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 the schemes.

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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 (SPOOKIE) 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 restraining extreme daily precipitation that otherwise develops. Systematic effects on lapse rate and humidity are likewise modest compared with the inter-model 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.

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*, 1993]. 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 which previously caused the model to quickly deteriorate [*Manabe et al.*, 1965, see references within] 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 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 organised 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 inter-model spread in cloud feedbacks, which is known to be important for model equilibrium climate sensitivity. *Webb et al.*

[2015] found the range of cloud feedbacks were similar with and without parameterized convection suggesting that the convective parameterizations are not a leading-order source of inter-model 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 modelling centers on what biases are a direct result of the convection schemes.

2 Methods and Data

SPOOKIE consists of ten global atmospheric models, identical to the standard 'AMIP' configuration except without parameterized convection, herein 'ConvOff', [*von Salzen et al.*, 2013; *Neale et al.*, 2012; *Voldoire et al.*, 2013; *Anderson et al.*, 2004; *Zhao et al.*, 2009; *Martin et al.*, 2011; *Dufresne et al.*, 2013; *Watanabe et al.*, 2010; *Giorgetta et al.*, 2012; *Yukimoto et al.*, 2012]. See supplementary Table 1 for models, resolutions, and time periods. See acknowledgement 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 $+4K$ 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 is only available for four out of the ten models. A cross-validation approach was used to check for outlier models that could strongly influence the multi-model mean precipitation; see supplementary Fig. 1. No outlier models were found and all models are included in the multi-model means.

Modelled 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 supplementary for details.

The Southern ITCZ bias metric [*Bellucci et al.*, 2010] is used to measure the double ITCZ, defined as the climatological precipitation model minus observations in the $20°S{-}0S°$ and $210°{-}260°$ domain. The edge of the ITCZ is measured using the moisture ITCZ definition [*Byrne and Schneider*, 2016] where the edge is defined as the latitude where evaporation dominates over precipitation.

3 Results

Climatological precipitation for GPCP and the multi-model means of AMIP and ConvOff are shown in Fig. 1a-c, together with their differences in Fig. 1d-f. 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 (Fig. 1d). These AMIP biases are also present in the CMIP5 coupled models in the 2013 IPCC report [*Flato et al.*, 2014, see their Fig. 9.4b], hence the biases originate from the atmospheric models, noting that they include about fifty 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 (Fig. 1e). In addition to amplifying the excessive precipitation over the Indian and western Pacific Oceans, ConvOff has 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 (supplementary Fig. 5).

The most striking similarities occur between AMIP and ConvOff in Fig. 1f (see also supplementary Fig. 8 and Fig. 10). The multi-model 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 precipitation. In the Northern Hemisphere eastern Pacific there is a poleward shift in the ITCZ in ConvOff. Over tropical land there is reduced precipitation which does not occur in AMIP.

Without a convection scheme each models precipitation response is similar in spatial structure (supplementary Fig. 10) and in each case AMIP is closer to GPCP than ConvOff, with errors quantified in a Taylor diagram (supplementary Fig. 3). 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 (supplementary Fig. 2). 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 ocean, 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 multi-model mean AMIP and ConvOff runs (supplementary Fig. 4). Some models have an improved double ITCZ bias and some worsen with individual models having similar magnitude biases to coupled CMIP3-5 models [*Tian*, 2015, see their Fig. 1b]. The multi-model 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 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 Fig. 2 reveal larger differences between ConvOff and AMIP than seen in climatologies (supplementary Fig. 6). Over land GPCP has 55% of its grid cells without precipitation, defined as $P \leq 1.0$ mm day^{-1}, 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 non-precipitating grid cells in ConvOff than AMIP, too many dry land grid cells compared to GPCP but an improvement in dry ocean grid cells which are known to produce too much drizzle [*Stephens et al.*, 2010]. The distribution of precipitating grid cells, over land Fig. 2b) and ocean Fig. 2d), highlights that there are fewer ConvOff grid cells with light-to-medium rain rates and more grid cells with extreme precipitation, i.e., 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 non-precipitating grid cells in ConvOff can also be seen in daily snapshots of precipitation (supplementary Fig. 7). Daily snapshots also indicate that precipitation is more organised 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 organisation in ConvOff is also present in the multi-model mean wave-frequency plots in Fig. 3 (supplementary Fig. 15-16). ConvOff actually has a more realistic Kelvin wave power spectra than AMIP. This enhancement in the Kelvin waves occurs in each of the four models, especially in IPSL for lower wave numbers. Only minor differences occur in the equatorial Rossby wave response and, perhaps surprisingly, in the MJO region. There is some evidence to suggest that the IPSL model has improved variability at MJO wave numbers but closer investigate is required to determine if the signal is MJO-like.

Differences in ConvOff temperature and moisture response compared to AMIP are shown in Fig. 4 (also supplementary Fig. 9, 11-14). As expected with fixed-SST model runs, the near-surface temperature and moisture differences are small (Fig. 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 (Fig. 4c). Tropical cooling also occurs in the middle and upper troposphere, however the response is not robust between models, see supplementary Fig. 14, hence the temperature response appears as two subtropical lobes.

Without parameterized convection the middle and upper tropical troposphere are drier (Fig. 4f). In the Southern Hemisphere storm tracks AMIP and ConvOff multi-model means are moister in, 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 multi-model means for CMIP3 [*John and Soden*, 2007, see their Fig. 1 rows 1-2] and CMIP5 [*Tian et al.*, 2013, see their Fig. 2-5].

4 Discussion

Running a global climate model without parameterized convection is a fairly extreme perturbation, given that most rainfall occurs in convective clouds which 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 occurs. We interpret this response to changes in Convective Available Potential Energy (CAPE). Over land in the afternoon there is a rapid increase in CAPE which 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 a 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 fixed 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 which has a lower precipitation efficiency and moistens the mid-levels, 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 mid-lower troposphere. This moist bias has previously been identified in coupled CMIP5 models [*Tian et al.*, 2013, see their Fig. 3 and 5] and occurs in a region with known cloud biases [*Grise and Polvani*, 2014, see reference within]. 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] has shown that in atmosphere-only GCMs the Southern Hemisphere mid-level clouds are missing in the storm track region. Their absence removes a fundamental condensation process which 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 multi-model mean is not qualitatively different to AMIP suggesting that convective schemes are not likely the root cause of the bias. The inter-model response of the double ITCZ is broad (supplementary Fig. 4), 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 and Stevens*, 2012] and coupled models [*Song and 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 multi-model mean is smaller than the response in individual models.

A second deficiency of GCMs is represent convective organization, 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 improvement in the MJO.

Unlike the MJO, we find Kelvin waves are more realistic without convective parameterizations. Convection schemes affect the generation of convective coupled waves and so it is not surprising that the wave spectra is different in runs with and without parameterized convection. Fully coupled GCMs in general have less wave activity than is 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 the use of fixed SSTs. However, fixed 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] has 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 sea-surface temperatures. However, there are some interesting differences in runs with and without parameterized convection. Specifically, excessive ocean precipitation biases, deficient land precipitation, a robust 1K cooling in the subtropical mid-upper levels and a robust 5% drying of the equatorial mid-upper levels.

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 rate rates almost double observations and AMIP. The convection schemes thus constrain unrealistically large precipitation extremes. There is an improvement in the number of non-precipitating grid-cells over the ocean but this comes at the expense of too many non-precipitating grid cells over land and too fewer light-to-medium rain rates. Excessive light rainfall rates is a well known model bias in comprehensive. Another well known model bias is inhibited organization due to over-active convection schemes, as opposed to suppressed schemes which are harder to initiate. We show that the Kelvin wave power spectra is improved 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 modelled 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 fixed-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.

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References

Adler, R. F., G. J. Huffman, A. Chang, R. Ferraro, P.-P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin (2003), The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present), *Journal of Hydrometeorology*, *4*(6), 1147–1167.

Ajayamohan, R. S., B. Khouider, and A. J. Majda (2013), Realistic initiation and dynamics of the Madden-Julian Oscillation in a coarse resolution aquaplanet GCM, *Geophysical Research Letters*, *40*(23), 6252–6257, doi:10.1002/2013GL058187.

Anderson, J. L., et al. (2004), The New GFDL Global Atmosphere and Land Model AM2-LM2: Evaluation with Prescribed SST Simulations, *Journal of Climate*, *17*(24), 4641–4673, doi:10.1175/JCLI-3223.1.

Becker, T., B. Stevens, and C. Hohenegger (2017), Imprint of the convective parameterization and sea-surface temperature on large-scale convective self-aggregation, *Journal of Advances in Modeling Earth Systems*, doi:10.1002/2016MS000865.

Bellucci, A., S. Gualdi, and A. Navarra (2010), The Double-ITCZ Syndrome in Coupled General Circulation Models: The Role of Large-Scale Vertical Circulation Regimes, *Journal of Climate*, *23*(5), 1127–1145, doi:10.1175/2009JCLI3002.1.

Bodas-Salcedo, A., K. D. Williams, M. A. Ringer, I. Beau, J. N. S. Cole, J.-L. Dufresne, T. Koshiro, B. Stevens, Z. Wang, and T. Yokohata (2014), Origins of the Solar Radiation Biases over the Southern Ocean in CFMIP2 Models, *Journal of Climate*, *27*(1), 41–56, doi:10.1175/JCLI-D-13-00169.1.

Boyle, J. S., S. A. Klein, D. D. Lucas, H.-Y. Ma, J. Tannahill, and S. Xie (2015), The parametric sensitivity of CAM5's MJO, *Journal of Geophysical Research: Atmospheres*, *120*(4), 1424–1444, doi:10.1002/2014JD022507, 2014JD022507.

Byrne, M. P., and T. Schneider (2016), Energetic Constraints on the Width of the Intertropical Convergence Zone, *Journal of Climate*, *29*(13), 4709–4721, doi:10.1175/JCLI-D-15-0767.1.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thépaut, and F. Vitart (2011), The ERA-

Interim reanalysis: configuration and performance of the data assimilation system, *Q.J.R. Meteorol. Soc.*, *137*(656), 553–597.

Dufresne, J.-L., et al. (2013), Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, *Climate Dynamics*, *40*(9), 2123–2165, doi: 10.1007/s00382-012-1636-1.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S. C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, P. G. C. Fores and, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and M. Rummukainen (2014), *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Chapter 9, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Frierson, D. M. W. (2007), The Dynamics of Idealized Convection Schemes and Their Effect on the Zonally Averaged Tropical Circulation, *J. Atmos. Sci.*, *64*(6), 1959–1976.

Giorgetta, M. A., et al. (2012), The atmospheric general circulation model ECHAM6 - Model description.

Grise, K. M., and L. M. Polvani (2014), Southern Hemisphere Cloud-Dynamics Biases in CMIP5 Models and Their Implications for Climate Projections, *J. Climate*, *27*(15), 6074–6092, doi:10.1175/JCLI-D-14-00113.1.

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind (2001), Global Precipitation at One-Degree Daily Resolution from Multisatellite Observations, *Journal of Hydrometeorology*, *2*(1), 36–50.

John, V. O., and B. J. Soden (2007), Temperature and humidity biases in global climate models and their impact on climate feedbacks, *Geophysical Research Letters*, *34*(18), n/a–n/a, doi:10.1029/2007GL030429, l18704.

Kasahara, A. (1993), *General Circulation Model Development*, *International Geophysics Series*, vol. 70, chap. Chapter 7: On the Origins of Cumulus Parameterization for Numerical Prediction Models., pp. 199–224, Academic Press.

Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy (2009), Convectively coupled equatorial waves, *Rev. Geophys.*, *47*(2), RG2003–.

Lin, J.-L., M.-I. Lee, D. Kim, I.-S. Kang, and D. M. W. Frierson (2008), The Impacts of Convective Parameterization and Moisture Triggering on AGCM-Simulated Convectively Coupled Equatorial Waves, *J. Climate*, *21*(5), 883–909, doi: 10.1175/2007JCLI1790.1.

Manabe, S., J. Smagorinsky, and R. Strickler (1965), SIMULATED CLIMATOLOGY OF A GENERAL CIRCULATION MODEL WITH A HYDROLOGIC CYCLE, *Monthly Weather Review*, *93*(12), 769–798.

Martin, G. M., et al. (2011), The HadGEM2 family of Met Office Unified Model climate configurations, *Geoscientific Model Development*, *4*(3), 723–757, doi:10.5194/gmd-4-723-2011.

McCoy, D. T., I. Tan, D. L. Hartmann, M. D. Zelinka, and T. Storelvmo (2016), On the relationships among cloud cover, mixed-phase partitioning, and planetary albedo in GCMs, *Journal of Advances in Modeling Earth Systems*, *8*(2), 650–668, doi:10.1002/2015MS000589.

Mechoso, C., A. Robertson, N. Barth, M. Davey, P. Delecluse, P. Gent, S. Ineson, B. Kirtman, M. Latif, H. L. Treut, T. Nagai, J. Neelin, S. Philander, J. Polcher, P. Schopf, T. Stockdale, M. Suarez, L. Terray, O. Thual, and J. Tribbia (1995), The Seasonal Cycle over the Tropical Pacific in Coupled Ocean-Atmosphere General Circulation Models, *Monthly Weather Review*, *123*(9), 2825–2838.

Möbis, B., and B. Stevens (2012), Factors controlling the position of the Intertropical Convergence Zone on an aquaplanet, *Journal of Advances in Modeling Earth Systems*, *4*(4), n/a–n/a, doi:10.1029/2012MS000199, m00A04.

Neale, R., et al. (2012), Description of the NCAR community atmosphere model (CAM5)., *Tech. rep.*, Boulder, CO: NCAR., technical report no. NCAR/TN-486+STR.

Simmons, A. J., A. Untch, C. Jakob, P. Kallberg, and P. Undn (1999), Stratospheric water vapour and tropical tropopause temperatures in Ecmwf analyses and multi-year simulations, *Quarterly Journal of the Royal Meteorological Society*, *125*(553), 353–386, doi:10.1002/qj.49712555318.

Siongco, A. C., C. Hohenegger, and B. Stevens (2017), Sensitivity of the summertime tropical Atlantic precipitation distribution to convective parameterization and model resolution in ECHAM6, *Journal of Geophysical Research: Atmospheres*, *122*(5), 2579–2594, doi:10.1002/2016JD026093, 2016JD026093.

Song, X., and G. J. Zhang (2009), Convection Parameterization, Tropical Pacific Double ITCZ, and Upper-Ocean Biases in the NCAR CCSM3. Part I: Climatology and Atmospheric Feedback, *Journal of Climate*, *22*(16), 4299–4315, doi:10.1175/2009JCLI2642.1.

Stephens, G. L., T. L'Ecuyer, R. Forbes, A. Gettlemen, J.-C. Golaz, A. Bodas-Salcedo, K. Suzuki, P. Gabriel, and J. Haynes (2010), Dreary state of precipitation in global models, *J. Geophys. Res.*, *115*(D24), D24,211.

Tian, B. (2015), Spread of model climate sensitivity linked to double-Intertropical Convergence Zone bias, *Geophysical Research Letters*, *42*(10), 4133–4141, doi: 10.1002/2015GL064119, 2015GL064119.

Tian, B., E. J. Fetzer, B. H. Kahn, J. Teixeira, E. Manning, and T. Hearty (2013), Evaluating CMIP5 models using AIRS tropospheric air temperature and specific humidity climatology, *Journal of Geophysical Research: Atmospheres*, *118*(1), 114–134, doi: 10.1029/2012JD018607.

Tobin, I., S. Bony, C. E. Holloway, J.-Y. Grandpeix, G. Sze, D. Coppin, S. J. Woolnough, and R. Roca (2013), Does convective aggregation need to be represented in cumulus parameterizations?, *Journal of Advances in Modeling Earth Systems*, *5*(4), 692–703, doi:10.1002/jame.20047.

Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S. Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D. Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, and F. Chauvin (2013), The CNRM-CM5.1 global climate model: description and basic evaluation, *Climate Dynamics*, *40*(9), 2091–2121, doi:10.1007/s00382-011-1259-y.

von Salzen, K., J. F. Scinocca, N. A. McFarlane, J. Li, J. N. S. Cole, D. Plummer, D. Verseghy, M. C. Reader, X. Ma, M. Lazare, and L. Solheim (2013), The Canadian Fourth Generation Atmospheric Global Climate Model (CanAM4). Part I: Representation of Physical Processes, *Atmosphere-Ocean*, *51*(1), 104–125, doi: 10.1080/07055900.2012.755610.

Watanabe, M., T. Suzuki, R. O'ishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, M. Sekiguchi, K. Takata, D. Yamazaki, T. Yokohata, T. Nozawa, H. Hasumi, H. Tatebe, and M. Kimoto (2010), Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity, *Journal of Climate*, *23*(23), 6312–6335, doi:10.1175/2010JCLI3679.1.

Webb, M. J., A. P. Lock, C. S. Bretherton, S. Bony, J. N. S. Cole, A. Idelkadi, S. M. Kang, T. Koshiro, H. Kawai, T. Ogura, R. Roehrig, Y. Shin, T. Mauritsen, S. C. Sherwood, J. Vial, M. Watanabe, M. D. Woelfle, and M. Zhao (2015), The impact of parametrized convection on cloud feedback, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, *373*(2054), doi:10.1098/rsta.2014.0414.

Wheeler, M., and G. N. Kiladis (1999), Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber-Frequency Domain, *J. Atmos. Sci.*, *56*(3), 374–399, doi:10.1175/1520-0469(1999)056¡0374:CCEWAO¿2.0.CO;2.

Yukimoto, S., Y. Adachi, M. Hosaka, T. Sakami, H. Yoshimura, M. Hirabara, T. Y. Tanaka, E. Shindo, H. Tsujino, M. Deushi, R. Mizuta, S. Yabu, A. Obata, H. Nakano, T. Koshiro, T. Ose, and A. Kitoh (2012), A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3;Model Description and Basic Performance, *Journal of the Meteorological Society of Japan. Ser. II*, *90A*, 23–64, doi:10.2151/jmsj.2012-A02.

Zhang, X., H. Liu, and M. Zhang (2015), Double ITCZ in Coupled Ocean-Atmosphere Models: From CMIP3 to CMIP5, *Geophysical Research Letters*, *42*(20), 8651–8659, doi:10.1002/2015GL065973, 2015GL065973.

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi (2009), Simulations of Global Hurricane Climatology, Interannual Variability, and Response to Global Warming Using a 50-km Resolution GCM, *Journal of Climate*, *22*(24), 6653–6678, doi:10.1175/2009JCLI3049.1.

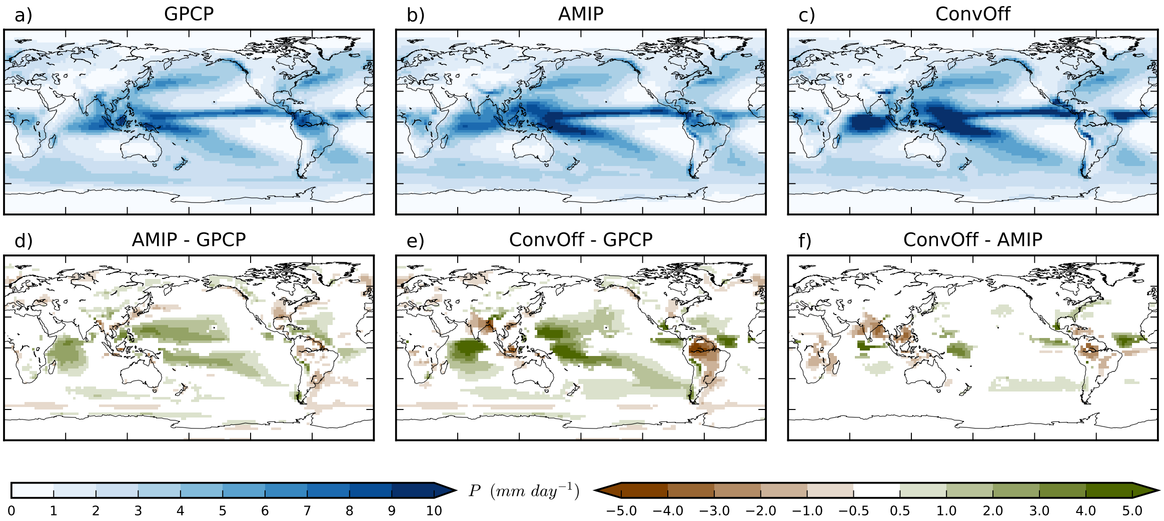

Figure 1. Average precipitation for a) GPCP, the multi-model means of b) AMIP and c) ConvOff. Difference in GPCP with the multi-model means of d) AMIP and e) ConvOff and f) their differences. All plots have the same common resolution of $2.5° \times 2.5°$. In d-f) differences are only plotted when 90%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

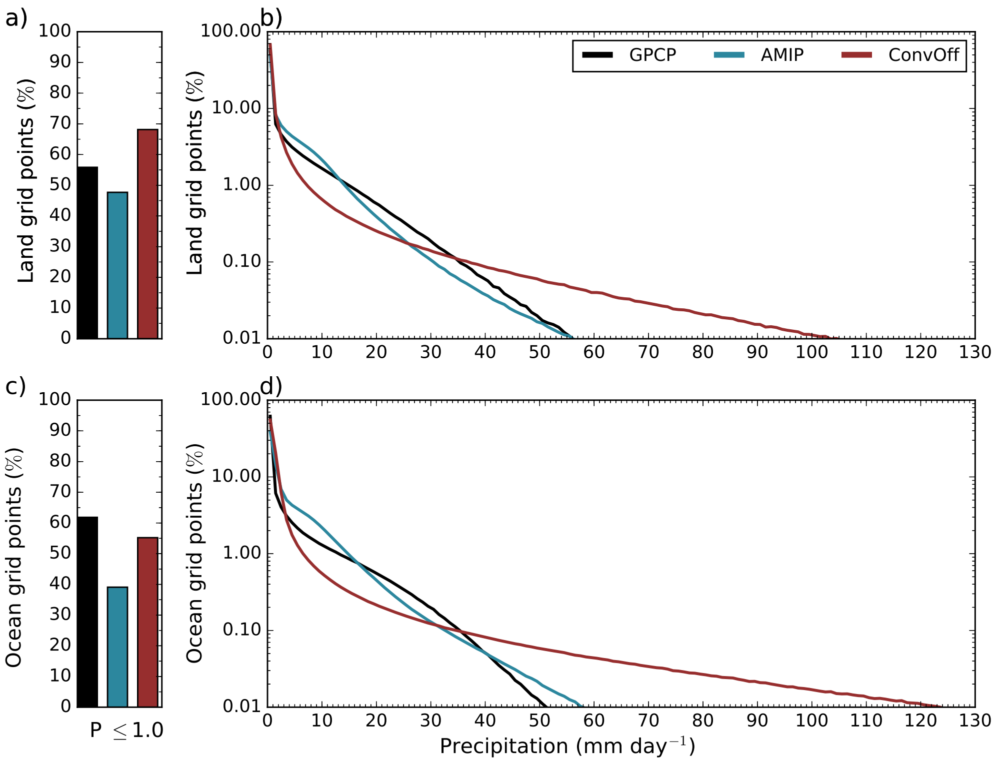

Figure 2. Daily tropical (15° S-15° N) precipitation for a-b) land and c-d) ocean grid points. Bar plots in a) and c) are the number of grid points with precipitation less than 1 mm day^{-1} (ie non-precipitating). Histograms in b) and d) are daily precipitation rates from $1 - 130$ mm day^{-1} with a bin width of 1 mm day^{-1}. The percentage of grid points in b) and d) terminates at 0.01%, which for a common 2.5° × 2.5° grid is 1443 tropical ocean points and 429 tropical land points per time step corresponds to 300-500 points over land and 1000-1600 over ocean (ranging from 20-30 years). The plot includes all available daily data (four of the ten models). The multi-model mean is the average of each models histogram computed on the common grid.

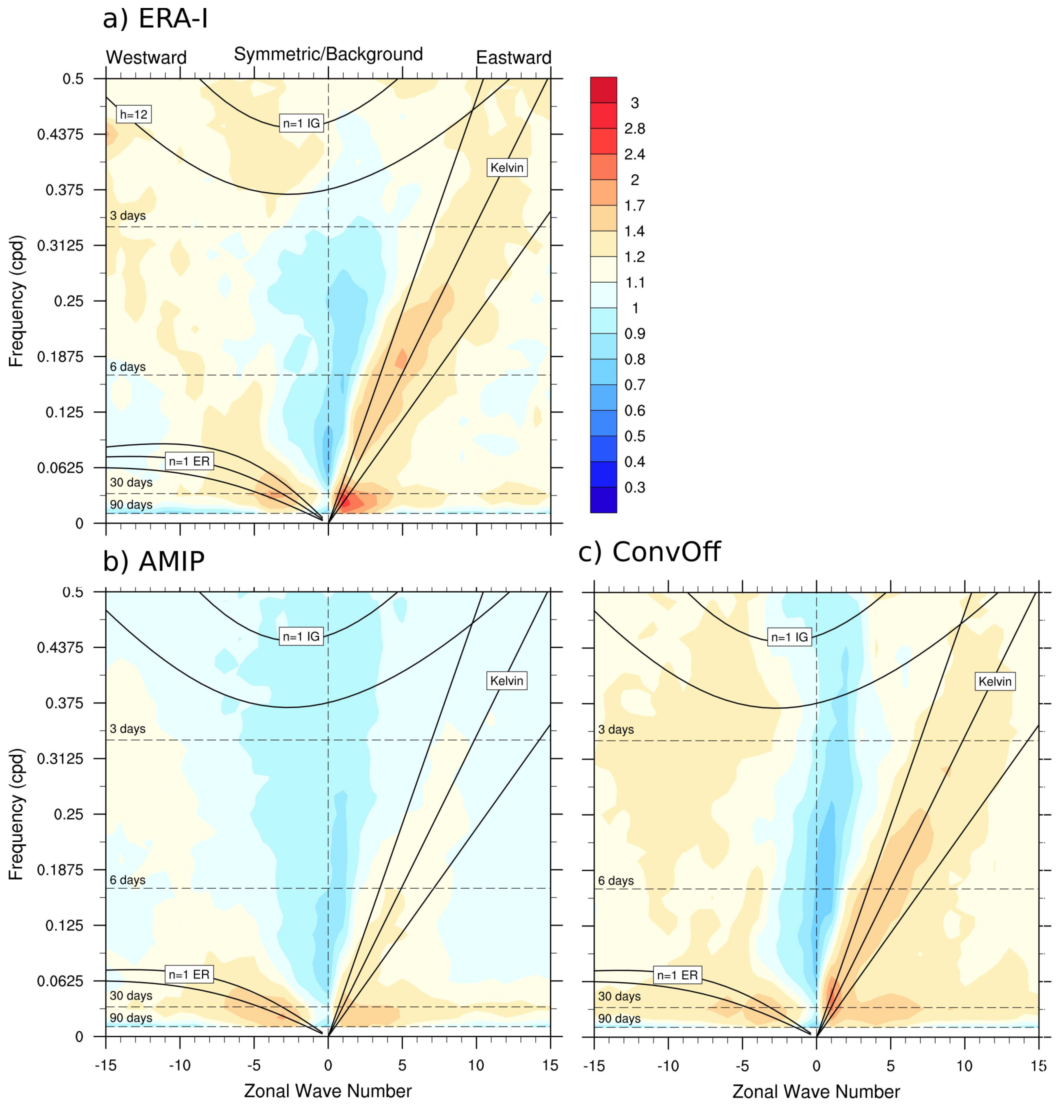

Figure 3. *Wheeler and Kiladis* [1999] diagrams for a) ERA-Interim (1979-2015) b) AMIP (1979-2008) and b) ConvOff (1979-2008) using daily outgoing longwave radiation. The plot includes all available model daily (four out of the ten models). The wave-frequency spectra was computed for each model on its native grid and the resulting wave-frequency values were averaged for the multi-model mean plotted.

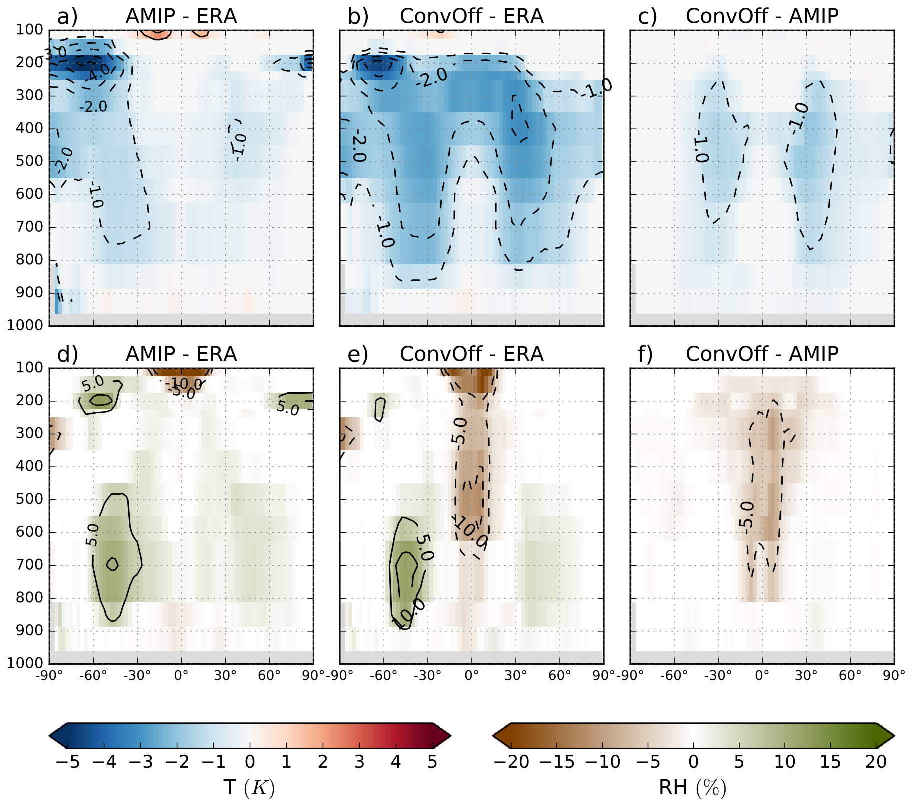

Figure 4. Temperature differences between the multi-model mean of a) AMIP and b) ConvOff with ERA-Interim, and c) their differences. Likewise relative humidity differences in d-f). Grey contouring masks orography. Contour lines are a guide for magnitude only. Differences are only plotted when 90% or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