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The Role of Isotope-Enabled GCM Complexity in Simulating Tropical Circulation Changes in High-CO_2 Scenarios

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Key Points:
- An intermediate-complexity climate model, SPEEDY-IER, can simulate first-order tropical circulation changes in high-CO_2 scenarios
- The evaluation of water isotopes in SPEEDY-IER reveals hidden biases in its simplified convection scheme
- Introducing condensation and detrainment to intermediate convection levels improves simulations of water isotopes in SPEEDY-IER

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
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- Figure S5
- Figure S6
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Abstract Stable water isotopes are data-rich tracers of the hydrological cycle, and, recently, the advent of isotope-enabled climate models has allowed for investigations into the utility of water isotopes for tracking changes in the large-scale atmospheric circulation. Among the suite of published isotope-enabled climate models, those with intermediate complexity offer the benefits of efficiency, allowing for long ensemble runs. However, the ability of these models to simulate the response to global warming with the same fidelity as state-of-the-art models is questionable. Here we evaluate an intermediate complexity model, SPEEDY-IER, in a high-CO_2 scenario and compare its performance to an Intergovernmental Panel on Climate Change (IPCC)-class model, iCAM5. SPEEDY-IER can generally simulate changes in tropical circulation, the weakening of the Walker circulation, and the narrowing of the deep tropics. A deeper investigation of water isotope fields indicates SPEEDY-IER simulates qualitative trends in precipitation and vapor isotopes with fidelity, but it does not simulate amplitudes or spatial patterns of water isotope changes shown in iCAM5. This bias in SPEEDY-IER is mainly due to its coarse resolution and simplified convection scheme. We then modify the model by introducing condensation and detrainment in intermediate convection levels; this modification successfully improves SPEEDY-IER's simulation of water isotope fields, though the response of the Walker circulation to climate change is weakened. We demonstrate that evaluating water isotope fields reveals hidden biases in a climate model and guides improvements to the model's performance. Thus, the examination of water isotope fields and validation against available observations likely provides more stringent constraints for model physics.

Plain Language Summary Climate models are utilized to project climate change as we enter a world with ever-higher CO_2 concentrations, but running these models usually takes a huge amount of time and computational resources. Intermediate-complexity models circumvent this issue by simplifying model physics and thus save time for long simulations. Moreover, the addition of stable water isotopes in these climate models provides unique constrains in the global water cycle. However, to use intermediate-complexity models with water isotopes to study the climate of a high-CO_2 world, we need to verify their simulations, and evaluations of these models are sorely lacking. This study evaluates one of these models, SPEEDY-IER, in a high-CO_2 world. We find that SPEEDY-IER can simulate fundamental tropical circulation changes, and it is suitable for studies of future climate change.
In addition, the evaluation of water isotopes in SPEEDY-IER reveals hidden biases of the model, and the subsequent modifications based on this evaluation improve SPEEDY-IER. This provides an example of how diagnosing water isotope fields can improve the performance of climate models.

1. Introduction

Stable water isotopes constitute a powerful framework for tracing climate variability over time and space and are acutely sensitive to changes in the hydrological cycle. Because water isotopes preserve the history of phase changes of water, they provide unique information of many physical processes such as detrainment, reevaporation of raindrops, and subsidence in convection (Galewsky et al., 2016). Thus, they are useful for constraining climate change and feedbacks in both the past and present. In the time domain, water isotope ratios are preserved in paleohydroclimate records such as ice core δD and $\delta^{18}O$ (e.g., Barnola et al., 1987; Landais et al., 2015; Legrand & Mayewski, 1997, and others), coral $\delta^{18}O$ (e.g., Corrège, 2006; Gagan et al., 2000; Lough, 2010, and others), and speleothem calcite $\delta^{18}O$ (e.g., Fairchild et al., 2006; Lachniet, 2009; McDermott, 2004, and others), facilitating reconstructions of climate variability over longer time scales. In the present, water isotopes help us better understand convective activity (e.g., Bony et al., 2008; Field et al., 2014; Kurita, 2013; Risi et al., 2012, and others) and circulation changes (e.g., Bailey et al., 2017; Dee et al., 2018, and others). Over the past few decades, isotope-enabled models have been developed to expand the use of water isotopes in climate variability studies (Dee et al., 2015; Hoffmann et al., 1998; Joussaume et al., 1984; Jouzel et al., 1987; Lee et al., 2007; Nusbaumer et al., 2017; Risi et al., 2010; Roche & Caley, 2013; Schmidt et al., 2005; Werner et al., 2011; Yoshimura et al., 2008). These models have, most recently, provided unique constraints on convection and cloud schemes in general circulation models (GCMs) (Bony et al., 2008; Field et al., 2014; Lee et al., 2009; Nusbaumer et al., 2017; Risi et al., 2012; Tharammal et al., 2017). Since water isotopes are sensitive to the condensation and evaporation history of water, evaluating water isotopes in GCMs can often reveal hidden model biases, absent or opaque in typical diagnostic fields such as temperature and precipitation. For example, Risi et al. (2012) revealed that the vertical diffusion in the model LMDZ4 is too high using water isotope fields as diagnostics.

Among the available suite of isotope-enabled models, those with intermediate complexity (IC hereafter) physics offer the benefits of efficiency, saving computational resources and allowing for long ensemble runs (Dee et al., 2015; Petoukhov et al., 2000; Roche & Caley, 2013; Severijns & Hazeleger, 2010). These models are particularly suitable for running ensembles of perturbed initial conditions or physical parameters to investigate the internal variability of the climate system (Molteni, 2003). Furthermore, IC models are capable of simulating long time periods much faster than state-of-art models (Jungclaus et al., 2010; Liu et al., 2009; Sepulchre et al., 2019), making them particularly suitable for examining climate variability over millennial and longer time scales. For example, IC models can simulate transient climate changes comparable in length to proxy data, making them invaluable in paleoclimate research (Caley et al., 2014). However, the ability of these simpler models to simulate the dynamical response to global warming and associated impacts on water isotopes fields with the same fidelity as state-of-the-art models is questionable. What level of model complexity is needed to project changes in the large-scale atmospheric circulation and the hydrological cycle under climate change?

Multiple studies have documented the sensitivity of climate models (including isotope-enabled models) to horizontal and vertical resolutions, generally focusing on relatively high resolutions (e.g., <250 km horizontally and >15 levels vertically) (Nusbaumer et al., 2017; Roeckner et al., 2006; Wehner et al., 2014; Werner et al., 2011). These results show that models with relatively low resolutions (e.g., T31L19 in ECHAM5 and 1.9°N × 2.5°E with 31 levels in iCAM5) can robustly simulate large-scale features of circulation and stable water isotopes, while models with finer resolutions are better suited for regional-scale studies because they resolve topography and mesoscale circulation features. However, considerably less attention has been cast toward the influence of model complexity on performance in simulating changing climate with various forcings (e.g., high-CO_2 or glacial maximum scenarios). In addition, previously published evaluations of Earth system models of IC mainly focus on the global average responses to climate forcing (Eby et al., 2013; Roche & Caley, 2013; Zickfeld et al., 2013) due to the coarse atmospheric resolution of these models. To date, the performance of IC-GCMs in simulating the large-scale features of the tropical overturning circulations has not been extensively benchmarked.

Given the necessity of evaluating the performance of GCMs under different mean climate forcing, we here use a high-CO_2 forcing scenario. Periods of elevated CO_2 occurred in the past, and atmospheric greenhouse gas concentrations are increasing rapidly in the Anthropocene. Apart from evaluating precipitation and circulation changes, we also examine stable water isotopes for the future climate simulation. Water isotope fields provide additional constraints for circulation changes and are sensitive to changes in vertical motion that are difficult to measure in situ or via remote sensing data. For example, Dee et al. (2018) reveal how the observations of water vapor isotopes from satellite retrievals can be used to trace the large-scale vertical motion induced by the Walker circulation, and Torri et al. (2017) suggest that precipitation isotopes can be used to represent vertical profiles of atmospheric vertical motion.

To characterize the potential for IC isotope-enabled models to correctly simulate future changes of circulation and stable water isotopes, this study explores the difference between an isotope-enabled model with IC, SPEEDY-IER (Dee et al., 2015), and a state-of-the-art, Intergovernmental Panel on Climate Change (IPCC)-class isotope-enabled model, iCAM5 (Nusbaumer et al., 2017), with specific attention to their simulations of climate and water isotopes changes with high CO_2 forcing. We note that there are no observations for future climate, so we use the simulation of the IPCC-class model iCAM5 to represent the "truth" because the physical schemes of this complex model are more realistic. We apply a high-CO_2 scenario designed to mimic the Representative Concentration Pathway (RCP) 8.5 scenario described in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). This experiment informs both future projections and interpretations of paleoclimate data from warm periods in Earth's geologic past and provides a test bed for isotope-enabled GCMs of varying complexities. We explicitly answer the question: How much complexity is needed to simulate a high-CO_2 climate in the geologic past and future? iCAM5 is chosen based on its demonstrated response to high-CO_2 forcing (Lau & Kim, 2015). Although it is not possible to obtain explicit atmospheric measurements from high-CO_2 climates, the consistency of the responses in state-of-the-art models such as iCAM5 provides a useful benchmark to evaluate the performance of an IC model.

This study focuses on tropical circulation. The tropics are the engine of the global hydrological cycle, and there is still considerable debate surrounding changes in tropical overturning circulations—namely, the Walker and Hadley circulations—in modern observations and climate simulations of the future (Chemke & Polvani, 2019; Hu et al., 2018; L'Heureux et al., 2013; Mitas & Clement, 2006; Nguyen et al., 2013; Sandeep et al., 2014). Most models predict weakening trends of the intensity of the Walker circulation and the Hadley cell in a warmer world, but reanalysis data show increasing trends over the past several decades (Chemke & Polvani, 2019; Held & Soden, 2006; Hu et al., 2018; Sandeep et al., 2014; Soden & Held, 2006; Vecchi et al., 2006). In this study, we explore whether SPEEDY-IER simulates similar changes in large-scale circulation and stable water isotopes when compared to iCAM5, and explore the limitations of IC models in simulating a warm climate.

Finally, after evaluating the biases of SPEEDY-IER, we diagnose the physical deficiencies driving the bias and modify the model. We illustrate that evaluating model circulation, and especially water isotopes, provides unique constraints that improve the model physics.

2. Climate Model Description and Experimental Design

SPEEDY-IER is a water isotope-enabled atmospheric model with IC physics (Dee et al., 2015). The model is an extension of the atmospheric model SPEEDY (Molteni, 2003) via the addition of stable water isotope physics. SPEEDY is a spectral model with a horizontal resolution of 3.75° × 3.75° (T30) and eight vertical layers (Molteni, 2003), and here we run SPEEDY-IER with the same resolution. Fractionation processes in ocean evaporation, raindrop condensation and exchange in clouds, and reevaporation below clouds are all included in this model. SPEEDY-IER has the advantage of fast computations (e.g., it completes approximately 125 model years per 24 hr on a single Intel(R) Xeon(R) CPU X5650 processor at 2.67 GHz), yet this comes at the cost of simplified physical schemes and relatively low resolution.

iCAM5 is a state-of-the-art atmospheric model implementing stable water isotopes (Nusbaumer et al., 2017). The model has a horizontal resolution of 0.9°N × 1.25°E and 30 vertical levels. Similarly, the water isotope physics schema includes equilibrium and kinetic fractionation during surface evaporation and condensation, moist convection, cloud microphysics, and rain evaporation.

We run these two models in a modern climate and a future climate. For the modern simulations, both models are forced by the observed sea surface temperature (SST) and sea ice during 1974–1999 following the Atmospheric Model Intercomparison Project (AMIP) protocol (Hurrell et al., 2008) with an equivalent CO_2 level of 380 ppm for 25 years. SPEEDY-IER generally capture key features of modern climatological circulation and water isotopes, though there are some biases such as a negative bias of midtropospheric temperature and positive bias of precipitation δ^{18}O values in polar regions (Dee et al., 2015; Molteni, 2003). For the future simulations, both models are forced with the RCP 8.5 scenario in CMIP5 (Riahi et al., 2011), characterized by the equivalent CO_2 levels which reach 1,370 ppm by 2100, along with bias-corrected SSTs and sea ice from a similarly forced simulation by the fully coupled CESM (Bacmeister et al., 2018) during 2074–2099. Here SSTs and sea ice data are averages of the last 25 years of the fully coupled CESM RCP 8.5 simulation. In the following text, we refer to these simulations run using RCP 8.5 greenhouse gas forcing as the *future experiments*. Unless otherwise noted, all analyses use

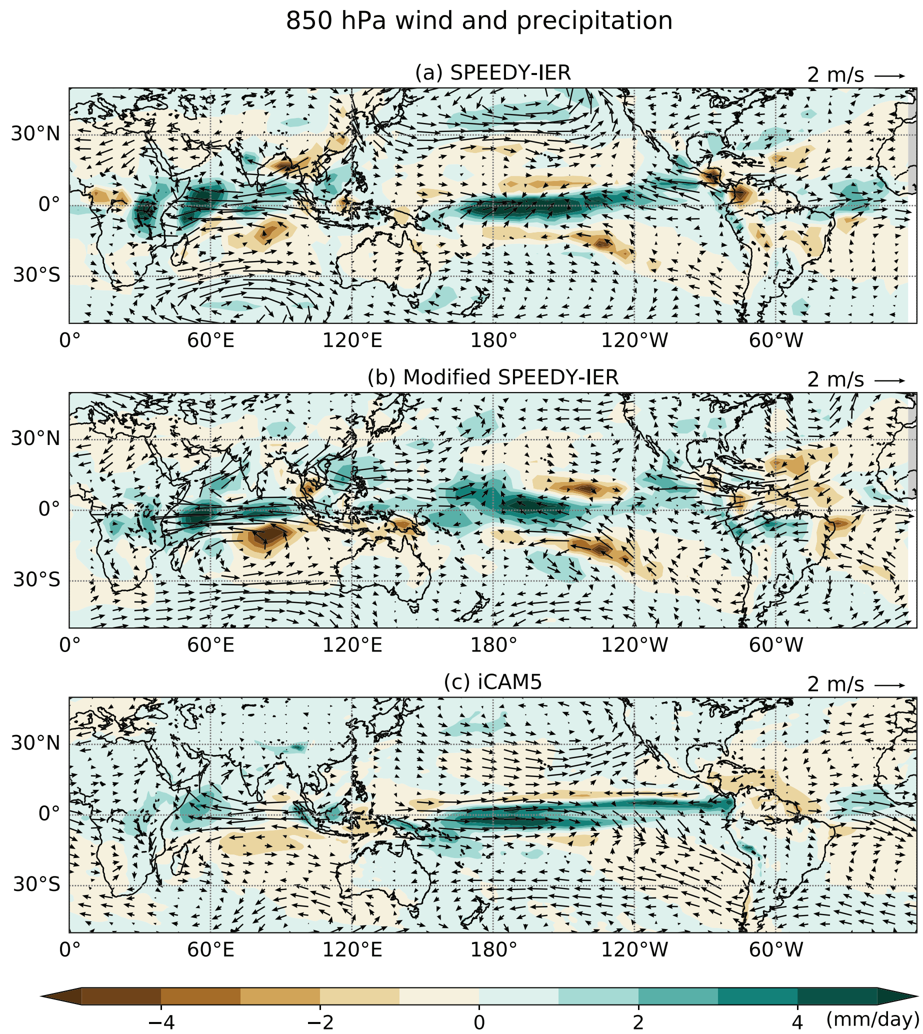

Figure 1. Changes of precipitation (color shades) and wind (vectors) at 850 hPa in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). This is the difference between the future experiment and modern control run.

the climatological annual mean over 1974–1999 for the modern experiment and 2074–2099 for the future experiment. We compare the difference between the high CO_2 simulation and modern simulation in both models (future minus modern). Finally, the iCAM5 simulation is taken to represent the "truth," or nature, with respect to future climate change, since iCAM5 simulates the atmosphere more realistically than SPEEDY-IER and its future simulation is most consistent with other IPCC-class models (Lau & Kim, 2015). Thus, we refer to the difference between SPEEDY-IER and iCAM5 as a "bias" or "discrepancy" relative to nature.

We use a single-column Rayleigh distillation model to estimate the changes of water vapor δD due to changes in thermodynamics alone (Dee et al., 2018). The model assumes that a given air mass is always saturated as it rises vertically and that condensed water is removed immediately; then the heavy-light isotope ratio (R) is calculated as follows:

$$R_i = R_{i-1}\left(\frac{qs_i}{qs_{i-1}}\right)^{\alpha}, \tag{1}$$

where i and $i-1$ denotes the current model layer and the next lower layer, qs is the saturated specific humidity, and α is the temperature-dependent equilibrium fractionation factor for liquid water (Dee et al., 2018; Majoube, 1971). In the tropics, the assumption of the pseudoadiabatic process is a reasonable approximation (Mapes, 2001). Because qs is only dependent on temperature, the change of water isotope ratios estimated by this model reflects the contribution of temperature changes alone, which can be quantified and subtracted to isolate the change due to dynamics.

To compare the modified SPEEDY-IER to observations, we use the Global Precipitation Climatology Project (GPCP) monthly precipitation data set from 1979 to 1999 (the common periods of GPCP and model simulations) (Adler et al., 2003) and the Global Network of Isotopes in Precipitation (GNIP) monthly precipitation δ^{18}O from 1975 to 1999 (IAEA/WMO, 2006). We compute the root-mean-square error (RMSE) of precipitation and precipitation δ^{18}O for both versions of SPEEDY-IER via:

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-obs_i)^2} \tag{2}$$

where x_i is precipitation or precipitation δ^{18}O of SPEEDY-IER in a given grid cell, obs_i is the observational counterpart in the same grid cell, and N is the number of all grid cells considered in the comparison. For precipitation, we interpolated climatological annual mean GPCP precipitation to grid cells of SPEEDY-IER and calculated RMSE from all grid cells. For precipitation δ^{18}O, we interpolated climatological annual mean precipitation δ^{18}O of SPEEDY-IER to locations of GNIP stations and calculated RMSE from all GNIP stations.

3. Results

3.1. Tropical Circulation

The tropics are the "heat engine" of Earth: The Hadley Cell transports energy and moisture from the tropics to extratropical regions, and the Walker circulation redistributes water resources across the tropics. Long-term changes in climatic forcing alter tropical circulation, which in turn has a large impact on the global hydrological cycle. To investigate whether SPEEDY-IER is broadly capable of simulating hydroclimate changes under high greenhouse gas forcing, we focus on evaluating how the models simulate both the Walker and Hadley circulations.

3.1.1. Precipitation and Winds

Both models simulate similar precipitation anomalies in the future experiment (Figure 1). Precipitation intensifies around the equator, particularly over the equatorial western Indian Ocean and the equatorial central Pacific, though the amplitude of the precipitation anomaly in SPEEDY-IER (the maximum rainfall anomaly is larger than 5 mm/day over the Indian Ocean) is larger than iCAM5 (the maximum rainfall anomaly is less than 3 mm/day over the Indian Ocean). We note that the future change of rainfall over the equatorial central Pacific in SPEEDY-IER is within the range of CMIP5 models, but the change over the Indian Ocean is likely not (Kent et al., 2015; Oueslati et al., 2016). Regions where rainfall increases (i.e., the central equatorial Pacific and the Indian Ocean) are characterized by an increase in low-level convergence. In the tropical Pacific, precipitation decreases in the regions adjacent to the equator (5–10°N and 5–10°S) in both models. The corresponding low-level circulation (see wind vectors, Figure 1) is also qualitatively similar in both models in the tropics, characterized by an easterly wind anomaly over the Indian Ocean and a westerly wind anomaly over the western and central Pacific; these features are consistent with a weakening of the Walker circulation. However, differences are evident in the eastern Pacific. iCAM5 simulates northwesterly wind anomalies from the central equatorial Pacific to South America, while SPEEDY-IER simulates southeasterly anomalies. In addition, the responses in the extratropics are dissimilar in both models. SPEEDY-IER simulates westerly wind anomalies over the southern Indian Ocean (around 30°S), while iCAM5 simulates easterly anomalies. SPEEDY-IER also simulates strong westerly wind anomalies across Eurasia around 40°N, in contrast to iCAM5.

3.1.2. Overturning Circulation

The tropical overturning circulations, including the Walker and Hadley circulations, exert first-order controls on the global hydrological cycle. Thus, it is important to evaluate IC model skills in simulating these circulations in the future experiment. The modern climatology of the Walker circulation is characterized

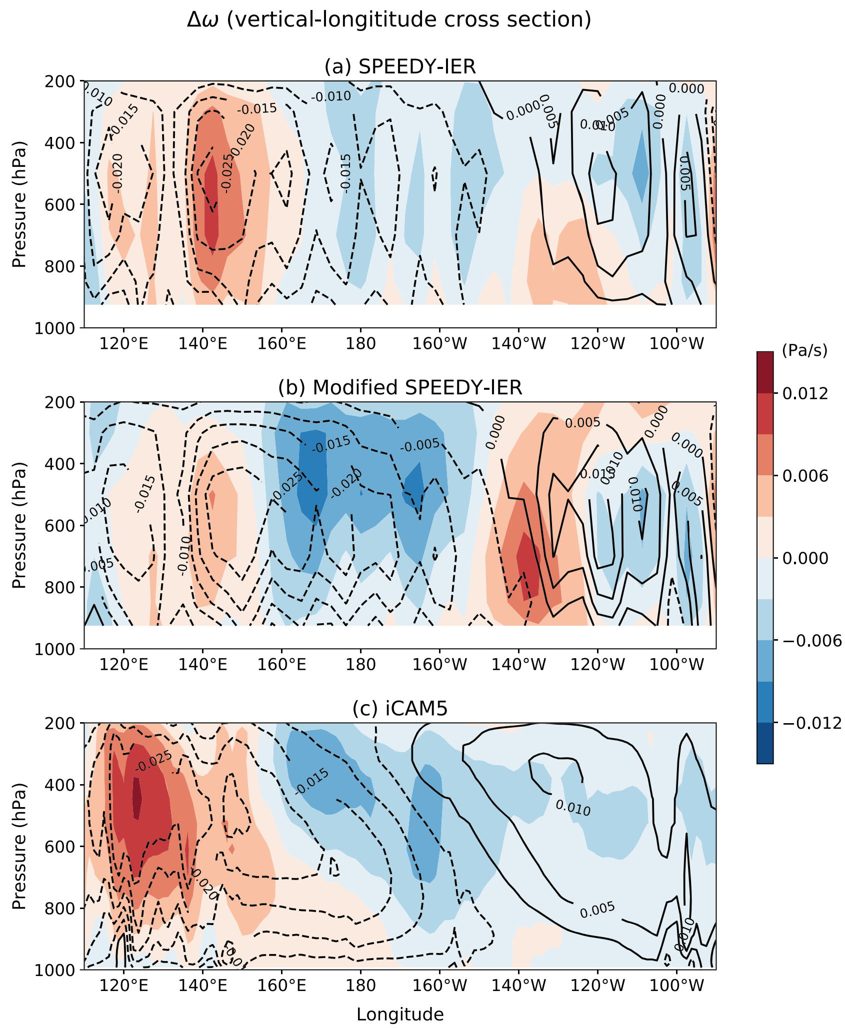

Figure 2. Changes of vertical velocity (ω; the future minus modern experiment) across the tropical Pacific in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). Sign convention is negative = upward motion, positive = downward motion. The color shades show the difference between the future experiment and modern control run in the tropics (averaged between 20°S and 20°N). The black contour lines show the control simulation for both models. Solid lines mean negative, and dashed lines mean positive.

by zonal overturning circulation (Lau & Yang, 2003), with ascending motion over the warm pool of the western Pacific and Indonesian region and descending motion over the eastern Pacific. The winds in the lower atmosphere flow from the high pressure system over the cool eastern equatorial Pacific toward the warmer, low-pressure system over the western equatorial Pacific. The westerly return flow dominates in the upper troposphere. The Hadley circulation is a meridional overturning circulation (Diaz & Bradley, 2004; Nguyen et al., 2013): Air masses rise over the equator and move poleward in both hemispheres in the upper atmosphere. Air masses lose moisture and cool and then sink in the subtropics (~30°) in both hemispheres and flow back to the equator via surface trade winds.

Figure 2 shows that both models generally simulate a slowdown of the ascending branch of the Walker circulation in the future experiment: There is weaker upward motion (denoted by red colors in Figure 2) over the Warm Pool. The weakening of the ascending branch mainly occurs over the Maritime Continent in both models. However, the decrease of the ascending motion is weaker in SPEEDY-IER, and the center of maximum decrease (around 145°E) is further east than in iCAM5 (around 125°E). Both models show anomalous upward motion over the central Pacific (from 160°E to 150°W), indicating the Walker circulation is not weakened in that region. For the descending branch (from 150°W to 100°W), the responses are different, though the amplitudes are smaller than the ascending branch. iCAM5 simulates anomalous upward motion,

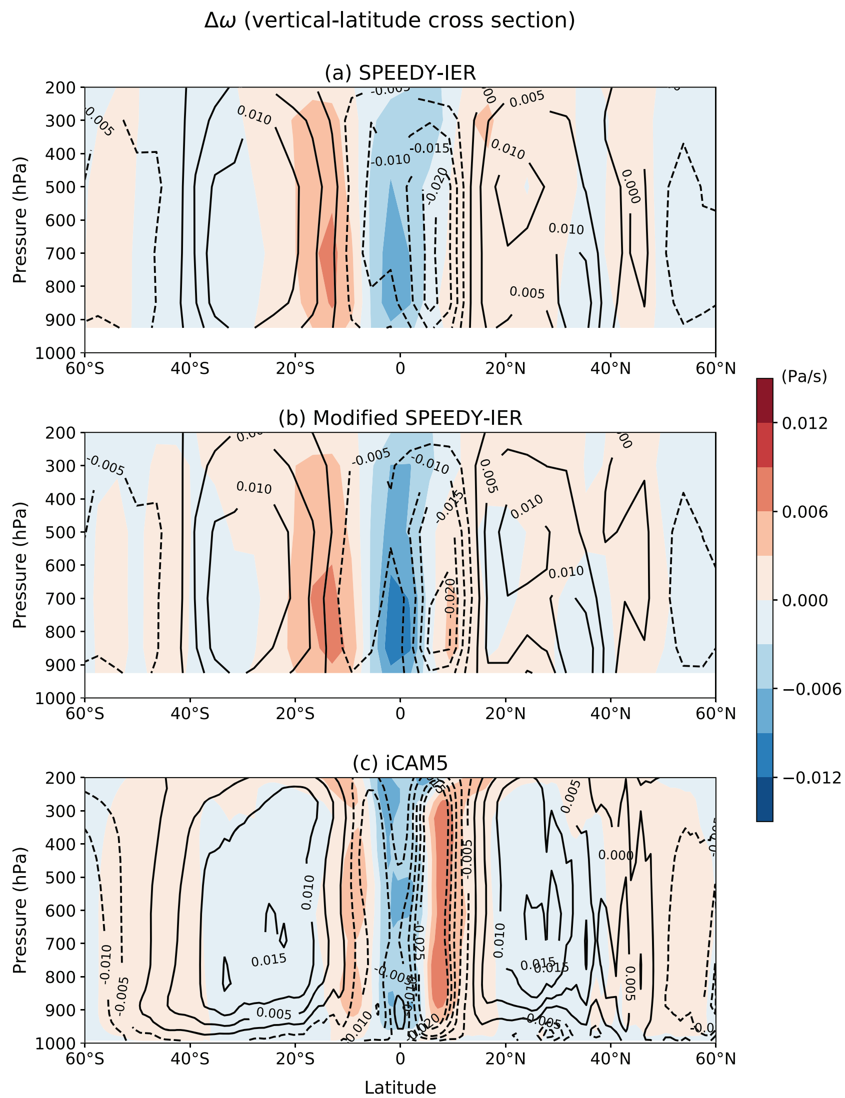

Figure 3. Changes of zonal mean vertical velocity (*ω*; the future minus modern experiment) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). Sign convention is negative = upward motion, positive = downward motion. The color shades show the difference between the future experiment and modern control run. The black contour lines show the modern control simulation. Solid lines mean negative, and dashed lines mean positive.

meaning a weakening of the descending branch, but SPEEDY-IER simulates anomalous downward motion between 140°W and 120°W, indicating that the descending motion is slightly strengthened. In addition,, iCAM5 simulates a tilted structure of the meridional mean vertical velocity in both modern climatological mean and the future change.

Figure 3 shows the change in the Hadley cell in both models in the future experiment. Both models simulate a strengthening of the upward motion in the deep tropics and the extension of the descending arms of the Hadley circulation in the midlatitudes, though SPEEDY-IER does not simulate the extension of the Hadley cell in the Southern Hemisphere. iCAM5 exhibits a clear narrowing of the upward motion region in the deep tropics, a feature observed in several other CMIP5 models (Lau & Kim, 2015). SPEEDY-IER also simulates this change (there is an upward vertical anomaly superimposed on the climatological ascending branch around 10°N and 10°S) but with much smaller amplitudes and extensions. This bias can be attributed to the coarse resolution of SPEEDY-IER. The narrowing deep tropical region is about 5° wide (between 5–10°N and 5–10°S), so it is hard for a model with T30 resolution (3.75° × 3.75°) to resolve this narrowing

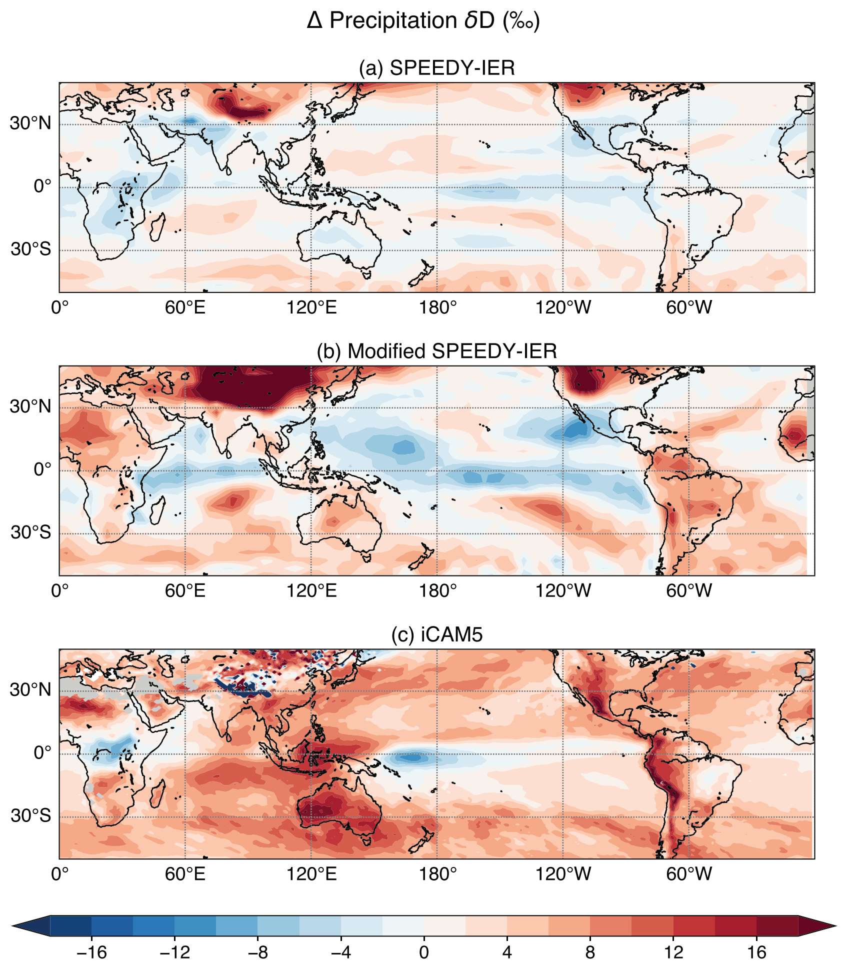

Figure 4. Changes of precipitation δD (the future minus modern experiment) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). This is the difference between the future experiment and modern control run.

feature. The extension of the Hadley cell in SPEEDY-IER predominantly appears in the Northern Hemisphere, but not in the Southern Hemisphere.

In summary, SPEEDY-IER simulates the general changes of tropical precipitation and low-level circulation, the weakening of the Walker circulation, and the strengthening of upward motion in the deep tropics in the future experiment. There are some discrepancies in the spatial patterns of these changes, which are likely due to low horizontal and vertical resolution, consistent with previous studies surrounding the impacts of model resolution (Nusbaumer et al., 2017; Roeckner et al., 2006; Wehner et al., 2014; Werner et al., 2011).

3.2. Stable Water Isotope Fields

Stable water isotopes are sensitive to the history of water phase changes, so they provide extra information surrounding convection, evaporation, and large-scale circulation. Previous studies have shown that evaluating water isotopes exposes additional biases and shortcomings in the atmospheric physics of climate models (Bony et al., 2008; Field et al., 2014; Nusbaumer et al., 2017; Risi et al., 2012; Tharammal et al., 2017). Thus, we here examine how the IC isotope-enabled model SPEEDY-IER simulates stable water isotope ratios in the future experiment (focusing on δD as a performance metric).

3.2.1. Precipitation Water Isotopes

Both models simulate positive precipitation δD and δ^{18}O anomalies in the future experiment between 45°S and 45°N. iCAM5 simulates positive anomalies except over the equatorial Africa and the equatorial Pacific

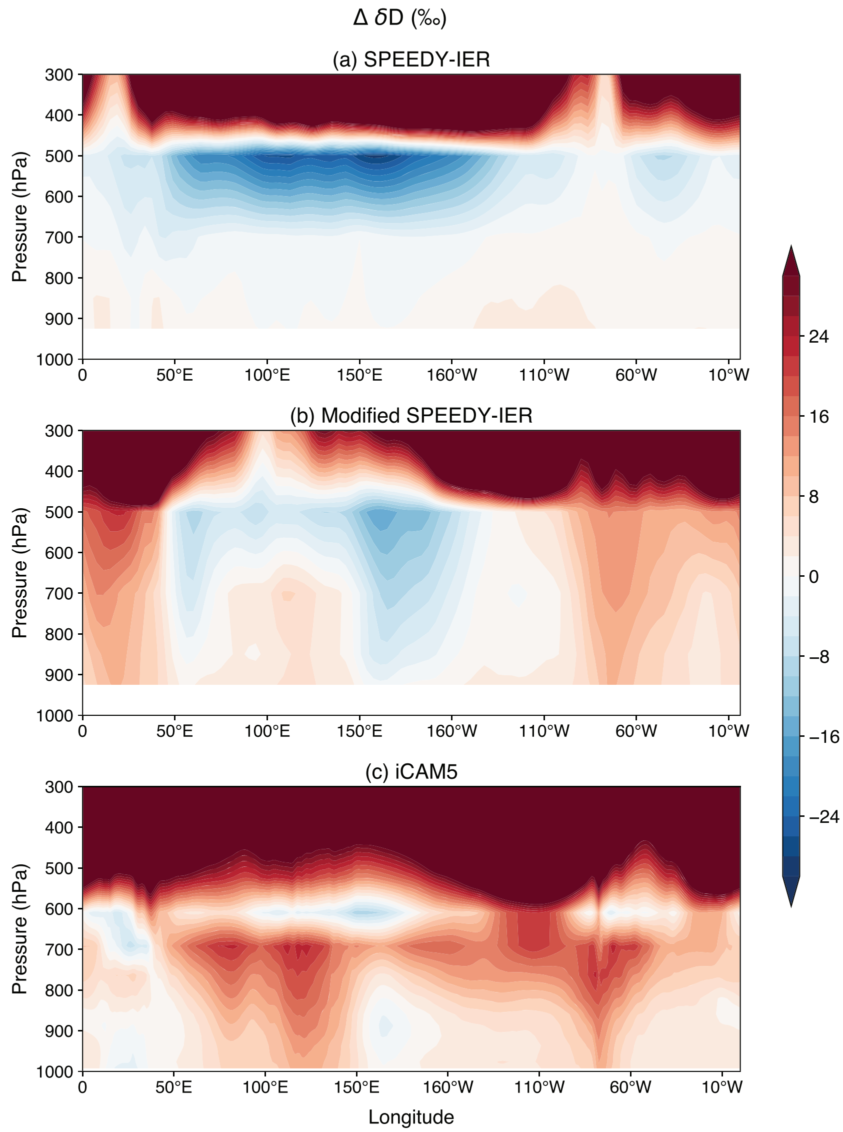

Figure 5. Changes of water vapor δD (the future minus modern experiment) across the tropics (averaged between 20°S and 20°N) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). This is the difference between the future experiment and modern control run. Please note that the longitudes range around the globe instead of the Pacific.

(Figure 4a and Figure S1a in the supporting information); SPEEDY-IER simulates positive anomalies north of 30°N and over large parts of the Indian Ocean, Pacific, and Atlantic (Figures 4c and S1c). However, SPEEDY-IER generally simulates much weaker changes in precipitation δD than iCAM5. This result suggests that caution is needed when using SPEEDY-IER to compare the amplitude of modeled precipitation water isotope changes to paleohydroclimate records. There is a similar bias in water vapor δD (Figures 5a and 5c): SPEEDY-IER cannot simulate comparable amplitudes of positive water vapor δD (δD_V) in the future experiment as iCAM5. Since water vapor δD is more positive in iCAM5 than SPEEDY-IER in the future, the resultant precipitation δD is more positive. Both models simulate positive anomalies in water isotopes because the equilibrium fractionation of water isotopes decreases as temperature increases in the future, and thus, water vapor δD is more positive as condensation occurs in a higher temperature environment given the same initial water vapor δD.

To understand the changes of δD_V, Figure 6 shows the modern climatological δD_V in both models. iCAM5 features a smooth vertical gradient of δD_V (Figure 6c), but SPEEDY-IER shows an abrupt shift of δD_V

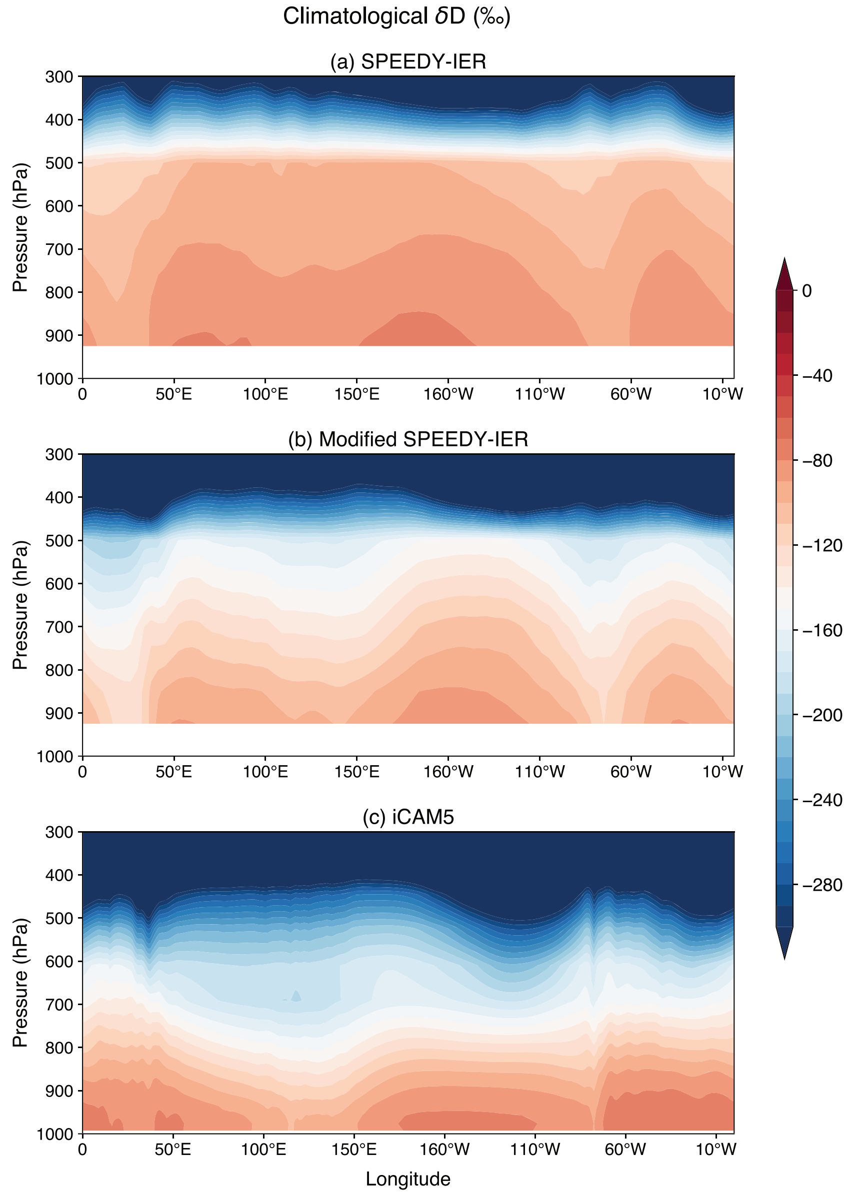

Figure 6. Modern climatological water vapor δD over the tropics (averaged between 20°S and 20°N) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). Please note that the longitudes range around the globe instead of the Pacific.

around 500 hPa (Figure 6a). This major difference in δD_V is mainly due to the simplified convection scheme, in which the condensation of precipitation only occurs at the top convection layers. Thus, in SPEEDY-IER, the fractionation of water isotopes due to condensation processes only occurs at the top-most convection layers. We can also see this abrupt change through the vertical profiles of δD_V (Figure 7a): δD_V decreases little below 500 hPa in SPEEDY-IER, and it does not follow the theoretical Rayleigh distillation profile. This suggests that there is little fractionation due to condensation below 500 hPa. This explanation is confirmed by the fact that the modern climatological cloud top level (which can be used to estimate the top convection levels) (Molteni, 2003; Luo et al., 2008) in the tropics is located at approximately ~530 hPa in SPEEDY-IER, which corresponds to the level where δD_V rapidly changes in the vertical dimension.

Since condensation only occurs at top convection layers in the convection scheme of SPEEDY-IER, and convective precipitation comprises a majority of tropical precipitation in the model (>90%) (Figure S2), we use

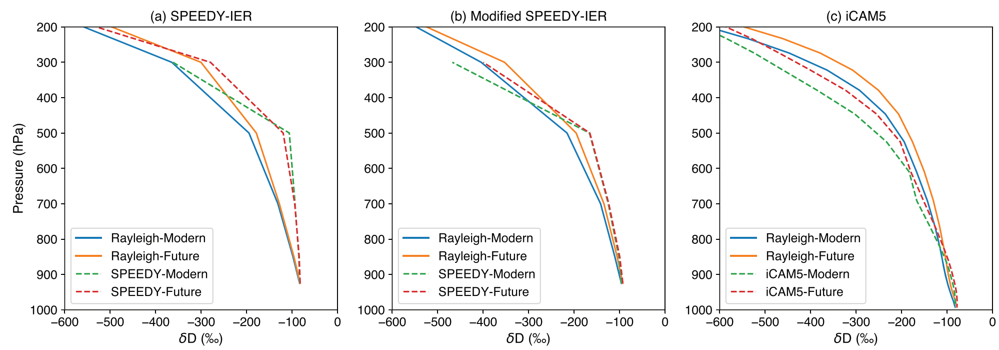

Figure 7. Profiles of water vapor isotope ratios across the tropical Pacific (meridional mean between 20°S and 20°N, unit: ‰) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). Solid lines show the theoretical profiles of water vapor δD_V assuming Rayleigh fractionation.

cloud top levels to estimate condensation heights in SPEEDY-IER. Figure 8 shows that the tropical cloud top levels are higher in the future experiment. This suggests that condensation occurs at higher altitudes where δD_V is more negative. Thus, the raindrops forming at top convection layers entrain more negative δD. When raindrops fall to the ground, rain reevaporation leads to exchange of ambient water vapor and water in raindrops; this in turn decreases δD_V in the midtroposphere, as shown in Figure 5a.

Thus, SPEEDY-IER approximates the broad-scale pattern of tropical circulation and precipitation changes, as shown in section 3.1. However, the use of this convection scheme results in a large bias in water isotope fields. By prioritizing water isotope fields as diagnostics for model evaluations, it is possible to improve the performance of SPEEDY-IER. We illustrate how to implement such improvements in section 3.3.

3.2.2. Case Study: Tracing the Walker Circulation Using Water Isotopes

We examine the Walker circulation through a water isotopic lens as a case study, given previous work (Dee et al., 2018) suggesting that isotopes can be used to track changes in this overturning circulation; by contrast, there is no documentation of water isotope tracers effectively tracking changes in the Hadley cell. The mechanism for how water vapor isotopes track Walker circulation changes is as follows: The climatological Walker circulation brings water vapor with high δD upward over the Maritime Continent and transports water vapor with low δD downward over the eastern tropical Pacific, leading to a gradient of δD_V in the midtroposphere. Changes in the slope of this gradient in tropical Pacific δD_V in the midtroposphere can be used to track the strength of the Walker circulation, and Dee et al. (2018) validated this using available satellite retrievals spanning El Niño–Southern Oscillation (ENSO) events. Here, we investigate whether SPEEDY-IER is capable of simulating similarly realistic changes of the Walker circulation in future experiments.

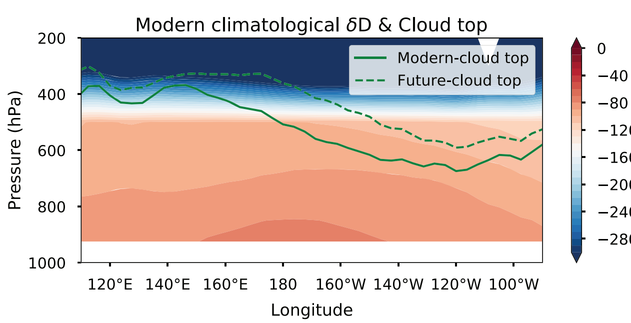

Figure 8. Cloud top levels (green solid line: modern climate mean; green dashed line: future climate mean; unit: hPa) and modern climatological water vapor δD over the tropics (averaged between 20°S and 20°N) in SPEEDY-IER.

We remove the changes of δD_V due to the thermodynamic component with a Rayleigh distillation model; the remaining signal in δD_V is due to condensation and horizontal and vertical advection, and we thus label this residual as the dynamics term (δD_{V-DYN}), used to track the change in the Walker circulation (following the methodology of Dee et al., 2018). Figures 9a and 9c show the changes of the dynamics terms of δD_V in both models over the tropics, and Figure S3 specifically shows the change of δD_V in the midtroposphere. Both models simulate negative δD_V anomalies over the Warm Pool and the Intertropical Convergence Zone at 600 hPa, but iCAM5 also simulates positive δD_V anomalies in the cold tongue region of the eastern tropical Pacific. This pattern of δD_V responses can be explained by the weakening of the Walker circulation in a warmer climate (Dee et al., 2018; Held & Soden, 2006; Soden & Held, 2006; Tokinaga et al., 2012; Vecchi et al., 2006) (Figure 10). Here the vertical advection of water vapor δD is calculated by the gradient

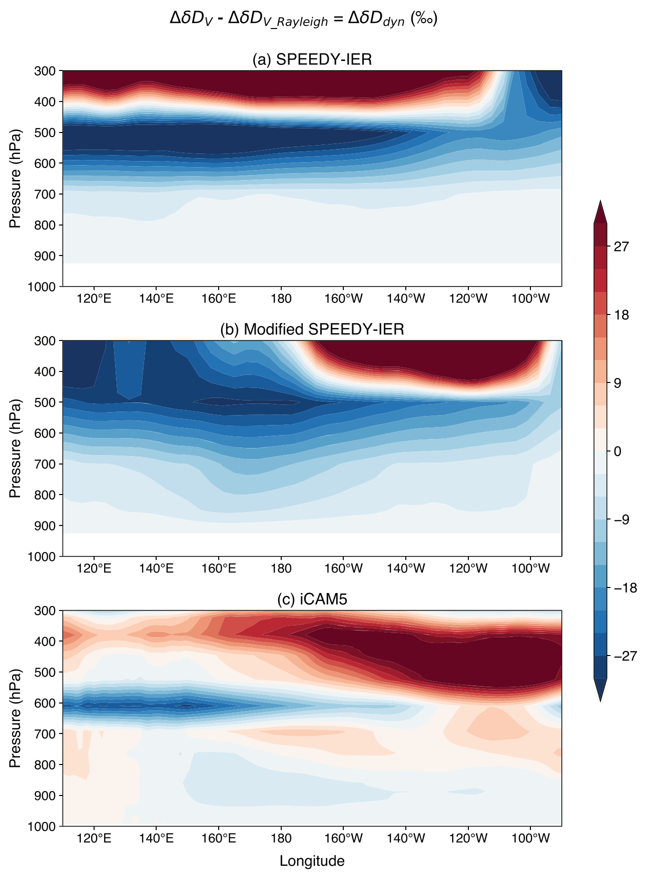

Figure 9. Changes of water vapor isotope ratios (the future minus modern experiment) across the tropical Pacific (meridional mean between 20°S and 20°N) in SPEEDY-IER (a), modified SPEEDY-IER (b, discussed in section 3.3), and iCAM5 (c). This is simulated δD_V minus the Rayleigh-only component.

of the water vapor isotope ratios multiplied by vertical or horizontal motion: $-u\frac{\partial R}{\partial x} - \omega\frac{\partial R}{\partial p}$, where R is the water isotope ratio (HDO/H2O), u is the zonal wind, and ω is the vertical motion. The anomalous downward motion in the ascending branch brings more negative δD_V down to the midtroposphere, which corresponds to the negative vertical advection of δD_V (Figure 10). In the descending branch, the anomalous upward motion also brings enriched δD_V upward, and Figure 10 shows that the vertical advection in the eastern Pacific occurs only in the upper troposphere. SPEEDY-IER therefore properly simulates the weakening of the ascending branch of the Walker circulation, a signal visible in the water vapor isotopes, but it does not reproduce the enrichment in the eastern tropical Pacific accompanying a weakening of subsidence in the descending branch.

SPEEDY-IER generally simulates the trends (or qualitative signs) of the changes of water isotopes in the future experiment, but it does not match the amplitudes of precipitation δD changes observed in iCAM5. Once again, it is likely that these biases derive from the simplified convection scheme and coarse spatial and vertical resolution of the model.

The fact that SPEEDY-IER can simulate the weakening of the Walker circulation and the narrowing of the deep tropics in the future experiment in general agreement with IPCC-class models confirms that these tropical climate responses are not strongly dependent on model complexity (Frierson et al., 2007), even though discrepancies exist. In other words, SPEEDY-IER sufficiently simulates mechanisms of tropical circulation changes in a high-CO_2 world. Furthermore, the simplicity of the model physics in SPEEDY-IER enables us to isolate impacts of various physical processes on tropical circulation via ensemble experiments with various initial conditions and physical parameter sets, at a lower computation cost compared to IPCC-class models.

3.2.3. SPEEDY-IER Deficiencies and Improvements

The analysis presented in section 3.2 suggests that the consequential biases in the simulation of future climate in SPEEDY-IER emerge in the water isotope fields. This bias is likely caused by the simplified convection scheme: Condensation only occurs at the top-most convection layer. This simplification leads to the unrealistically sharp vertical gradients of water vapor isotopes and subsequently results in precipitation isotope biases in Africa, Australia, and South America (Figure 4). To improve the performance of SPEEDY-IER in simulating water isotopes, we next focus on iterating toward more realistic δD_V profiles shown in Figure 7, shifting them closer to the Rayleigh distillation profile by letting condensation take place in intermediate convection layers.

3.3. Improvement of SPEEDY-IER

We hypothesize that restricting condensation to the top convection layers may be responsible for the bias in SPEEDY-IER when simulating water isotope changes under high-CO_2 forcing, as well as the simulated sharp vertical gradients in water vapor isotopes (Figures 6a and 7a). This section probes whether addressing this key deficiency improves the overall performance of SPEEDY-IER. Specifically, we modified the convection scheme and ran the same modern and future experiments using the altered version of SPEEDY-IER.

The first change to the convection scheme allows condensation to occur in the intermediate convection layers; this facilitates fractionation of water isotopes due to condensation in all convection layers. This change opposes the original model physics wherein all isotope fractionation occurs in the top convection layer, which is expected to smooth vertical gradients of water vapor isotopes. The original convection

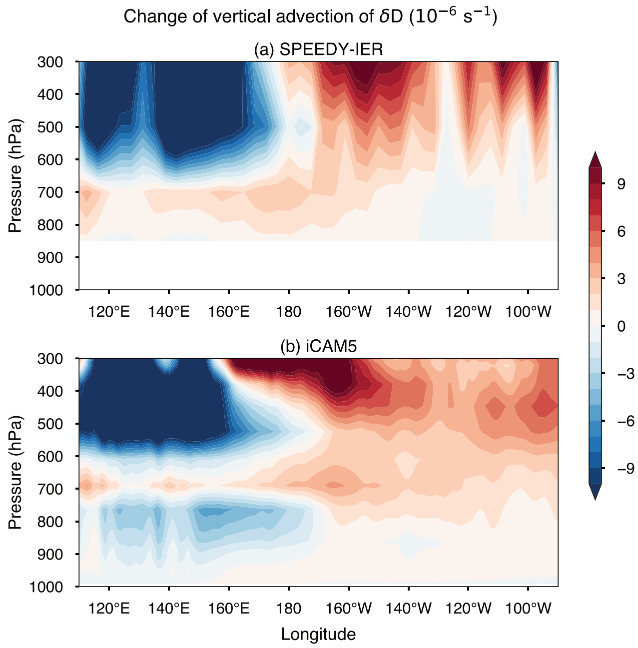

Figure 10. Changes of the vertical advection of water vapor isotope ratios (the future minus modern experiment) across the tropical Pacific (meridional mean between 20°S and 20°N, unit: 10^{-6} s^{-1}) in SPEEDY-IER (a) and iCAM5 (b).

scheme also excludes detrainment for simplicity, but this process is necessary as it allows isotopic signals in updrafts to alter their local moisture environment.

We modify the convection scheme of SPEEDY-IER by:

(1) Adding condensation (including the resultant change of moisture and diabatic heating) of rainfall in updrafts at intermediate layers. The calculation of condensation amount is the same as the condensation in the original model: $Q_k - Q_{sat}$, where Q_k is the moisture at one level and Q_{sat} is the saturated moisture at this level.
(2) Adding isotopic fractionation due to condensation at intermediate layers.
(3) Adding detrainment (including detraining moisture and diabatic heating of updrafts to the environment) at intermediate layers. The detrainment profile is shown in Figure S4. We assumed that the fractional detrainment rate is proportional to the change in entrainment rate with height (Neale et al., 2012), excluding the surface and cloud top layers, where we assume both are 0.

After successfully implementing condensation and detrainment at intermediate convection layers, SPEEDY-IER's water isotope fields show modest improvements. Vertical gradients of δD_V are much smoother and do not concentrate at 500 hPa (Figures 6b and 7b); the profile of δD_V is closer to a theoretical profile assuming Rayleigh distillation below 500 hPa (Figure 7b), indicating condensation is active in all convection layers.

Having implemented this change, we reevaluated the simulation of future δD_V changes (Figure 5b). The reduction in δD_V in the midtroposphere is largely damped in the modified SPEEDY-IER. Though the top convection layers are elevated in the future simulation (Figure 8), the mean condensation levels are not elevated as much as the original model since condensation can occur at any layer, resulting in less negative changes in δD_V. Along with this improvement, the residual term of δD_V after removing the Rayleigh distillation effect (δD_{V-DYN}) in SPEEDY-IER is now similar to the pattern of iCAM5, showing negative δD_V changes in the western tropical Pacific and positive δD_V changes in the eastern tropical Pacific (Figure 9b).

The improvements to the vertical water isotope profiles causes the future precipitation δD to more closely match iCAM5 as well (Figure 4b). Amplitudes of positive trends in precipitation δD due to high CO_2 forcing are increased in the modified version, mainly in Africa, Australia, the Maritime Continent, and South America. However, differences between SPEEDY-IER and iCAM5 remain, mainly over the Pacific. The negative changes of precipitation δD in SPEEDY-IER are concentrated over the central Pacific because of the coeval increase in rainfall amount. The response of precipitation δD to high-CO_2 forcing is large over tropical and subtropical land masses (Africa, Australia, the Maritime Continent, and South America) after modifying the convection scheme, indicating heightened sensitivity in these regions to changes in the model physics.

To ensure that the above-described modifications did not reduce the accuracy of SPEEDY-IER's circulation, we compared simulated climotological precipitation and precipitation δ^{18}O for both the modified and original versions alongside modern observations (Figures S5 and S6). The key spatial structures of the overturning circulations remain intact. For the Walker circulation, the modified SPEEDY-IER still shows a weakening trend, but the simulated weakening in the ascending branch is less pronounced; conversely, the weakening of the descending branch is strengthened (Figure 2b). This indicates that some aspects of the circulation become more dissimilar to iCAM5, although the isotope fields are improved. In addition, there is an increase in precipitation over the northwestern Pacific in the modified version, a departure from iCAM5 (Figure 1b). However, we note that the shrinking of the deep tropics is more evident in the modified version (Figure 3b). All of these changes in circulation are due to the addition of detrainment in the convection scheme. The circulation changes result from detrainment, which alters moisture and diabatic heating profiles in the environment, subsequently altering circulation. During convection, moist air masses ascend from the boundary layer, and detrainment expels some of the moistened air out to the midtropospheric environment. This increases the convective stability and suppresses subsequent convection. Reduced convection causes decreased diabatic heating, thus driving circulation anomalies.

The magnitude of precipitation amount changes with the addition of detrainment, for example, over New Guinea and the western Indian Ocean. The isotopes also change: Precipitation δD is more negative globally in the modified version, likely because water vapor δD is decreased via condensation and detrainment in intermediate tropospheric layers (below 500 hPa).

We computed the RMSE of precipitation and precipitation δ^{18}O for both versions to quantify the impacts to these fields (please see section 2 for details): RMSE decreases in the modified SPEEDY-IER (from 1.45 to 1.30 mm/day), but the RMSE of precipitation δ^{18}O increases (from 3.61‰ to 3.72‰), likely due to the larger departure in the model compared to observations in the tropics. Scatter plots (Figure S7) comparing GNIP and model results show that precipitation δ^{18}O in the modified version is generally lower than GNIP observations, while in the original version, more than half of the isotope ratio values are higher than the GNIP data. Regression analysis shows that the original model version fits the GNIP data better with a higher r squared value (Figure S7). It is possible that these biases can be reduced by re-tuning parameters such as the evaporative exchange coefficient and the scaling for effective humidity in the model, akin to the process followed in Dee et al. (2015).

Finally, we note the modifications we enacted to improve the water isotope fields slow SPEEDY-IER by 5.1% (the run time for one model year increases from 6.5 to 6.8 min on a single Intel(R) Xeon(R) Gold 6230 CPU @ 2.10 GHz). We consider this small increase as negligible; it does not hinder SPEEDY-IER's ability to run fast millennial-scale simulations and ensemble experiments efficiently.

In summary, introducing condensation and detrainment at intermediate convection layers is shown to improve the simulation of water isotopes in SPEEDY-IER by making its vertical profiles of δD_V more realistic (i.e., closer to iCAM5's fields), and the modifications do not significantly reduce the efficiency of SPEEDY-IER.

4. Discussion

We evaluate an IC model (SPEEDY-IER) in a high-CO_2 scenario, comparing it to a state-of-the-art model (iCAM5) within an identical experimental setting. We specifically examine how well SPEEDY-IER simulates changes of tropical circulation, precipitation, and stable water isotope ratios in this high-CO_2 world.

We find that the IC model SPEEDY-IER is capable of simulating first-order changes of tropical hydroclimate in the future experiments. SPEEDY-IER can simulate the general changes of tropical circulation, including changes in precipitation, the weakening of the Walker circulation, and the strengthening of the upward motion in the deep tropics. Our examination of the water isotope fields reveals that SPEEDY-IER simulates the correct signs of precipitation δD and water vapor δD changes, but it does not simulate the correct amplitudes and spatial patterns of water isotope changes in the future experiment. The bias of SPEEDY-IER is mainly due to its coarse resolution and simplified convection scheme. Moreover, changes of global mean and zonal mean water isotopes are more reliable than the changes in the spatial pattern.

Importantly, this study demonstrates how the full evaluation of water isotope fields reveals hidden biases of the general circulation in models due to the heightened sensitivity of water isotopes to phase changes (Bony et al., 2008; Field et al., 2014; Nusbaumer et al., 2017; Risi et al., 2012; Tharammal et al., 2017). Through a simple case study focusing on the Walker circulation, we show that a closer examination of water isotope diagnostics may help highlight and streamline necessary modifications and enhancements to model performance.

As one example, broad-scale patterns in tropical precipitation changes appear similar in both models (Figure 1), yet precipitation δD reveals large discrepancies (Figure 4) in SPEEDY-IER′ physics. The simplicity of the convection scheme (where condensation only occurs at the top convection layer) leads to a weak response of precipitation δD in SPEEDY-IER. This model deficiency was addressed by introducing condensation and detrainment at intermediate convection layers in the convection scheme. The modification still maintains SPEEDY-IER's simplicity and speed. Thus, we provide an illustrative example showing how evaluating water isotopes facilitates identification and diagnosis of model biases.

Since SPEEDY-IER can broadly simulate the responses of the Walker and Hadley circulations to CO_2 forcing more efficiently than IPCC-class models, the model constitutes a helpful tool for investigating forced changes to the tropical overturning circulations. SPEEDY-IER is especially useful for running long simulations and large ensemble runs with various initial conditions and physical parameter sets, all at a relatively low computational cost. Finally, due to its simplified physics, the model provides an opportunity to understand the various contributions of physical processes without the complexity represented in IPCC-class models, potentially useful for detection and attribution studies.

We acknowledge several limitations of this work. First, IC models such as SPEEDY-IER are inherently limited due to their simplified physics. They cannot resolve fine topography and mesoscale circulation features due to their coarse resolution. Second, the simulation of iCAM5 in the future experiment is not nature or "truth," and it has noticeable isotopic biases when compared to (isotopic) observations (Nusbaumer et al., 2017). We are using iCAM5 to evaluate SPEEDY-IER because iCAM5 is closer to observations than SPEEDY-IER in the instrumental era. However, results from iCAM5 do not represent all isotope-enabled IPCC-class models. Efforts from modeling intercomparison projects such as CMIP5 demonstrate the need for a rigorous comparison across IPCC-class GCMs with isotope physics in the future. Isotope fields usually lag behind updates to other model physics, and yet this work demonstrates the usefulness of intermodel comparisons focusing on isotope fields. In addition, this study only evaluates one IC model, SPEEDY-IER. Our results are likely not representative of all isotope-enabled models of similar complexity; this motivates additional model intercomparison projects for isotope-enabled models of IC in the future.

Finally, we note that we do not discuss the isotopic imprints of the Hadley circulation to the extent that we do for the Walker circulation: To date, there are no studies showing that water isotopes can be directly used to track the Hadley circulation. Further investigation into this topic is ongoing among the authors of this manuscript. Despite the improvement to the simulated water isotope fields in SPEEDY-IER via adjusting its convection scheme, some aspects of the modified model are not as good as the original version. For example, the RMSE of global precipitation δ^{18}O increases by 3%, and the weakening of the Walker circulation in the future is suppressed. The inclusion of detrainment inevitably affects the model's temperature and moisture adjustments; additional tuning and testing to fully balance these influences will be performed as a set of next steps to finalize the modifications and assess their trade-offs. The main purpose of this manuscript is thus to illustrate the model development workflow one can apply, driven by the water isotopes, to refine model physics; so often, these fields are evaluated as an afterthought.

We have taken a first step toward developing a framework for critically evaluating IC models and their physics, and highlight the benefits of evaluating stable water isotopes. Further studies are needed to evaluate more IC models under various climate forcings and apply these models to better understand climate in the past and future. Future work should take advantage of the efficiency of IC models to investigate climate in different forcing scenarios by running long simulations and large ensemble runs with suites of initial conditions and physical parameters. SPEEDY-IER is a publicly available IC-AGCM, and we hope that this paper serves to promote such an approach to the broader scientific community. Given the immense bearing of tropical hydroclimate changes on society, understanding future tropical climate variability with IC models could help to reduce uncertainties in future climate projections.

Data Availability Statement

SPEEDY-IER is available on Zenodo (https://doi.org/10.5281/zenodo.3770468). The simulation results of both models and scripts for analysis are stored on Zenodo (https://doi.org/10.5281/zenodo.3766473).

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