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Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL076826

The Impact of Parameterized Convection on Climatological Precipitation in Atmospheric Global Climate Models

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Key Points:
- Climatological precipitation patterns with and without parameterized convection schemes are surprisingly similar
- Daily precipitation extremes are too strong without convective schemes, but in contrast, tropical wave activity is more realistic
- Tropical ocean rainfall, double ITCZ, and SH storm track moist biases all persist without convection schemes

Supporting Information:
- Supporting Information S1

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Citation:
Maher, P., Vallis, G. K., Sherwood, S. C., Webb, M. J., & Sansom, P. G. (2018). The impact of parameterized convection on climatological precipitation in atmospheric global climate models. *Geophysical Research Letters*, *45*, 3728–3736. https://doi.org/10.1002/2017GL076826

Received 15 DEC 2017
Accepted 12 MAR 2018
Accepted article online 25 MAR 2018
Published online 20 APR 2018

Abstract

Convective parameterizations are widely believed to be essential for realistic simulations of the atmosphere. However, their deficiencies also result in model biases. The role of convection schemes in modern atmospheric models is examined using Selected Process On/Off Klima Intercomparison Experiment simulations without parameterized convection and forced with observed sea surface temperatures. Convection schemes are not required for reasonable climatological precipitation. However, they are essential for reasonable daily precipitation and constraining extreme daily precipitation that otherwise develops. Systematic effects on lapse rate and humidity are likewise modest compared with the intermodel spread. Without parameterized convection Kelvin waves are more realistic. An unexpectedly large moist Southern Hemisphere storm track bias is identified. This storm track bias persists without convection schemes, as does the double Intertropical Convergence Zone and excessive ocean precipitation biases. This suggests that model biases originate from processes other than convection or that convection schemes are missing key processes.

Plain Language Summary

Accurately modeling rainfall is critical for predicting weather and climate. Convective clouds are much smaller than climate models can simulate so the rainfall generated is estimated using a convection scheme. Rainfall is difficult to estimate, and deficiencies in the schemes result in model errors. Using simulations with and without convection schemes, we assess what impact convection schemes have on mean rainfall in state-of-the-art climate models. We find that long-term rainfall patterns are similar regardless of whether the convection schemes are used or not. Without convection schemes the atmosphere is drier and cooler. However, these differences are smaller than might be expected. In this study we show that convection schemes are not required for reasonable long-term rainfall patterns for prescribed SST model runs but are essential for reasonable daily precipitation. We aim to provide guidance for modeling centers on the impact of convection schemes on long-term mean rainfall and on long standing model biases.

1. Introduction

The parameterization of convection was borne out of necessity. In the 1960s the primitive-equation moist atmospheric models required a convection scheme for stable time integrations (Kasahara, 2000). The moist adjustment scheme of Manabe et al. (1965) was one of the first, and simplest, convection schemes implemented into a radiative-convective equilibrium model. The scheme successfully prevented grid-scale convection that previously caused the model to quickly deteriorate (Manabe et al., 1965, see references therein) and become numerically unstable.

Fifty years after Manabe et al. (1965), convective parameterizations are still implicitly assumed to be an important component of global climate models (GCM), as they are used at all the major modeling centers and in the models submitted to the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. More recently, model runs were performed without parameterized convection by Frierson (2007) in developing a simplified convection scheme and Lin et al. (2008) in testing the sensitivity of convective equatorial waves to convection schemes. The first organized collection of atmosphere-only models run without parameterized convection is the Selected Process On/Off Klima Intercomparison Experiment (SPOOKIE) by Webb et al. (2015). The motivation for SPOOKIE was to test if convection schemes are a leading source of intermodel spread in cloud feedbacks, which is known to be important for model equilibrium climate sensitivity. Webb et al. (2015) found that the range of cloud feedbacks was similar with and without parameterized convection suggesting that the convective parameterizations are not a leading-order source of intermodel spread.

The SPOOKIE simulations also disprove a second commonly held assumption, namely that convection parameterizations are still required for numerical stability in modern GCMs. This is likely due to the improved numerical schemes and much higher horizontal and vertical resolution. The question that remains unanswered, and is the aim of this study, is *what impact does parameterized convection have on climatological precipitation?* A first step in a systematic approach to improving convection parameterizations is to establish what impact the schemes have on model climatology and the distribution of daily rain rates. In this way we hope to provide guidance for modeling centers on what biases are a direct result of the convection schemes.

2. Methods and Data

SPOOKIE consists of 10 global atmospheric models, identical to the standard Atmospheric Model Intercomparison Project (AMIP) configuration forced with observed sea surface temperature (SST) except without parameterized convection, herein "ConvOff," (Anderson et al., 2004; Dufresne et al., 2013; Giorgetta et al., 2012; Martin et al., 2011; Neale et al., 2012; Voldoire et al., 2013; von Salzen et al., 2013; Watanabe et al., 2010; Yukimoto et al., 2012; Zhao et al., 2009). See supporting information Table S1 for models, resolutions, and time periods. See acknowledgment for data storage locations.

Both deep and shallow convection parameterizations (if they exist) are deactivated in ConvOff. Large-scale precipitation is generated in the microphysics scheme, where precipitation results from grid-scale condensation. The boundary layer scheme and large-scale dynamics are still free to remove instability and to transport heat and moisture vertically; see Webb et al. (2015) for further details. SPOOKIE output is also available with +4 K and $4 \times CO_2$ forcings and aquaplanet configurations; however, none of these are used in this study.

Daily and monthly data are interpolated, using bilinear interpolation, for each model to a common resolution of $2.5^\circ \times 2.5^\circ$, although daily data are only available for 4 out of the 10 models. A cross-validation approach was used to check for outlier models that could strongly influence the multimodel mean precipitation; see supporting information Figure S1. No outlier models were found, and all models are included in the multimodel means.

Modeled precipitation is compared to observed Global Precipitation Combined Precipitation (GPCP) data for the 30-year period from 1979 to 2008 (monthly, GPCP v2.3, Adler et al., 2003) and the 20-year period from 1996 to 2015 (daily, GPCP v1.2, Huffman et al., 2001). Monthly ERA-Interim reanalysis (Dee et al., 2011) is used for the 30-year period from 1979 to 2008. In calculating relative humidity, ERA-Interim uses a weighted ice- and liquid-water saturation vapor pressures between −23°C and 0°C following Simmons et al. (1999). We convert ERA-Interim relative humidity data using pressure with respect to ice below 0°C rather than apply the weighting of Simmons et al. (1999) to AMIP and ConvOff, see supporting information for details.

The double Intertropical Convergence Zone (ITCZ) is measured using the southern ITCZ index (Bellucci et al., 2010), defined as the climatological model precipitation minus observations in the 20°S–0S° and 210°–260° domain. The edge of the ITCZ is measured using the moisture ITCZ definition (Byrne & Schneider, 2016) where the edge is defined as the latitude where evaporation dominates over precipitation.

3. Results

Climatological precipitation for GPCP and the multimodel means of AMIP and ConvOff are shown in Figures 1a–1c, together with their differences in Figures 1d–1f. AMIP precipitation is generally similar to the satellite-derived GPCP, though enhanced AMIP precipitation exists in each of the tropical ocean basins, in particular the western Indian Ocean and off-equatorial bands in the western and central Pacific Oceans (Figure 1d). These AMIP biases are also present in the CMIP5 coupled models in the 2013 Intergovernmental Panel on Climate Change report (Flato et al., 2014, see their Figure 9.4b); hence, the biases originate from the atmospheric models, noting that they include about 50 models and a slightly shorter time period, but these differences are not expected to affect climatological biases. The enhanced AMIP precipitation bias over the ocean, compared to GPCP observations, persists and is worse without parameterized convection (Figure 1e). In addition to amplifying the excessive precipitation over the Indian and western Pacific Oceans, ConvOff has

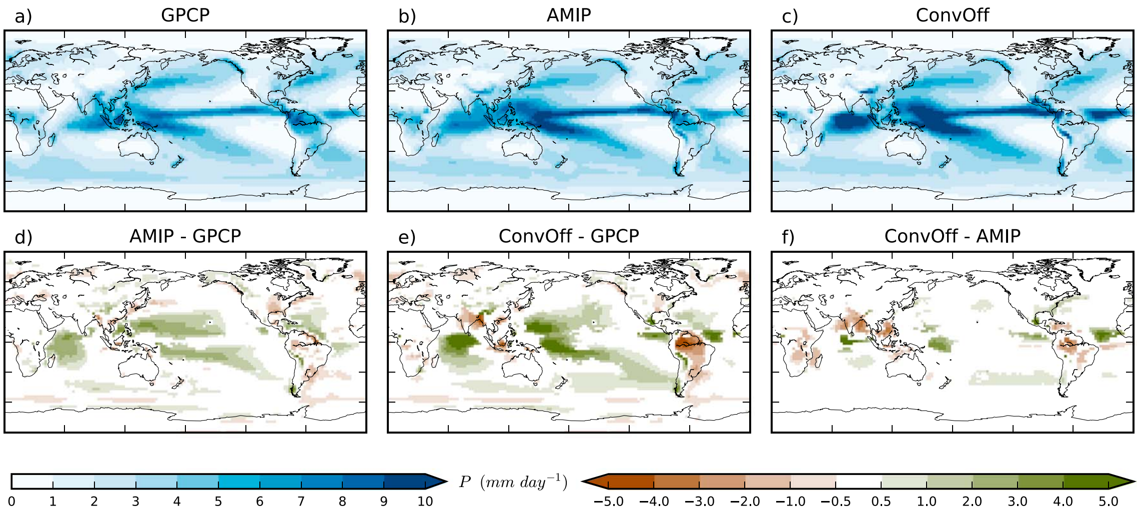

Figure 1. Average precipitation for (a) GPCP, the multimodel means of (b) AMIP and (c) ConvOff. Difference in GPCP with the multimodel means of (d) AMIP and (e) ConvOff and (f) their differences. All plots have the same common resolution of 2.5° × 2.5°. In Figures 1d–1f differences are only plotted when 90% or more of the models agree on the sign of the multimodel difference and is statistically significant with a two-tailed 95% significance level ($\pm 2\sigma$), where σ is the internal variability of the multimodel mean. AMIP = Atmospheric Model Intercomparison Project; GPCP = Global Precipitation Combined Precipitation.

more precipitation in the equatorial western Atlantic and eastern Pacific Oceans. In the zonal mean these differences are small; AMIP and ConvOff are similar at all latitudes (supporting information Figure S5).

The most striking similarities occur between AMIP and ConvOff in Figure 1f (see also supporting information Figures S8 and S10). The multimodel precipitation differences over the ocean are much smaller in magnitude and spatial extent than differences between GPCP and AMIP and are largest in regions of strongest

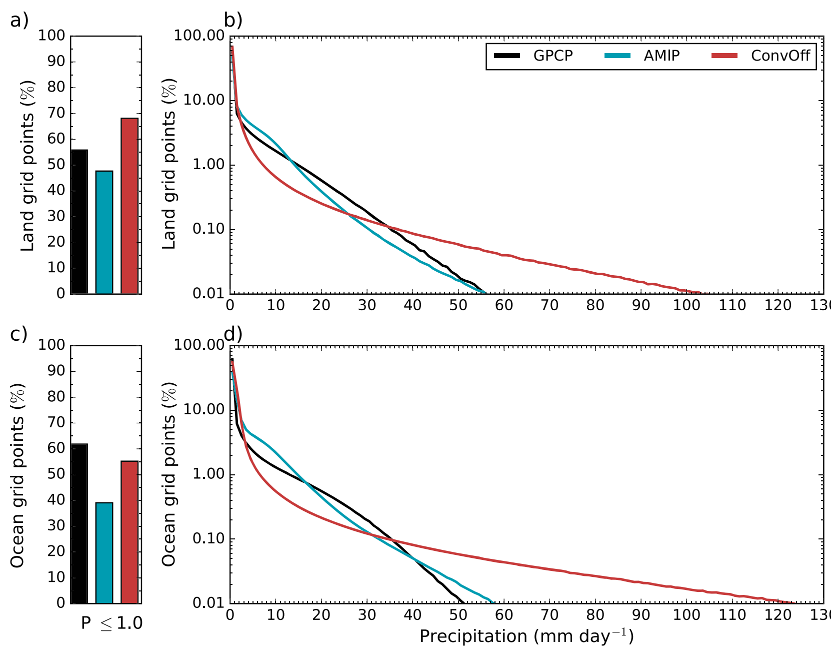

Figure 2. Daily tropical (15°S–15°N) precipitation for (a and b) land and (c and d) ocean grid points. Bar plots in Figures 2a and 2c are the number of grid points with precipitation less than 1 mm/day (i.e., nonprecipitating). Histograms in Figures 2b and 2d are daily precipitation rates from 1 to 130 mm/day with a bin width of 1 mm/day. The percentage of grid points in Figures 2b and 2d terminates at 0.01%, which for a common 2.5° × 2.5° grid is 1,443 tropical ocean points and 429 tropical land points per time step correspond to 300–500 points over land and 1000–1600 over ocean (ranging from 20 to 30 years). The plot includes all available daily data (4 of the 10 models). The multimodel mean is the average of each models histogram computed on the common grid. AMIP = Atmospheric Model Intercomparison Project; GPCP = Global Precipitation Combined Precipitation.

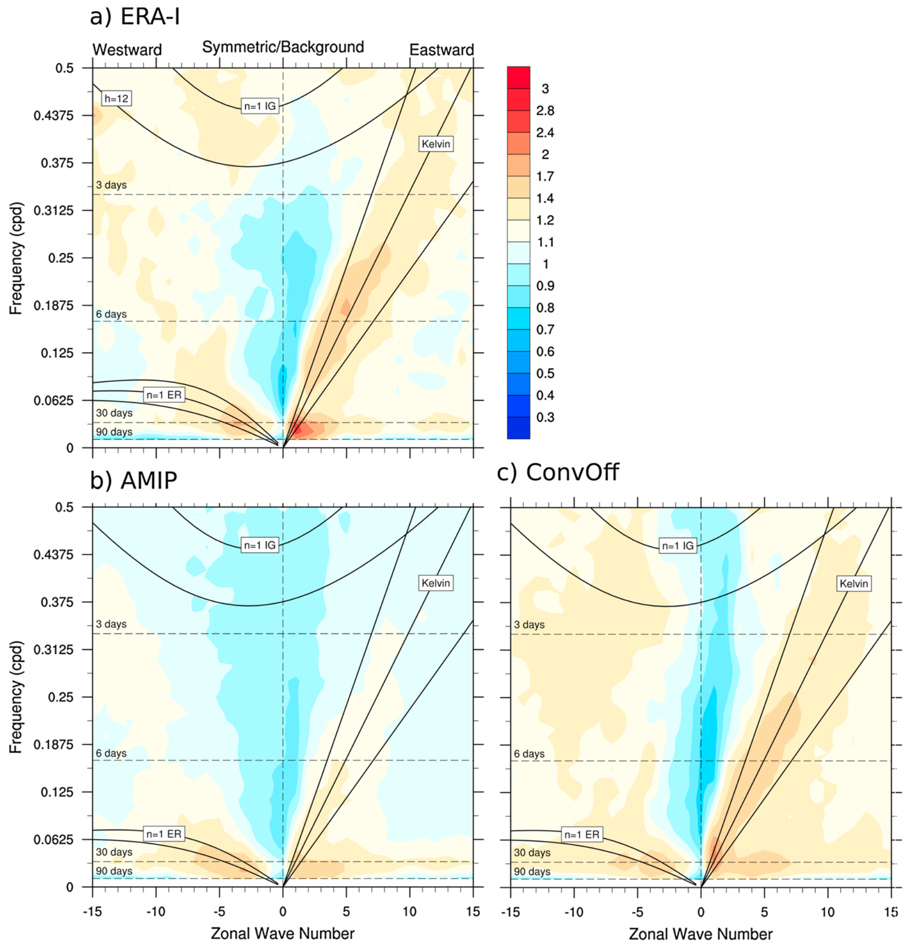

Figure 3. Wheeler and Kiladis (1999) diagrams for (a) ERA-Interim (1979–2015) (b) AMIP (1979–2008), and (c) ConvOff (1979–2008) using daily outgoing longwave radiation. The plot includes all available model daily data (4 out of the 10 models). The wave-frequency spectra were computed for each model on its native grid, and the resulting wave-frequency values were averaged for the multimodel mean plotted. AMIP = Atmospheric Model Intercomparison Project.

precipitation. In the Northern Hemisphere eastern Pacific there is a poleward shift in the ITCZ in ConvOff. Over tropical land there is reduced precipitation that does not occur in AMIP.

Without a convection scheme each models precipitation response is similar in spatial structure (supporting information Figure S10), and in each case AMIP is closer to GPCP than ConvOff, with errors quantified in a Taylor diagram (supporting information Figure S3). There is some evidence to suggest that higher-resolution models have smaller differences between AMIP and ConvOff precipitation, which have lower root-mean-square errors; however, the sample size (number of models) is too small to draw any quantitative conclusions (supporting information Figure S2). There is no evidence to suggest that AMIP models have a dependence on resolution for the ratio of convective to large-scale precipitation.

Known CMIP5 precipitation biases also persist in ConvOff. These include deficient precipitation over the Amazon region, India and its surrounding oceans, southern Africa, and South China Sea. The double ITCZ bias also persists and appears somewhat worse with a broader South Pacific convergence zone and more precipitation. However, the double ITCZ bias, as measured by the southern ITCZ bias metric of Bellucci et al. (2010), is very similar for the multimodel mean AMIP and ConvOff runs (supporting information Figure S4). Some models have an improved double ITCZ bias and some worsen with individual models having similar magnitude biases to coupled CMIP3–CMIP5 models (Tian, 2015, see their Figure 1b). The multimodel mean width of the ITCZ is narrower in ConvOff (14°) compared to AMIP (17°). The ITCZ is expected to narrow with global warming, and so understanding the sensitivity of the width is important. In this study, the model agreement on the size

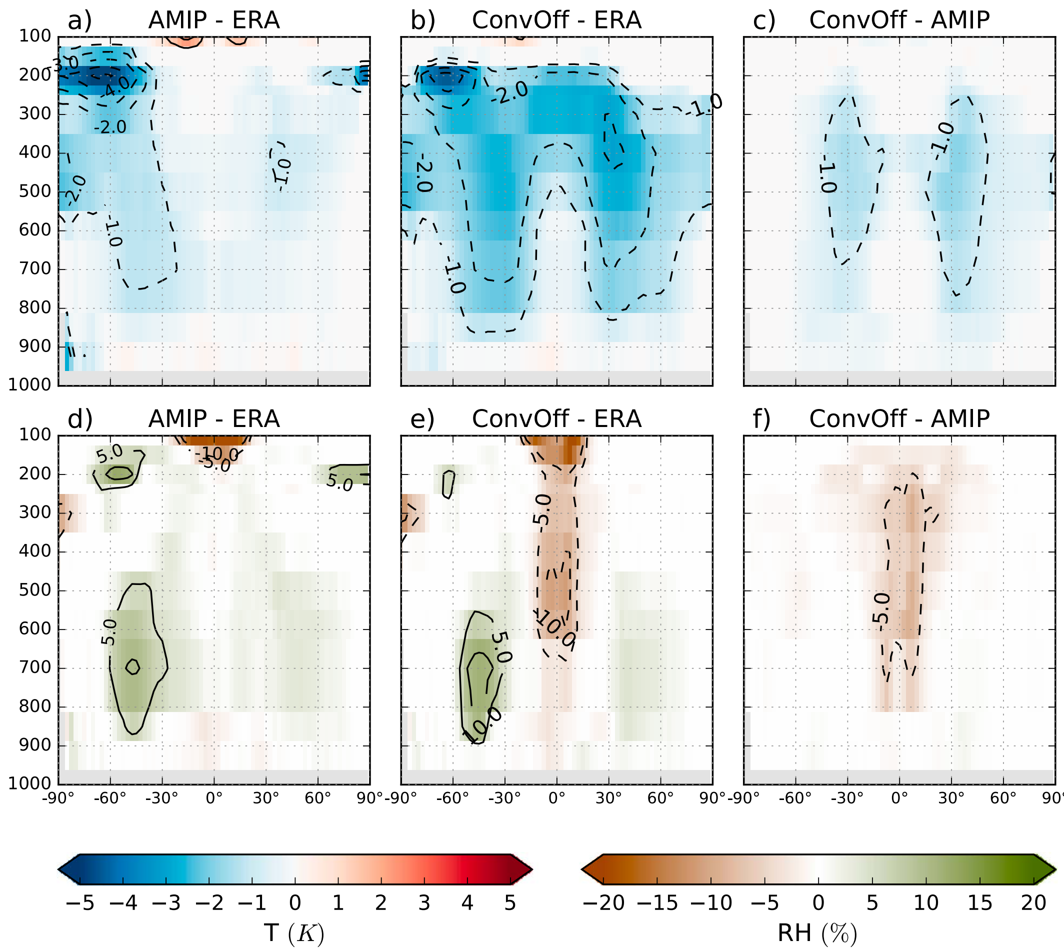

Figure 4. Temperature differences between the multimodel mean of (a) AMIP and (b) ConvOff with ERA-Interim, and (c) their differences. Likewise, relative humidity differences in Figures 4d–4f. Gray contouring masks orography. Contour lines are a guide for magnitude only. Differences are only plotted when 90% or more of the models agree on the sign of the multimodel mean difference and are statistically significant with a two-tailed 95% significance level ($\pm 2\sigma$), where σ is the internal variability of the multimodel mean. Points that are not significant are set to zero. Each subplot has a common interpolated grid. AMIP = Atmospheric Model Intercomparison Project.

and sign of the change is limited and it is unclear what impact running models without parameterized convection has on the width of the ITCZ.

Daily precipitation histograms in Figure 2 reveal larger differences between ConvOff and AMIP than seen in climatologies (supporting information Figure S6). Over land GPCP has 55% of its grid cells without precipitation, defined as $P \leq 1.0$ mm/day, fewer in AMIP (50%) and more in ConvOff (70%). Over the ocean GPCP has 60% of its grid cells without precipitation, less for AMIP (40%) and ConvOff (55%). There are more nonprecipitating grid cells in ConvOff than AMIP, too many dry land grid cells compared to GPCP but an improvement in dry ocean grid cells that are known to produce too much drizzle (Stephens et al., 2010). The distribution of precipitating grid cells, over land (Figure 2b) and ocean (Figure 2d), highlights that there are fewer ConvOff grid cells with light-to-medium rain rates and more grid cells with extreme precipitation, that is, biases that are worse in ConvOff than in AMIP, compared to GPCP. The extreme rain rates in ConvOff are almost twice as large as GPCP and AMIP and somewhat worse over the ocean.

The more intense precipitation and increased number of nonprecipitating grid cells in ConvOff can also be seen in daily snapshots of precipitation (supporting information Figure S7). Daily snapshots also indicate that precipitation is more organized and intensely clustered into grid cell storms, while AMIP is more uniform, consistent with Becker et al. (2017) who show more aggregation in a GCM without parameterized convection in radiative-convective equilibrium. The increased organization in ConvOff is also present in the multimodel mean wave-frequency plots in Figure 3 (supporting information Figures S15 and S16). ConvOff actually has more realistic Kelvin wave power spectra than AMIP. This enhancement in the Kelvin waves occurs in each of the four models, specially for lower wave numbers in the model from the Institute Pier Simon Laplace (IPSL). Only minor differences occur in the equatorial Rossby wave response and, perhaps surprisingly, in the Madden-Julian Oscillation (MJO) region. There is some evidence to suggest that the IPSL model has improved variability at MJO wave numbers but closer investigation is required to determine if the signal is MJO like.

Differences in ConvOff temperature and moisture response compared to AMIP are shown in Figure 4 (also supporting information Figures S9 and S11–S14). As expected with prescribed SST model runs, the near-surface temperature and moisture differences are small (Figure 4). Farther aloft, AMIP and ConvOff are both cooler than ERA-Interim, especially in the Southern Hemisphere polar region. In the middle and upper subtropical troposphere, ConvOff is cooler than AMIP (Figure 4c). Tropical cooling also occurs in the middle and upper troposphere; however, the response is not robust between models, see supporting information Figure S14, hence the temperature response appears as two subtropical lobes.

Without parameterized convection the middle and upper tropical troposphere are drier (Figure 4f). In the Southern Hemisphere storm tracks AMIP and ConvOff multimodel means are moister compared to ERA-Interim, less so in the Northern Hemisphere. The AMIP moist Southern Hemisphere storm track bias and Southern Hemisphere polar stratospheric cool bias, compared to ERA-Interim, are broadly consistent with those shown in coupled ocean-atmosphere multimodel means for CMIP3 (John & Soden, 2007, see their Figure 1 rows 1 and 2) and CMIP5 (Tian et al., 2013, see their Figures 2–5).

4. Discussion

Running a GCM without parameterized convection is a fairly extreme perturbation, given that most rainfall occurs in convective clouds that are far from being resolved in GCMs. Convection must occur irrespective of whether there is a convection scheme as latent heating is needed to balance radiative cooling.

Without parameterized convection, excessive ocean and deficient land precipitation biases occur. We interpret this response to changes in Convective Available Potential Energy (CAPE). Over land in the afternoon there is a rapid increase in CAPE that can be more easily consumed by a convection scheme than resolved convection, hence more AMIP land precipitation and presumably less over the ocean in order for moisture conservation in the model. In terms of moisture conservation, the global precipitation amount does not depend on the convection scheme as differences in the atmospheric temperature, humidity, and total cloud cover do not appear to be large enough to strongly affect global mean net radiative cooling of the atmosphere. There are statistically significant differences in climatological precipitation in runs with and without convection schemes; however, the magnitude and spatial coverage of these differences are smaller than perhaps expected. Furthermore, AMIP biases compared to GPCP are much larger and cover a greater area than the differences between AMIP and ConvOff.

We suspect a key difference between AMIP and ConvOff is how unstable the atmosphere needs to be in order to drive the convection required to transport heat and moisture in the vertical. By design, parameterized convection initiates before grid-scale saturation occurs. Without parameterized convection, the explicitly resolved motions require more convective instability to drive the convective overturning. In order to increase the overturning the atmosphere must presumably be more unstable, hence the lapse rate must increase. This instability could originate from either surface warming (unlikely for prescribed SST runs) or cooling of the troposphere. Indeed, ConvOff is cooler than AMIP but perhaps surprisingly the difference in temperature is small and ConvOff is not that much more unstable than AMIP. We do not believe the turbulence schemes alone could explain the cooling response as they do not normally transport a significant amount of heat except near unstable temperature profiles.

Net moistening might have been expected in ConvOff, compared to AMIP, as convection is harder to initiate. However, we find net drying in ConvOff and offer two interpretations. First, AMIP models can produce shallow convection that has a lower precipitation efficiency and moistens the midlevels, whereas explicitly simulated convection at such coarse resolution is mostly deep convection hence has very high precipitation efficiency. Second, convection is more organized in ConvOff, and more organized convection results in a drier domain (Tobin et al., 2013).

An AMIP Southern Hemisphere storm track moist bias occurs in the midlower troposphere. This moist bias has previously been identified in coupled CMIP5 models (Tian et al., 2013, see their Figures 3 and 5) and occurs in a region with known cloud biases (Grise & Polvani, 2014, see references therein). We believe ours is the first study to report this moist bias in AMIP models, indicating the bias arises from the atmospheric models rather than ocean temperature errors in coupled models. The bias may be a consequence of cloud and microphysics schemes (McCoy et al., 2016), their coupling to large-scale circulation or boundary layer schemes. Bodas-Salcedo et al. (2014) have shown that in atmosphere-only GCMs the Southern Hemisphere midlevel clouds are missing in the storm track region. Their absence removes a fundamental condensation process that could result in a moist bias; however, further work is needed to test this idea.

The double ITCZ is a well-known model bias (Zhang et al., 2015) that persists without parameterized convection. Interestingly, the ConvOff multimodel mean is not qualitatively different to AMIP, suggesting that convective schemes are not likely the root cause of the bias. The intermodel response of the double ITCZ is broad (supporting information Figure S4); some models show a large response and others small. Previous studies have shown that convection schemes play a key role in forming the double ITCZ in aquaplanets (Möbis & Stevens, 2012) and coupled models (Song & Zhang, 2009). Our results are not inconsistent with such studies, rather our conclusions differ in that the net impact of the convection schemes in the multimodel mean is smaller than the response in individual models.

A second deficiency of GCMs is the representation of convective organisation, of which self aggregation and the MJO are prime examples. Becker et al. (2017) found that a GCM, in radiative-convective equilibrium, has more aggregation without parameterized convection. Furthermore, a difference in the MJO might have been expected in ConvOff as the MJO accuracy in GCMs is hindered by convection parameterizations (Ajayamohan et al., 2013). Furthermore, it has previously been found by Boyle et al. (2015), amongst others, that suppressing convection schemes improves the MJO when the entrainment rate was increased. However, in this study we find no robust change in the MJO.

Unlike the MJO, we find Kelvin waves are more realistic without convective parameterizations. Convection schemes affect the generation of convectively coupled waves, and so it is not surprising that the wave spectra are different in runs with and without parameterized convection. Fully coupled GCMs in general have less wave activity than are seen in observations; however, the source of the reduced wave activity is difficult to isolate (Kiladis et al., 2009). Reduced wave activity in GCMs has previously been linked to convective parameterizations, specifically the moisture sensitivity of trigger functions, and to the treatment of stratiform precipitation that result in errors in the heating profiles (Kiladis et al., 2009). The improved wave response in ConvOff may be the results of increased instability, where gravity waves are more easily generated in regions with more stratification, or it may be that parameterized convection suppresses gravity wave generation. Further work is needed to isolate why Kelvin waves are more realistic without parameterized convection.

A limitation of SPOOKIE is the use of prescribed SSTs. However, prescribed SSTs are necessary to prevent the untuned ConvOff climatology from drifting too far away from AMIP and observations. Such a drift would prevent an intercomparison such as this, as it would be almost impossible to interpret the direct impact of the convection schemes. A further limitation is only using one observational and one reanalysis product; however, we believe this is justified as we are primarily focused on the impact of convective schemes on models rather than model evaluation per se. A final limitation is in using daily precipitation data, as exact comparison of modeled and observed short-term statistics is challenging because of the sampling characteristics of observing systems (e.g., Stephens et al., 2010), but it appears unlikely that observational uncertainties are as large as the impact of convective schemes.

5. Conclusions

Webb et al. (2015) have previously shown that convection schemes do not contribute to the spread in cloud feedbacks. We build on their study by showing that parameterized convection does not strongly impact climatological precipitation, temperature, or relative humidity. This contradicts a common expectation that parameterized convection is required for realistic mean-state climatologies, given realistic SSTs. However, there are some interesting differences — excessive ocean precipitation biases, deficient land precipitation, a robust 1 K cooling in the subtropical middle-upper levels, and a robust 5% drying of the equatorial middle-upper levels — in runs with and without parameterized convection.

At daily time scales the absence of convection parameterizations has a clearer impact where storms are more intense and organized into clustered grid cells. Without the convection schemes the most intense tropical storms have daily rainfall rates almost double observations and AMIP. The convection schemes thus constrain unrealistically large precipitation extremes. Without convection schemes, there is an improvement in the number of nonprecipitating grid cells over the ocean, but this comes at the expense of too many nonprecipitating grid cells over land and too fewer light-to-medium rain rates. Excessive light rainfall rates are well-known model bias in comprehensive models. Another well-known model bias is inhibited organization due to overactive convection schemes, as opposed to suppressed schemes that are harder to initiate. We show that the Kelvin wave power spectra are more realistic without parameterized convection, although no change is found in the MJO.

We find that a number of known GCM biases persist without parameterized convection. Persistent precipitation biases include the double ITCZ, excessive precipitation over the ocean, and deficient precipitation over land. These biases are a little worse without parameterized convection over the ocean but considerably worse over land. Hence, convective parameterizations are reducing biases but not substantially. A large AMIP moist bias is identified, present with and without parameterized convection, over the Southern Hemisphere storm tracks. We suspect this is linked to known cloud biases in the region.

The persistence of modeled precipitation biases without parameterized convection suggests they originate from processes other than convection or that convection schemes are missing key processes and their absence is preventing the schemes from fully ameliorating the biases. Candidate processes include upscale convective momentum transport, convective organization, convective memory, sensitivity to tropospheric humidity, or missing feedbacks.

Our results show that model climatologies are relatively insensitive to convective parameterization for prescribed SST runs. If convection parameterizations are not, to first order, controlling the intensity and spatial distribution of climatological precipitation then what is? Furthermore, if known precipitation biases persist without convective parameterizations, then where are they generated? We believe these questions warrant further investigation, as well as the deficient land precipitation bias and moist AMIP bias in the Southern Hemisphere storm tracks. These could be addressed in a follow-up mechanism-denial-type study where other key processes are deactivated.

Some of the results presented in this study might have been anticipated by model developers. However, the broader community may well be surprised that model climatologies are so similar with and without convective parameterizations. In this study we are not advocating abandoning convection parameterization, rather we were motivated to understand what impact convection schemes have on precipitation and if their impact is as large as commonly expected. The results of this study are important for attributing biases in fully coupled climate models to model physics, testing long standing expectations about the role of convection schemes, and in understanding what impact convection schemes have on model climatologies.

Acknowledgments
P. M., G. K. V., and P. G. S. are funded by the Natural Environment Research Council and Met Office as part of the EuroClim project (grant NE/M006123/1), ParaCon project (grant NE/N013123/1), and the Royal Society (Wolfson Foundation). M. J. W. is supported by the Joint UK BEIS/Defra Met Office Hadley Centre Climate ProgrammeGA01101. S. C. S. acknowledges the Australian Research Council (grant FL150100035). GPCP courtesy of NOAA and ERA-Interim courtesy of ECMWF. We thank the climate modeling groups for producing model output and its storage at the German Climate Research Centre DKRZ (Deutsches Klimarechenzentrum) and Centre for Environmental Data Analysis (CEDA). SPOOKIE data are stored at DKRZ (https://cera-www.dkrz.de), with the exception of IPSL found on the Earth system grid (e.g., search for convoffamip https://esgf-data.dkrz.de). Thanks to John Thuburn, Michael Whittall, Kerry Emanuel, and others at the Future of Cumulus Parameterization workshop in Delft July 2017 for helpful discussions. We thank the reviewers, especially Hideaki Kawai for his supportive and constructive review.

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