitation rate. MPAS-A develops a similar structure to CFMIP-3 models, regardless of horizontal resolution: the highest precipitation rates happen in the tropics, with secondary peaks in the middle latitudes associated with storm tracks. All experiments show double maxima in the tropics, indicative of a double intertropical convergence zone (ITCZ); however, results

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Pressure-latitude analyses of time-averaged, zonally averaged (a, c, e) temperature (shading, every 5 K) and zonal wind (contours, every 2.5 m s⁻¹) and (b, d, f) relative humidity (shading, every 5%) and meridional circulations (streamlines) from MPAS-A experiments with 120 km (top), 30 km (middle), and 15 km (bottom) cell spacing. Solid lines in panels (a, c, e) represent westerlies, dashed lines represent easterlies, and the thick solid line represents the zero contour.
from APE indicate that some models produce a single peak with the same underlying SST profile (Blackburn et al., 2013). The dry subtropics and cold polar latitudes are characterized by small zonally averaged precipitation rates below 2 mm day$^{-1}$.

Evidently, the largest discrepancies between MPAS-A and other models happen in the tropics. While all models develop a double peak near the equator, the magnitude of the maximum time-averaged, zonally averaged precipitation rate varies between 8 and 13 mm day$^{-1}$ between the models considered. MPAS-A lies near the upper end, with time-averaged zonally averaged precipitation rates of approximately 12 mm day$^{-1}$ at 3.5° latitude. There is considerably less variability among models outside the tropics as illustrated by daily precipitation variations below 2 mm day$^{-1}$ poleward of 10°. MPAS-A remains near the upper end of precipitation rates, with a secondary maximum of approximately 4 mm day$^{-1}$ at 41.5° latitude associated with middle latitude storm tracks. Given these results, MPAS-A also produces $\sim$2% larger globally averaged precipitation rates than CFMIP-3 models (Table 1).

MPAS-A experiments with different horizontal cell spacing continue to hint at a possible convergence using the same model (Figure 4b). All three experiments show similar time-averaged, zonally averaged precipitation rates, except in the tropics where the 30-km and 15-km experiments are similar to each other yet different from the 120-km experiment. Both the 30-km and 15-km experiments show maximum precipitation rates of 13 mm day$^{-1}$ at 3° latitude. In contrast, the 2-year average from the 120-km experiment yields a maximum zonally averaged precipitation rate of 11.6 mm day$^{-1}$ at 4° latitude. All experiments develop a double peak, indicative of a double ITCZ. This commonality may be driven by the underlying “QOBS” SST profile or by the use of the same cumulus parameterization in all MPAS-A experiments as over 90% of the zonally

Figure 4. Comparison of time-averaged, zonally averaged (a, b) daily precipitation rate, (c, d) cloud liquid water path, and (e, f) cloud ice path from (left) MPAS-A and CFMIP-3 models and (right) MPAS-A experiments with different horizontal cell spacing. Line colors represent different models or experiments as given by the legends on panels (a) and (b).
averaged tropical precipitation is parameterized. Outside the tropics, however, all experiments yield similar precipitation rates with differences of less than 0.1 mm day$^{-1}$ between MPAS-A experiments.

The representation of clouds also shows discrepancies between MPAS-A and other models at all latitudes—not only in the tropics. This result is illustrated in Figures 4c and 4e through time and zonal averages of column-integrated cloud liquid water and cloud ice. MPAS-A shows several maxima associated with the ITCZ and the middle latitude storm tracks. Overall, MPAS-A produces slightly more cloud water and cloud ice in the middle latitudes than in the tropics. All other models show the same general structure—one or two peaks in the tropics and another comparable or higher peak associated with middle latitude storm tracks. Yet, the amount of cloud water, both liquid and ice, can vary by as much as a factor of three between the least and most cloud-producing models. MPAS-A produces the least amount of cloud water and ice in the polar latitudes along with a latitudinal gradient that is present only in one of the available CFMIP-3 models (GFDL-CM4).

This variability in simulated cloud water is also evident in MPAS-A experiments with differing horizontal resolution: those experiments show three times as much cloud liquid water at 120-km cell spacing than at 15-km cell spacing in the tropics (Figure 4d). An important difference from the CFMIP-3 inter-model spread is the small cloud ice variability among MPAS-A experiments with different horizontal resolutions (Figure 4f). This result suggests that zonally averaged cloud ice is not sensitive to horizontal resolution in MPAS-A. Nonetheless, the large variability in cloud liquid water between models and between horizontal resolution in MPAS-A stresses one of the biggest challenges for general circulation models with parameterized convection: the representation of clouds.

In spite of these small differences between experiments, so far the results show encouraging similarities between the mean climate simulated by MPAS-A and other aquaplanet experiments. Next, we evaluate the properties of transient features by comparing transient eddy fluxes defined as $\overline{A'B'}$, where $A$ and $B$ are the variables of interest, the bracket and overline denote zonal and temporal averages, respectively, and the prime and star symbols denote deviations from those averages. We focus only on transient eddies because stationary eddies are small in the aquaplanet framework with zonally symmetric, fixed SST. Daily data, interpolated to a 1° × 1° grid, were used to calculate transient eddy fluxes at each latitude. Figure 5 summarizes the results by showing select fluxes in the upper and lower troposphere for MPAS-A and three CFMIP-3 models with available daily data. Results from MPAS-A experiments with different horizontal resolutions are very similar; therefore, only the results from the 120-km experiment are discussed here.

Overall, the 120-km MPAS-A experiment simulates structurally similar yet stronger midlatitude eddies than CFMIP-3 models with available data. The eddy kinetic energy $\left(\overline{u'^2} + \overline{v'^2}\right)$ peaks just equatorward of 40° at 250 hPa and around 40° at 700 hPa in MPAS-A (Figures 5a and 5b). The maximum eddy kinetic energy is stronger in MPAS-A than in all other models, which could result from the higher vertical resolution or weaker horizontal diffusion of MPAS-A. The meridional eddy momentum $\overline{u'v'}$ and heat fluxes $\overline{v'q'}$ show the expected pattern with poleward fluxes peaking between 20° and 60° latitude (Figures 5c–5f)—indicative of the poleward redistribution of heat and momentum taking place in the aquaplanet with meridionally varying SST and solar insolation. Likewise, the meridional eddy water vapor flux $\overline{v'q'}$ shows the overall redistribution of moisture from the tropics to higher latitudes, especially in the lower troposphere (Figures 5g and 5h). Intriguingly, the eddy meridional water vapor flux opposes the equatorward flux of water vapor by the mean circulation (Figures 2c and 2d). MPAS-A is associated with stronger eddy meridional fluxes than all other models. This overall pattern of eddy fluxes was unchanged in the 30-km and 15-km MPAS-A experiments, but their magnitudes increased by ~2–10%, respectively, with increasing resolution (not shown).

### 3.2. Rainfall Variability

Extreme precipitation—resulting from both high-intensity and long-duration events—is highly disruptive to society yet difficult to predict at both weather and climate timescales. As such, aquaplanet experiments are useful for testing the representation of extreme precipitation events in global models. High-intensity precipitation events were assessed through distributions of daily precipitation rates, as shown in Figures 6a–6f.
These figures show the fraction of daily precipitation rates grouped into 1 mm day$^{-1}$ bins. A distribution from IMERG daily precipitation rates is also shown for reference and comparison against observations. Overall, the distribution of precipitation rates from MPAS-A is shifted toward lower values than the distributions from both IMERG and CFMIP-3 models. MPAS-A is associated with a substantially higher occurrence of precipitation rates below 50 mm day$^{-1}$ than IMERG. This result is also evident in all of the available CFMIP-3 models. MPAS-A also lies in the lower end of extreme precipitation rates in comparison to the available CFMIP-3 models. In particular, MPAS-A yields the lowest fraction of precipitation rates exceeding 40 mm day$^{-1}$, including lower occurrence of those rates than in IMERG. There is considerable variability among all other CFMIP-3 models, with some models producing precipitation rates of 300 mm day$^{-1}$ or larger. Precipitation rates above 100 mm day$^{-1}$ represent the top 0.05%; therefore, a precipitation “extreme” in an aquaplanet framework largely depends on the modeling system used.

Two important factors should be considered when interpreting the distribution of precipitation rates: (1) model variability due to parameterized versus resolved precipitation and (2) sensitivity to horizontal resolution. When the precipitation rates are partitioned into parameterized and grid-scale (or resolved) precipitation rates, it is evident that both the small fraction of extreme precipitation rates in MPAS-A and the large variability between models result from the resolved precipitation (Figures 6b and 6c). MPAS-A, with 120-km cell spacing and the Tiedtke cumulus scheme, yields a distribution of parameterized precipitation rates that lies within the distributions from available CFMIP-3 models (Figure 6b). The higher occurrence of light precipitation in MPAS-A stems from parameterized convection. In contrast, the small fraction of extreme precipitation rates above 40 mm day$^{-1}$ in MPAS-A and the large variations between models result from the resolved precipitation (Figure 6c). This result points at differences stemming from the various dynamical cores and microphysical parameterizations used by the models, or at differences caused by the influence of the cumulus schemes on background thermodynamic conditions for convection.
The comparison of MPAS-A experiments with different horizontal resolution, but all interpolated to the same $1^\circ \times 1^\circ$ grid, illustrates that the most extreme precipitation rates are highly dependent on horizontal cell spacing (Figure 6d). The MPAS-A experiment with 15-km cell spacing yields extreme precipitation rates beyond 200 mm day$^{-1}$; although rare, those extreme values are still smaller than the most extreme precipitation rates from IMERG. While there are some slight variations in the distribution of parameterized

Figure 6. Normalized distributions of (a–f) rainfall intensity from (a–c) MPAS-A and CFMIP-3 models and (d–f) MPAS-A experiments with varying horizontal resolution. (g–l) Normalized distribution of rainfall duration from (g–i) MPAS-A and CFMIP-3 models and (j–l) MPAS-A experiments with varying horizontal cell spacings. Left panels show distributions from the total rainfall, middle panels show distributions from only the convective (or parameterized) rainfall, and right panels show the distributions from the resolved (or grid-scale) rainfall. Line colors represent different models or experiments as given by the legends on the left panels. Note that the range on the abscissa varies between panels.
precipitation rates, the largest differences between MPAS-A experiments also result from differences in the resolved precipitation (Figures 6e and 6f). These differences appear despite comparing fields interpolated to the same grid—an indication that the Tiedtke cumulus parameterization cannot compensate for small-scale features that are explicitly resolved in the higher resolution simulations. We will explore the reason for these differences in a forthcoming publication.

Long-duration precipitation events also contribute to extreme precipitation totals; yet, their distributions are rarely assessed in aquaplanet experiments. Here, we compared the distribution of rainfall duration between MPAS-A and CFMIP-3 models through distributions of duration for events with precipitation rates exceeding 5 mm day$^{-1}$. This value is considered a threshold for “intermediate” precipitation rates (Trenberth & Zhang, 2018) and lies close to the 90th percentile of most experiments considered here. We obtained qualitatively similar results when we repeated the analysis with other thresholds (not shown). Using a fixed threshold is not ideal because a model could produce that amount in a single time step rather than during a continuous period, but the objective definition allows a robust comparison of rainfall duration between different data sets. For comparison against the real atmosphere, a distribution of rainfall duration was obtained from IMERG for the same geographical region as the distribution of precipitation rates, but with consideration of all months between March 2011 and March 2014. This 3-year period was chosen as a period with neutral or weak El Niño conditions.

The distributions of rainfall duration expose potential issues with the representation of long-duration precipitation extremes in the aquaplanet framework (Figures 6g–6l). Approximately 90% of events meeting the 5 mm day$^{-1}$ threshold in MPAS-A last for 10 days or less (Figure 6g). There are, however, a substantial number of events that last for tens of days. Compared against IMERG, that fraction of events is considerably large. This result suggests that the cumulus scheme is active too often, which is also true for most CFMIP-3 models. Distributions separated by parameterized (Figure 6h) and resolved (Figure 6i) rainfall support this suggestion because rainfall duration from resolved events last much shorter than those resulting from parameterized convection. Furthermore, this result is independent of horizontal resolution because the distributions from MPAS-A experiments are similar to each other and all show a larger fraction of events, resulting from parameterized convection, lasting longer in comparison to IMERG (Figures 6j–6l). It is possible that IMERG does not measure intermediate precipitation too often or that the aquaplanet framework yields longer lasting stationary systems than in the real world.

3.3. Convectively Coupled Equatorial Waves

Tropical rainfall variability, in terms of both intensity and duration, is largely driven by convectively coupled equatorial waves. Kelvin waves, for example, can contribute up to 10% of the climatological rainfall in the Central Pacific (Lubis & Jacobi, 2015) and between 10% and 30% of the climatological rainfall in tropical Africa (Schlueter et al., 2019). Aquaplanet experiments are suitable to study such phenomena because the simplified framework without land or seasons can be conducive to frequent and spontaneous occurrence of convectively coupled equatorial waves (e.g., Lorant & Royer, 2001; Maloney et al., 2010; Nasuno et al., 2008; Peatman et al., 2018). However, the Aqua-Planet Experiment demonstrated that not all models are capable of producing convectively coupled equatorial waves (as discussed in section 1).

To investigate if MPAS-A aquaplanet experiments capture convectively coupled equatorial waves, Figures 7 and 8 show normalized time-frequency spectral analyses of daily precipitation rates between 10°S and 10°N of each model using the method of Wheeler and Kiladis (1999). Figure 7 shows the analysis for symmetric disturbances about the equator, whereas Figure 8 shows anti-symmetric disturbances. Both spectral analyses were normalized by a smoothed background spectrum of daily precipitation rates from each model. In addition to CFMIP-3 models, Figures 7 and 8 also include results from three CFMIP-2 models. All panels use the same color shading to facilitate comparison.

The time-frequency spectral analysis demonstrates that MPAS-A, with 120-km cell spacing, captures convectively coupled equatorial waves. In particular, MPAS-A is associated with a spectral peak that closely matches the theoretical dispersion relationship of Kelvin waves (Figure 7a). A Hovmöller diagram of a sample 60-day period confirms the presence of eastward propagating features—Kelvin waves—driving most of the rainfall variability in the tropics (Figure 9a). Likewise, MPAS-A also shows a spectral peak characteristic of eastward propagating inertio-gravity waves (Figure 8a). As in other aquaplanet experiments, MPAS-A also
captures "westward advective disturbances" (Nakajima et al., 2013) or anti-symmetric disturbances that propagate westward with the background tropical easterlies without projecting onto any of the theoretical dispersion relationships for equatorial waves (Figure 8a). However, MPAS-A does not capture symmetric inertio-gravity waves or equatorial Rossby waves. There is no evidence of a Madden-Julian oscillation, which could be a result of the zonally symmetric SST profile (Maloney et al., 2010), among other factors. Results from the 30-km and 15-km MPAS-A experiments are very similar to those in Figures 7a and 8a (not shown).
Compared against CFMIP-3 models, MPAS-A aquaplanet experiments have overall more convectively coupled equatorial wave activity (Figures 7b–7e and 8b–8e). The normalized spectral peaks of CFMIP-3 models are much weaker than the peaks of MPAS-A. There is little evidence of Kelvin waves or eastward-propagating inertio-gravity waves in the CFMIP-3 models, except for the GFDL-CM4 model that shows a weak spectral peak associated with low-frequency Kelvin waves (Figure 7c). We repeated this spectral analysis with upper-tropospheric winds, but the results were very similar to those obtained from daily precipitation rate (not shown). The only commonality between most models, including MPAS-A, is the spectral peak representative of westward advective disturbances (Figure 8). The spread of solutions between available CFMIP-3 models is comparable to the spread shown by participating models of the Aqua-Planet

Figure 8. As in Figure 7, except for the anti-symmetric component of rainfall rate averaged between 10°S and 10°N. Magenta lines depict the theoretical dispersion relationships for mixed Rossby-gravity (MRG) waves and eastward inertia-gravity (EIG) waves.
Experiment (Blackburn et al., 2013; Nakajima et al., 2013) and of the second phase of CFMIP (not shown), with the important difference that some of those models captured Kelvin waves.

A Hovmöller diagram of a sample 60‐day period from each model further demonstrates the diversity of tropical rainfall solutions between models (Figure 9). MPAS‐A is associated with predominantly eastward‐propagating disturbances associated with Kelvin waves (Figure 9a). Other models show diverse

Figure 9. Hovmöller diagrams of daily precipitation rate (shading, every 2.5 mm day\(^{-1}\)) averaged between 10°S and 10°N during a sample 60‐day period from (a) MPAS‐A, (b) CESM2, (c) GFDL‐CM4, (d) CNRM‐CM6, (e) IPSL‐CM6A‐LR, (f) MIROC5, (g) MRI, and (h) MPI‐ESM‐LR.

 Experiment (Blackburn et al., 2013; Nakajima et al., 2013) and of the second phase of CFMIP (not shown), with the important difference that some of those models captured Kelvin waves.
solutions, with some models showing localized features (Figures 9b and 9d) and other models showing westward propagating disturbances (Figures 9c and 9e). These results highlight the continuous challenge of capturing equatorial waves in climate models while also suggesting that aquaplanet experiments with MPAS-A are suitable for studying tropical rainfall variability due to, for example, Kelvin waves.

None of the CFMIP-3 models with available data used the same cumulus scheme as in MPAS-A; however, two models from the previous phase of CFMIP (CFMIP-2) used the Tiedtke scheme. These models are included in panels g and h of Figures 7 and 8, along with MIROC5 in panel f. This latter model captures a similar signal associated with equatorial waves as in MPAS-A (Figures 7a and 7f). The other two CFMIP-2 models, despite using a similar cumulus scheme as MPAS-A, show a much weaker signal than MPAS-A or MIROC-5 (Figures 7f–7h). Hovmöller diagrams from these models further show that only MIROC5 produces eastward-propagating features akin to those in MPAS-A (Figures 9f–9h). This comparison suggests that the diversity of tropical rainfall variability among models is not solely attributable to the cumulus scheme.

4. Sensitivity Experiments With Different Model Configurations

The previous section demonstrated that MPAS-A captures tropical rainfall variability driven by Kelvin waves. Numerous studies have suggested that details of cumulus parameterizations may be the culprit of model uncertainty of tropical rainfall variability (cf. section 1). This hypothesis, however, has not been well-tested because other discrepancies between models (e.g., dynamical core and microphysics parameterizations) could also contribute to different tropical rainfall solutions among models. MPAS-A presently has three different options of cumulus parameterizations, thus allowing to conduct aquaplanet experiments with changes only to the cumulus scheme. To this end, we produced two additional 120-km MPAS-A sensitivity experiments with the Grell-Freitas (Grell & Freitas, 2014) and the Kain-Fritsch (Kain, 2004) schemes. Even though all three parameterizations considered are mass-flux type schemes, their different formulations allow to investigate if details of the schemes influence tropical rainfall variability in the aquaplanet framework. All other details were left the same as in the 120-km MPAS-A experiment ("control" hereafter).

MPAS-A experiments with different cumulus parameterizations show mixed results. The overall general circulation, including the tropospheric jets and overturning circulations, shares similarities with the control (Table 1), thus giving further confidence on the aquaplanet configuration of MPAS-A. Tropical rainfall variability, however, is not fully affected by the choice of cumulus scheme. This result is shown in Figures 10a–10c; only the symmetric analysis is shown in the interest of focusing on equatorial Kelvin waves. All experiments show a spectral peak that falls close to or within the theoretical dispersion relationship of Kelvin waves. The control is associated with the strongest spectral peak, corresponding to the largest variance of rainfall, driven by Kelvin waves. The experiment with Grell-Freitas shows the weakest signal, and that signal is displaced toward slow-moving waves. This experiment and the Kain-Fritsch experiment both lack high-frequency Kelvin waves (frequencies larger than 0.5 day$^{-1}$). Nakajima et al. (2013) hypothesized that tropical rainfall variability in aquaplanet experiments is modulated by heating profiles produced by different cumulus schemes. A comparison of diabatic heating profiles showed vastly different profiles between experiments (not shown), yet all experiments triggered Kelvin waves. These results suggest that the representation of convection by a deep cumulus scheme influences the speed and spatial scale of the waves but not the ability of a model to trigger those waves.

The presence of low-frequency Kelvin waves in all experiments also suggest that other model specifications—other than the cumulus scheme—are responsible for triggering and maintaining those waves. To test this hypothesis, another sensitivity experiment was produced with MPAS-A except with a different combination of physics packages. The control experiment used the “mesoscale reference” suite in MPAS-A (section 2); this sensitivity experiment used the “convection permitting” suite—a group of physics packages including the Grell-Freitas cumulus parameterization, MYNN planetary boundary layer and surface layer schemes (Nakanishi & Niino, 2006), Thompson non-aerosol-aware microphysics (Thompson et al., 2008), and RRTMG (Iacono et al., 2008) for both shortwave and longwave radiation. While this experiment differs in multiple ways from the aforementioned MPAS-A experiments, those differences should help determine if the combination of physics packages makes a large difference in tropical rainfall variability simulated in aquaplanet experiments. The general circulation is consistent with other MPAS-A experiments, except this experiment produces the weakest Hadley cell and the smallest globally averaged precipitation rate (Table 1).
The spectral analysis of tropical rainfall rate is similar to the previous experiment using the Grell-Freitas scheme. This result is evident by comparing Figures 10b and 10d. Both figures show similar wavenumber-frequency spectral analyses: Kelvin waves are still present in the model and substantially contribute to tropical rainfall variability, but the waves are slower than in the control. This result suggests that—at 120-km grid spacing—the combination of physics packages has little influence on whether or not the model captures equatorial waves. However, the choice of cumulus scheme influences the phase speed and spatial scale of simulated waves, as suggested by the close similarities between Figures 10b and 10d.

All experiments so far used the same vertical discretization, consisting of 75 levels with a model top at 40 km. Previous studies suggest that tropical rainfall variability in global models depends on their vertical resolution. For example, Inness et al. (2001) obtained a better representation of tropical variability in a general circulation model by doubling the number of vertical levels. Their results suggest that higher vertical resolution captures cumulus congestus and their associated midtropospheric moistening, which results in more accurate transitions between convectively active and suppressed periods. Furthermore, Skamarock et al. (2019) demonstrated that vertical resolution affects model convergence of real-data simulations. The aquaplanet experiments from the CFMIP-3 models used different vertical grids—from 32 levels in CESM2 to 79 levels in IPSL-CM6A-LR with a model top above the stratosphere in both cases. Such differences could provide another possible explanation for the lack of convergence and stark differences in tropical rainfall variability between MPAS-A and the CFMIP-3 models.

To test this possible explanation, we produced an additional MPAS-A experiment with 33 vertical levels and a model top at 40 km. This vertical grid effectively doubled the grid spacing between vertical levels while...
retaining all other details as in the control experiment. While there are some minor differences between the control and this experiment (Table 1), the spectral analysis still shows the presence of equatorial Kelvin waves with comparable spatial and temporal scales as in the experiment with 75 vertical levels (Figure 10e). The main difference is a weaker spectral peak in the experiment with 33 vertical levels. These results suggest that the different vertical grids of the CFMIP-3 models alone cannot explain their lack of equatorial Kelvin waves but also confirm that vertical resolution affects the nature of the simulated tropical rainfall variability.

Altogether, the sensitivity experiments and comparison against CFMIP-3 models suggests that other factors—such as the dynamical core or the physics-dynamics coupling in MPAS-A—play key roles in capturing tropical rainfall variability. Additional experiments varying the radiation scheme or turning off the cumulus scheme still showed the presence of Kelvin waves in MPAS-A (not shown). To take a closer look at the relationship between dynamics and physics in these models, we compared the relative location of lower-tropospheric convergence (at the 850-hPa level) and rainfall associated with Kelvin wave-like disturbances in MPAS-A experiments and CFMIP-3 models. Kelvin wave-like features were identified by filtering tropical rainfall for wavenumbers 1–14, time periods of 2.5–20 days, and equivalent depth between 8 and 90 m. The maximum filtered anomaly was used as the location, in space and time, of the waves in each experiment. Figure 11 shows a comparison of composite 850-hPa zonal winds and precipitation rate anomalies associated with Kelvin wave-like disturbances. The composites are shown with respect to the wave crest location in space and time. MPAS-A experiments, regardless of cumulus scheme, capture the expected structure of these disturbances (e.g., Straub & Kiladis, 2003): Lower-tropospheric easterlies appear ahead of westerlies, and the peak rainfall appears after the peak lower-tropospheric convergence (Figures 11a–11c). This result also appears with the MIROC5 model, which produces a similar pattern and amplitude as in MPAS-A (Figure 11g). CFMIP-3 models, however, show different patterns of rainfall and zonal winds (except CNRM-CM6) without a clear relationship between peak rainfall and peak lower-tropospheric convergence (Figures 11d–11f). These results are consistent with a recent study that also suggests that the relationship between lower-tropospheric convergence and rainfall is important for accurately simulating tropical rainfall variability (Dias et al., 2018).

Additionally, these results suggest that MPAS-A experiments have a clear phasing between winds and precipitation that is necessary to simulate Kelvin waves. We hypothesize that different numerical methods used to “couple” tendencies from convective parameterizations and dynamical cores (Lauritzen & Williamson, 2019; Williamson, 2002) could ultimately explain the different wind-rainfall phasing shown in Figure 11. For example, Thatcher and Jablonowski (2016) showed that gradual versus abrupt application of tendencies from moist physics can affect wave activity in aquaplanet simulations. In a future study, we plan to test different “physics-dynamics coupling” methods in MPAS-A to see if they are indeed responsible for different representation of Kelvin waves.

5. Summary and Future Opportunities

The main objective of this study was to document the aquaplanet configuration in the Model for Prediction Across Scales-Atmosphere (MPAS-A). MPAS-A is a community model that was specifically designed to study weather and climate. Aquaplanet experiments are typically performed with general circulation models used for climate projections; yet, this study demonstrated that aquaplanet experiments with MPAS-A produce consistent mean circulations compared to several general circulation models. In particular, a 3-year-long MPAS-A experiment with 120-km cell spacing compared satisfactorily with experiments from CFMIP-3. Similar results were obtained across a number of multi-year MPAS-A experiments designed to mimic the horizontal grid spacing of high-resolution climate models and global numerical weather prediction models. These results are encouraging for the use of MPAS-A to study phenomena within and across the weather-to-climate continuum.

In spite of the encouraging results, several discrepancies between MPAS-A and other aquaplanet experiments exposed the continuing challenges of simulating clouds and precipitation in global models. The amount of cloud water varied by as much as a factor of three among CFMIP-3 models and MPAS. Additional discrepancies were particularly noticeable in the tropics, where the magnitude of the maximum time-averaged, zonally averaged precipitation rate varied between 8 and 13 mm day$^{-1}$ between the models.
considered. All models produced double ITCZs, but this result may not hold true as more CFMIP-3 models become available. Results from the Aqua-Planet Experiment, which considered 16 models, showed that several models produced single ITCZ while others produced double ITCZs with the same underlying SST (Blackburn et al., 2013). Rainfall extremes, both of high intensity and long duration, also differed substantially between MPAS-A and CFMIP-3 models. MPAS-A showed a smaller fraction of extreme precipitation rates than CFMIP-3 models and observations. These discrepancies—resulting primarily from resolved rather than parameterized precipitation—imply continuing challenges in the representation of precipitation extremes in current and future climate simulations.

Aquaplanet experiments with MPAS-A showed a stronger signal of tropical rainfall variability driven by convectively coupled equatorial waves compared to available CFMIP-3 models. Wavenumber-frequency spectral analyses of daily precipitation rates showed that MPAS-A captures Kelvin waves and eastward inertio-gravity waves in the aquaplanet framework. Tropical rainfall variability in MPAS-A experiments was mostly driven by those phenomena, especially Kelvin waves. In contrast, none of the CFMIP-3 models showed spectral peaks within the expected dispersion relationships. Sensitivity experiments with MPAS-A investigated whether the presence and characteristics of equatorial waves was affected by the cumulus

Figure 11. Composite rainfall (contours, every 1 mm day$^{-1}$ starting at 1 mm day$^{-1}$) and lower-tropospheric wind anomalies (shading, every 0.3 m s$^{-1}$) with respect to zonally averaged, time-averaged fields. Panels show (a–c) MPAS-A experiments using (a) Tiedtke, (b) Grell-Freitas, and (c) Kain-Fritsch, (d–f) CFMIP-3 models, and (g–i) CFMIP-2 models.
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Data Availability Statement
MPAS-A source code, with modifications documented here for the aquaplanet experiments, can be accessed online (https://github.com/rosimarwx/MPAS-A_aquaplanet). Post-processed model output from the MPAS-A experiments can be accessed online (https://doi.org/10.5065/cam1-v353). CFMIP-3 model output was obtained online (https://esgf-data.dkrz.de/search/cmp6-dkrz/), and CFMIP-2 model output was retrieved online (https://esgf-data.dkrz.de/search/cmp5-dkrz/). IMERG data were provided by NASA via online (https://disc.gsfc.nasa.gov/).

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parameterization or vertical grid spacing. Although we only performed a limited number of experiments, our results showed that Kelvin waves were consistently present in all experiments. A key factor distinguishing MPAS-A experiments from CFMIP-3 experiments was the phasing between the lower-tropospheric winds and rainfall associated with Kelvin wave-like disturbances; while MPAS-A captured the expected pattern of peak rainfall following after peak lower-tropospheric convergence, CFMIP-3 models did not show such pattern. The main difference between MPAS-A sensitivity experiments was that changing the cumulative parameterization from Tiedtke to Grell-Freitas removed high-frequency Kelvin waves and yield slower-moving low-frequency Kelvin waves. We hypothesize that those differences are associated with different vertical mass flux profiles resulting from each scheme, which yield ascent over a broader region and larger-scale disturbances when using the Grell-Freitas scheme (not shown). These results suggest that the presence of convectively coupled equatorial waves in a model depends on the choice of numerical methods of atmospheric model—not only the cumulative parameterization—but specific characteristics of the waves indeed depend on details of the parameterized convection. We are continuing to explore this issue with further experiments using MPAS-A.

Overall, this study demonstrated that aquaplanet experiments with MPAS-A are well-suited for research studies of phenomena spanning the weather-to-climate continuum. Future studies should consider using similar experiments with MPAS-A to address fundamental questions about multi-scale weather phenomena. For example, MPAS-A has been already used with quasi-uniform storm-resolving resolution for select real-data case studies (Judt, 2018; 2020; Skamarock et al., 2014; Stevens et al., 2019; Weber & Mass, 2019). We are using this capability, except with a variable mesh, to produce aquaplanet experiments using storm-resolving resolution in the tropics. Such experiments can shed light on fundamental aspects of tropical phenomena, including interactions between convective systems and planetary-scale waves, and how those interactions affect rainfall variability on subseasonal timescales. Likewise, MPAS-A aquaplanet experiments with and without parameterized convection could also facilitate the improvement of physics packages by comparing, for example, the nature and distribution of precipitation systems produced in simulations with and without cumulus parameterizations. These are just examples of the many possible applications of aquaplanet experiments using MPAS-A.
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