9A.3 THE ROLE OF THE CLOUD RADIATIVE EFFECT IN THE SENSITIVITY OF THE INTERTROPICAL CONVERGENCE ZONE TO CONVECTIVE MIXING

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1 INTRODUCTION

Tropical rainfall is often associated with a discontinuous zonal precipitation band commonly referred to as the Intertropical Convergence Zone (ITCZ). The double ITCZ bias is a prominent error in current and previous generations of coupled and atmosphere-only general circulation models (GCMs) (Li and Xie, 2014; Oueslati and Bellon, 2015). The modelled ITCZ is too intense in the Southern Hemisphere (Lin, 2007), resulting in two annual-, zonal-mean tropical precipitation maxima, one in each hemisphere (Figure 1). To understand mechanisms that control characteristics of the ITCZ, the presented study will use aquaplanet simulations, as they provide an idealised modelling environment in which some complex boundary conditions in tropical circulation such as land/sea contrasts and orography are removed. Aquaplanet configurations of GCMs coupled to a slab ocean produce a broad range of tropical precipitation mean states (Voigt et al., 2016) and even prescribing zonally uniform sea surface temperatures (SSTs) does not resolve the inter-model variability (Blackburn et al., 2013).

Across a hierarchy of models it has been shown that the simulation of tropical precipitation is sensitive to the representation of convection (Chikira (2010); Mobis and Stevens (2012); Bush et al. (2015), and others). In full GCMs, increasing convection mixing strengthens deep convection in convergence zones associated with an increased moisture flux from subsidence regions (Terray, 1998; Oueslati and Bellon, 2013). Even in the absence of complex surface topography, aquaplanet studies show that characteristics of tropical precipitation, in particular the location and intensity of the ITCZ, are sensitive to the sub-gridscale treatment of convection (Hess et al., 1993; Chao and Chen, 2004; Mobis and Stevens, 2012). Characteristics of the simulated ITCZ are also sensitive to interactions between clouds and radiation (Fermepin and Bony, 2014; Harrop and Hartmann, 2016). The cloud radiative effect (CRE), atmospheric heating due to cloud-radiation interactions, is associated with a more prominent single ITCZ (Crueger and Stevens, 2015; Harrop and Hartmann, 2016). While the ITCZ has been shown to be sensitive to the CRE and the representation of convection, no study has separated these effects.

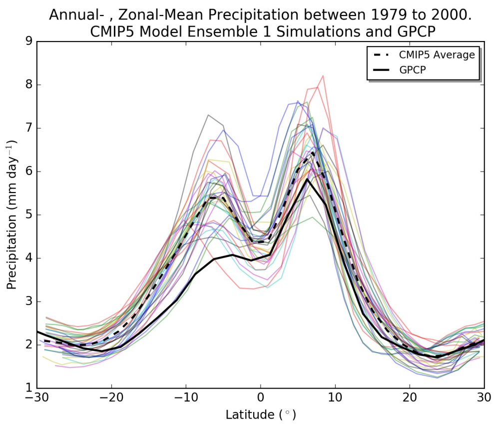

Figure 1: Annual-, zonal-mean precipitation from Coupled Model Intercomparison Project 5 simulations (coloured lines, with dashed black line representing multi-model mean) and Global Precipitation Climatology Project (solid black line).

To explore the role of the CRE in modulating the sensitivity of the ITCZ to convective mixing an atmospheric energy input (AEI) framework is used, as previous studies have shown that characteristics of the ITCZ are associated to the AEI (Bischoff and Schneider, 2014; Adam et al., 2016). Previous research on the response of the simulated ITCZ to variations in the CRE and the

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sub-gridscale representation of convection have not used an energy budget framework.

2 EXPERIMENTS

To explore the sensitivity of the simulated ITCZ to convective mixing we perform five N96 (1.25° latitude × 1.875° longitude) Met Office Unified Model aquaplanet simulations, (using Global Atmosphere 6.0 [GA6.0] configuration), where the lateral entrainment (ϵ) and detrainment (d_m) rate is varied in deep-level convection (Table 1). In GA6.0 ϵ and d_m are given by:

$$\epsilon = 4.5 f_{dp} \frac{p(z)\rho(z)g}{p_*^2} \quad (1)$$

$$d_m = 3.0(1 - RH)\epsilon \quad (2)$$

Both ϵ and d_m are given as a fractional mixing rate per unit length (m^{-1}). In (1) and (2), p and p_* are pressure and surface pressure (Pa); ρ is density ($kg\ m^{-3}$); g is gravitational acceleration ($kg\ m^{-2}$); f_{dp} is a constant with the default value of 1.13 in GA6.0; RH is relative humidity. We control ϵ and d_m by scaling f_{dp} to five different values between 0.25 and 1.5 × the default value, such that f_{dp} equals 0.28 (F0.28), 0.57 (F0.57), 0.85 (F0.85), 1.13 (F1.13) or 1.70 (F1.70). To then explore the influence of the CRE on the sensitivity of the ITCZ to convective mixing we perform a companion set of experiments where cloud-radiation interactions are removed (Table 1).

A third set of simulations are performed with a prescribed CRE (Table 2) to investigate the relative importance of f_{dp} and the CRE to characteristics of the ITCZ. The four simulations have a prescribed, diurnally varying CRE vertical profile computed from a single-year simulation with f_{dp} equal to 0.57 or 1.13, (PC0.57 and PC1.13 respectively). All simulations are run for a total of three years with a "Qobs" SST profile (Neale and Hoskins, 2001), with the first sixty days discarded as spin-up.

Table 1: Simulations varying f_{dp} with cloud-radiation interactions on (CRE-on) and off (CRE-off). F1.13 is the default integration for GA6.0.

f_{dp}	CRE-on	CRE-off
0.28	F0.28	F0.28NC
0.57	F0.57	F0.57NC
0.85	F0.85	F0.85NC
1.13	F1.13	F1.13NC
1.70	F1.70	F1.70NC

Table 2: Simulations with a prescribed climatology of the CRE diurnal cycle. PC1.13 and PC0.57 represent the prescribed CRE diurnal cycle from a one-year simulation where f_{dp} equals 1.13 or 0.57 (respectively).

f_{dp}	PC1.13	PC0.57
1.13	F1.13PC1.13	F1.13PC0.57
0.57	F0.57PC1.13	F0.57PC0.57

3 RESULTS

A sensitivity of the ITCZ to convective mixing is present with and without the CRE present (Figure 2a and c). When cloud radiation interactions are present, reducing f_{dp} leads to a double ITCZ with peak precipitation rates further away from the equator. Removing cloud radiation interactions altogether reduces the ITCZ intensity with the ITCZ broadening for f_{dp} values that produce a single ITCZ with and without cloud-radiation interactions (i.e. F1.70). If a double ITCZ is modeled when cloud-radiation interactions are present (i.e. F0.28), the precipitation maxima moves poleward when removing the CRE. The change from a single to a double ITCZ occurs at a higher f_{dp} value in CRE-off simulations than CRE-on simulations. Removing the CRE cools the tropics, decreasing atmospheric stability and intensifying deep convection over cooler SSTs (not shown). More intense convection at higher latitudes is associated with a reduction in equatorial moisture convergence and a double ITCZ structure.

Both the sensitivity of the ITCZ structure to the CRE and convective mixing is associated with AEI changes as simulations that produce a double ITCZ have a negative equatorial AEI (Figure 2b and d). When cloud-radiation interactions are present the sensitivity of the AEI to convective mixing is predominately due to cloud-sky radiation changes (Figure 3). In CRE-off simulations the sensitivity of the AEI to convective mixing still remains due to latent heat flux alterations (not shown). Changes in the latent heat flux are predominately due to alterations in near-surface wind rather than changes in near-surface specific humidity.

To further understand the influence of the CRE on the sensitivity of the ITCZ to convective mixing, we perform simulations with a prescribed CRE (Table 2). Prescribing the CRE reduces the sensitivity of the ITCZ to f_{dp}, for example changes between F1.13PC1.13 and F0.57PC1.13 are smaller than changes between F1.13 and F0.57 (Figure 2e and Figure 2a). However, even with a prescribed CRE the ITCZ remains sensitive to f_{dp}. Changes in AEI when varying f_{dp} in a prescribed CRE modeling environment are predominately driven by latent heat flux variations (Figure 4a, c). In simulations where the prescribed CRE is varied but the same f_{dp} value is used, AEI changes are mostly associated with cloud-sky radiation (Figure 4b, d).

Further analysis showed that meridional moist static energy (MSE) transport changes, associated with changes in the ITCZ structure when prescribing the CRE, are predominately due to circulation strength and structure changes rather than MSE profile changes. Furthermore, equatorward MSE transport at low latitudes is possible even with equatorial ascent due to a shallower Hadley circulation.

4 CONCLUSIONS

The modelled ITCZ is sensitive to convective mixing which is predominately associated to CRE changes. When prescribing the CRE as either zero or a meridionally, diurnally varying climatology, the ITCZ remains sensitive to convective mixing, associated with latent heat flux alterations. The CRE is an important component of the sensitivity of the ITCZ to convective mixing, but the response of surface turbulent fluxes modulates this sensitivity through the large-scale circulation.

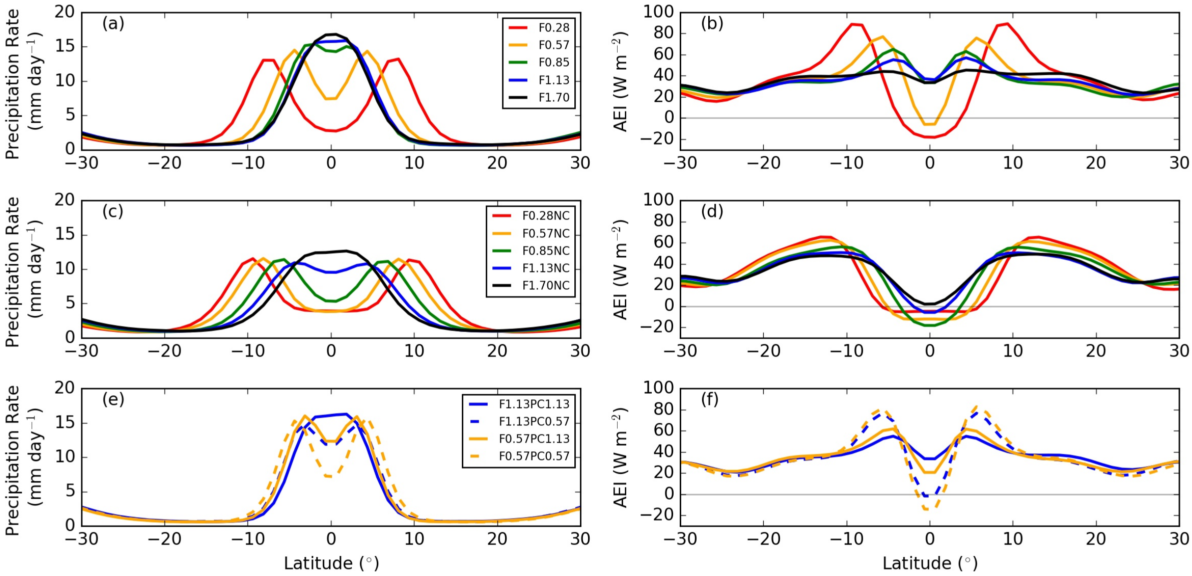

Figure 2: Zonal-, time-mean (a, c, e) precipitation rates (mm day^{-1}) and (b, d, f) AEI (Wm^{-2}), in simulations that vary f_{dp} (top row), simulations that vary f_{dp} with cloud-radiation interactions removed (middle row), and simulations with a prescribed CRE (bottom).

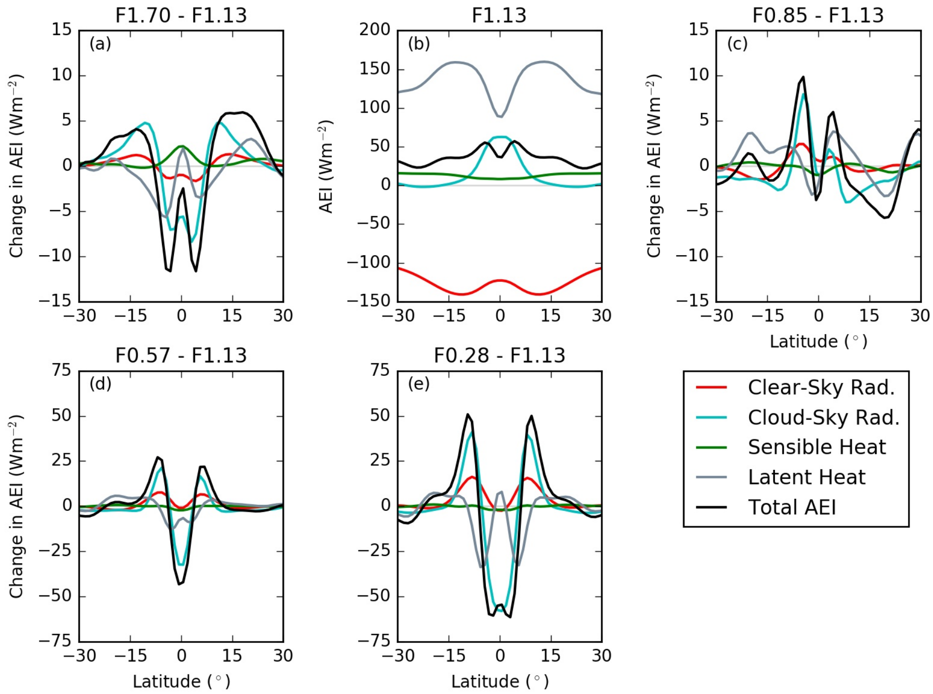

Figure 3: Zonal, time-mean AEI components (Wm^{-2}). (b): F1.13 and (a),(c)-(e): Change in AEI components compared to F1.13 for (a) F1.70; (c) F0.85, (d) F0.57, (e) F0.28. Red line is the clear-sky component, cyan line is the cloud-sky component. Green and grey lines represent the sensible and latent heat flux, respectively, and the black line is the total change in AEI. Note, (a) and (c) have axis limits -15 and 15 Wm^{-2}, whilst (d) and (e) have limits -75 and 75 Wm^{-2}.

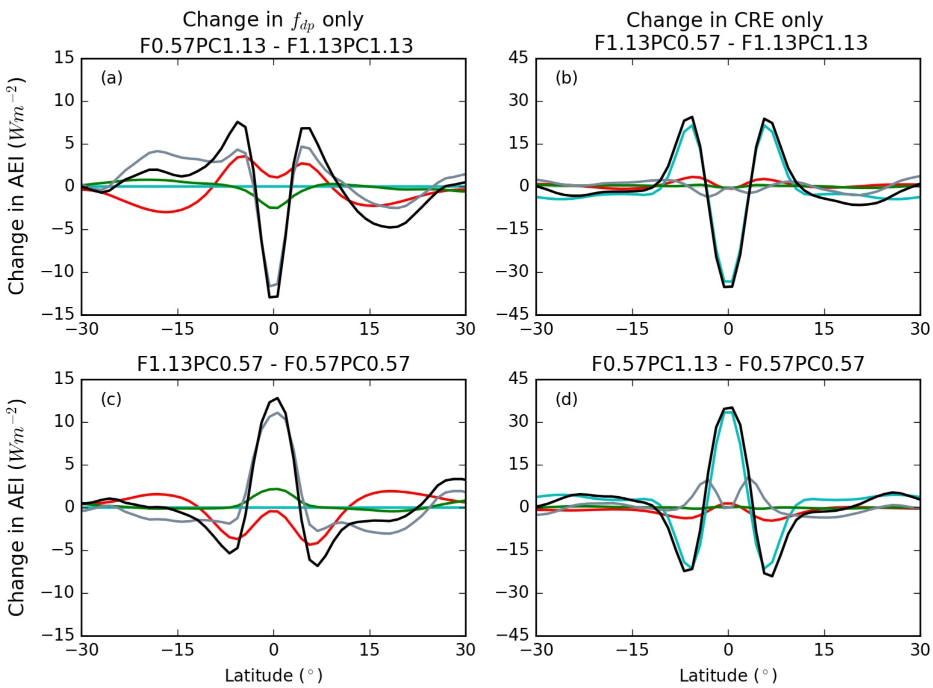

Figure 4: Changes in zonal-, time-mean AEI contributions (Wm^{-2}) for prescribed CRE simulations. Comparison of simulations with same f_{dp} constant (first column) have y-axis limits of -15 to 15 Wm^{-2}, whilst those with a different prescribed CRE (second column) have y-axis limits -45 to 45 Wm^{-2} . Colours as in Figure 3.

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