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Overview of climate change in the BESM-OA2.5 climate model

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Abstract. The main features of climate change patterns, as simulated by the coupled ocean-atmosphere version 2.5 of the Brazilian Earth System Model (BESM-OA2.5) are contrasted with those of other 25 CMIP5 models, focusing on temperature, precipitation and atmospheric circulation. The climate sensitivity to quadrupling atmospheric CO_2 concentration is investigated from two techniques: Gregory et al. (2004) and Radiative Kernel (Soden and Held, 2006; Soden et al., 2008) methods. Radiative kernels from both NCAR and GFDL are used in order to decompose the climate feedback responses of CMIP5 models and BESM-OA2.5 into different processes. Applying the Gregory method for equilibrium climate sensitivity (ECS) estimation, we obtain values ranging from 2.07 to 4.74 K for the CMIP5 models and 2.96 K for BESM, which is close to the ensemble mean value (3.30 K $\pm$ 0.76). The study reveals that BESM has shown zonally averaged feedbacks estimated from Radiative Kernel within the ensemble standard deviation of the other CMIP5 models. The exceptions are found in the high-latitudes of the Northern Hemisphere, where BESM shows values for lapse-rate and humidity feedbacks marginally out of the limit between minimum and maximum of CMIP5 multi-model ensemble, as well as in the Arctic region and over the ocean near the Antarctic for cloud feedback. Moreover, BESM shows physically consistent changes in the pattern of temperature, precipitation and atmospheric circulation.

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1 Introduction

The effects of increased atmospheric CO_2 concentration on the climate system has been studied over the last 120 years (Arrhenius, 1896; Callendar, 1938; Plass, 1956; Kaplan, 1960; Manabe and Wetherald, 1967, 1975; Manabe and Stouffer, 1980; IPCC, 2007, 2013; Pincus et al., 2016; Good et al., 2016, and many others). The human induced increase of atmospheric

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greenhouse gas (GHG) concentrations, commonly referred to as the CO_2-equivalent concentration, contributes to a radiation imbalance at the Top-Of-Atmosphere (TOA), causing less outgoing radiation to leave the Earth System. The trapping of infrared radiation results in temperature rise at the lower levels of the troposphere. In addition, the increased GHG concentration can act as a trigger for climate feedback processes that will either amplify or damp the initial radiative perturbation (Cubasch and Cess, 1990). Earth system models (ESM) are the most advanced tools available for analyzing the coupled climate system (atmosphere, ocean, land, and ice) physical processes and their interactions, although they still exhibit important uncertainties in their projections of climate change (IPCC, 2013).

The equilibrium global-mean surface temperature change induced by doubling the CO_2 concentration in the atmosphere, referred to as the Equilibrium Climate Sensitivity (ECS), remains a centrally important measure of a model's climate response to CO_2 forcing. In the fifth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5), climate model estimates of the ECS range from 2 K to 4.5 K. For more than 40 years, this inter-model spread has been considered one of the most critical uncertainties for the evaluation of future climate changes (IPCC, 2013). This inter-model dispersion arises principally from differences in how climate models simulate climate feedback processes. Among them, the cloud feedback constitutes the largest source of spread for climate sensitivity estimates (Cess et al., 1989, 1990; Dufresne and Bony, 2008; Vial et al., 2013; Caldwell et al., 2016).

Beyond ECS, the response of precipitation to anthropogenic GHG emissions is a topic of great interest in climate science, given the potential consequences on both societies and ecosystems. Changes in precipitation can generally be decomposed into two processes: a thermodynamic component due to increased moisture and no circulation change, and a dynamic component due to circulation change and no moisture change (Bony et al., 2006). The thermodynamic component gives rise to the well-known 'wet-gets-wetter' and 'dry-gets-drier' pattern of precipitation changes (Held and Soden, 2006). Although this thermodynamic response is robust in theory and models, it is governed by the global-mean surface warming, and therefore uncertainty is likely to arise as in the inter-model spread for ECS (Gregory et al., 2004; Andrews et al., 2012). As to the dynamic component associated with circulation change, it sometimes yields strong deviations from the thermodynamic pattern of precipitation, and is known to dominate the uncertainty in total precipitation due to uncertainties in the regional circulation change (Xie et al., 2015).

The recent development of the Brazilian Earth System Model, ocean-atmosphere coupled version 2.5 (BESM-OA2.5) is an evolution of BESM-OA2.3 first presented by Nobre et al. (2013). The authors scrutinized the BESM-OA2.3 model behavior for decadal climate variability and climate change using extended runs with ensemble members totaling over 2000 years of model simulations. El Niño/Southern Oscillation (ENSO) interannual variability over the equatorial Pacific and the inter-hemispheric gradient mode over the tropical Atlantic on decadal time scale are reproduced by BESM-OA2.3. Veiga et al. (2018) showed that BESM-OA2.5 is able to simulate the general mean climate state, as well as to reproduce the main climate variability, particularly over the Atlantic. Differences between BESM-OA2.3 and BESM-OA2.5 are discussed in the next section.

Here, we assess the main features of climate change patterns as simulated by BESM-OA2.5, with a focus on temperature (climate sensitivity and feedbacks), precipitation and atmospheric circulation. The recent development of the BESM-OA2.5 is a coordinated effort of the National Institute for Space Research (INPE) in Brazil in order to advance the understanding

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of the causes of the global and regional climate changes and their impacts on the socioeconomic sector. We evaluate how BESM's simulated climate change compares with Coupled Model Intercomparison Project phase 5 (CMIP5) models. The paper is structured as follows: section 2 presents the description of the new features of BESM2-OA2.5; section 3 presents the methodology, the results are presented in section 4; and section 5 presents the summary and conclusions.

2 Model Description

2.1 BESM-OA2.5

The coupled model BESM-OA2.5 is the result of coupling the Center for Weather Forecast and Climate Studies (CPTEC/INPE) Brazilian Atmospheric Model [BAM (Figueroa et al., 2016)] and the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4p1 (Griffies et al., 2004) via the Flexible Modular System (FMS) also from GFDL. The dynamical equations in BAM are discretized following a spectral transform with horizontal resolution truncated at triangular wavenumber 62 (approximately an equivalent grid size of 1.875°) and 28 layers unevenly spaced in the vertical sigma coordinate with the top level at around 2.73 hPa (if the surface pressure were considered as 1000 hPa). The oceanic component uses a tripolar grid at horizontal resolution of 1° in longitude, and in the latitudinal direction the grid spacing is 1/4° between 10°S-10°N, decreasing uniformly to 1° at 45° and to 2° at 90° in both hemispheres. The ocean grid has 50 vertical levels with a 10-m resolution in the upper 220 m, decreasing gradually to about 370 m at deeper levels.

The main differences between BESM-OA2.5 and the previous version BESM-OA2.3 described in Nobre et al. (2013) are in the atmospheric model. The current version of BESM uses the BAM defined by Figueroa et al. (2016), but with simpler and computationally cheaper parameterizations (as shown in Table 1).

The total energy balance at the TOA is better represented in BESM-OA2.5 than in BESM-OA2.3, which results in an improvement that reduced to around 2 W m^{-2} the mean global bias of -20 W m^{-2} presented by the latter. It should be noted that BESM-OA2.5 has a new set of parameterizations, mainly regarding a better microphysical processes representation. Moreover, BESM-OA2.5 underwent improvements in the representation of the wind, humidity and temperature in the surface layer, with the use of the similarity functions formulation presented by Jiménez et al. (2012). Based on Monin-Obukhov theory, the wind (u_{10m}), humidity (q_{2m}) and temperature (θ_{2m}) are estimated from the values of the first atmospheric model level and the surface, as described in Eq. (24), (25) and (26) of Jiménez et al. (2012). Furthermore, the similarity functions ψ_m and ψ_h depend on the stability regimes (Businger et al., 1971). For BESM-OA2.5, those regimes are associated with stable ($\zeta/L > 0$) and unstable ($\zeta/L \leq 0$) conditions (Arya, 1988).

One year long global simulations and 6 hourly outputs were done with BAM configured with surface layer schemes based on Arya (1988) and Jiménez et al. (2012), here called BAM-Arya (the original scheme) and BAM-Jimenez (the new scheme), respectively. The normalized root mean square error (RMSE) was computed with respect to the reanalysis NCEP-DOE (National Centers for Environmental Prediction – Department of Energy) version 2 (Kanamitsu et al., 2002). The normalized RMSE of the wind at 10 m, temperature and humidity at 2 m for the two surface layer schemes were investigated. Consistent improvements of BAM-Jimenez relative to BAM-Arya were noted in all the three variables over the oceanic regions, where

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these variables are used in ocean-atmosphere coupling. The normalized RMSE analysis over the continents presented less consistent results, with improved BAM-Jimenez representation of both winds and temperature, but degraded representation of the humidity field (figures not shown).

Veiga et al. (2018) showed that BESM-OA2.5 is able to simulate the general mean climate state. However, substantial biases appear at the simulation associated with double ITCZ over the Pacific and Atlantic Oceans and regional biases in the precipitation over the Amazon and Indian regions. It is worth noting that BESM-OA2.5 shows improvement in ITCZ representation in comparison with the previews version (Nobre et al., 2013). BESM-OA2.5 also is capable to reproduce the most important large-scale interannual and decadal climate variabilities, mainly that related to Atlantic Ocean. The Atlantic Meridional Mode (Nobre and Srukla, 1996) is well simulated by the model in term of the spatial pattern and temporal variability, whereas this mode is poorly represented in most CMIP5 models (IPCC, 2013; Liu et al., 2013; Richter et al., 2014; Amaya et al., 2017). The Atlantic Meridional Overturing Circulation (AMOC) represented by BESM-OA2.5 has a mean circulation which is similar to the ensemble AMOC simulated by the CMIP5 models, but slighter lower than the averaged value based on observation. Moreover, the spatial structure of both the North Atlantic Oscilation (NAO) and the Pacific Decadal Oscillation (PDO) variability is well captured (Veiga et al., 2018).

3 Methodology

3.1 Experiments design

For the purpose of this study, climate simulations are performed using BESM-OA2.5 (hereinafter BESM) for the piControl (pre-industrial control scenario, run for 300 years with atmospheric CO_2 concentration invariant at 274 ppmv) and abrupt4xCO_2 (run for 150 years after the abrupt quadrupling of atmospheric CO_2 at year 150 of the piControl simulation) scenarios, which means a spin-up of 150 years. These two scenarios that are commonly employed in CMIP5 studies for climate change assessment (Taylor et al., 2012). Climate change is evaluated from the difference between the abrupt4xCO2 and piControl experiments. In addition, BESM's results are compared with a selection of 25 CMIP5 models listed in Table 2. All models, including BESM, are interpolated at 2.5° x 2.5° longitude/latitude horizontal resolution. All CMIP5 models data are available in the Earth System Grid Federation (ESGF).

3.2 Estimates of climate change sensitivity

Here we estimate the climate feedback using two different techniques: Gregory et al. (2004) and Radiative Kernel (Soden et al., 2004, 2008) methods. This seemingly redundant procedure was done in order to document BESM climate change responses in face of others CMIP models through different ways. The Gregory method has a more straightforward computation, however it returns only a global-mean value. On the other hand, it is possible to obtain the seasonal feedback for every lat-lon point with Radiative Kernel method, besides the feedback can be decomposed into different processes. Moreover, with the Gregory et al. (2004) method, it is possible to estimate the ECS.

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3.2.1 Linear forcing-feedback regression analysis of Gregory et al. (2004)

Gregory et al. (2004) method to compute the thermal response to radiative forcing is applied for 26 CMIP5 models including BESM. The method consists of the linear regression between the annual change (considering abrupt4xCO2 minus piControl) of the global-mean near-surface temperature (ΔT_{as}) and the net radiation change (ΔR) at TOA.

If G is the radiative forcing imposed on the climate system (here, associated with an abrupt increase in atmospheric CO_2 concentration) and ΔR the resulting radiative imbalance in the global-mean net radiative budget at TOA, then at any time, the response of the climate system to this radiative imbalance responds to the radiative forcing according to the following equation:

$$\Delta R = \lambda \Delta \overline{T}_{as} + G \tag{1}$$

where λ (< 0) is the climate feedback parameter and $\Delta \overline{T}_{as}$ the global-mean near-surface temperature change. In a sufficiently long simulation (coupled atmosphere-ocean models take millennia), when the climate system reaches a new equilibrium (ΔR = 0), ECS can be estimated as $\mathrm{ECS} = -G/\lambda$.

By using this linear forcing-response framework, we can estimate climate sensitivity, radiative forcing, and feedback parameter following the method proposed by Gregory et al. (2004). The values of λ (slope) and G (y-intercept) are estimated through the ordinary least square regression of the global-annual-mean of ΔR against $\Delta \overline{T}_{as}$ in all-sky conditions. Using the same linear technique, we decompose the feedback parameter into shortwave (SW) and longwave (LW) radiation components and extract the clear-sky components in order to estimate the cloud radiative forcing or cloud radiative effect ($\Delta\mathrm{CRE}$) defined as the difference between the all-sky and clear-sky feedback parameters (Andrews et al., 2012). Estimates of G, λ, $\Delta\mathrm{CRE}$, and ECS for all models are presented in the next section.

3.2.2 Climate feedbacks (Radiative Kernel)

The radiative kernel technique [as in Soden and Held (2006), Soden et al. (2008), Vial et al. (2013)] is used next to partition the feedback parameter λ into contributions from the temperature response (λ_T), water vapor ($\lambda_{\mathrm{ln}q}$), surface albedo (λ_a), and cloud (λ_c) feedbacks plus a residual term Re (Vial et al., 2013), and expressed in Eq. (2).

$$\lambda = \lambda_T + \lambda_{\mathrm{ln}q} + \lambda_a + \lambda_c + \mathrm{Re} \tag{2}$$

Model intercomparison is easily achieved using this method as the same kernel can be applied to all models (Soden and Held, 2006; Soden et al., 2008). This however assumes that the kernel is independent of models and climate states and that uncertainties in the radiative transfer code used to compute them are small compared to the models' climate responses (Soden et al., 2008).

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Following Vial et al. (2013), we decompose the total feedback parameter (λ) into contributions from λ_T, $\lambda_{\ln q}$, λ_a, and λ_c as:

$$\lambda = \sum_x \lambda_x + \mathrm{Re} = \sum_x \frac{\partial R}{\partial x}\frac{dx}{d\overline{T}_{as}} + \mathrm{Re} = \sum_x K_x \frac{dx}{d\overline{T}_{as}} + \mathrm{Re}$$
$$\lambda = \left(K_{T_s}\frac{dT_s}{d\overline{T}_{as}} + K_T\frac{dT}{d\overline{T}_{as}}\right) + \left(K_{\ln q}\frac{d\ln q}{d\overline{T}_{as}}\right) + \left(K_a\frac{da}{d\overline{T}_{as}}\right) + \lambda_c + \mathrm{Re} \quad (3)$$

where the temperature feedback has been separated into the Planck feedback (vertically uniform tropospheric warming equal the surface warming) and lapse rate feedback (deviation from the tropospheric uniform warming):

$$\lambda_T = \lambda_p + \lambda_{lr} = \left(K_{T_s}\frac{dT_s}{d\overline{T}_{as}} + K_T\frac{dT_s}{d\overline{T}_{as}}\right) + \left(K_T\frac{dT}{d\overline{T}_{as}} - K_T\frac{dT_s}{d\overline{T}_{as}}\right) \quad (4)$$

and where the water vapor feedback is computed assuming constant relative humidity (Soden et al., 2008; Shell et al., 2008; Jonko et al., 2013).

In Eq. (3), K_x (the radiative kernel for a variable x) and x [temperature (T_s and T, in K), natural logarithm of humidity ($\ln q$, in kg/kg) and albedo (a, dimensionless)] are function of longitude, latitude, and pressure vertical coordinates in monthly climatology. To obtain tropospheric averages, the water vapor and temperature feedbacks are vertically integrated from surface up to the tropopause, defined as being 100 hPa in the Equator, and varying linearly to 300 hPa in the Poles.

We used both GFDL and National Center for Atmospheric Research (NCAR) radiative kernels to estimate climate feedbacks. More details on how the radiative kernels are obtained can be found in Soden et al. (2008) and Shell et al. (2008).

Due to the non-linearities involving clouds and net radiation at TOA (Soden et al., 2008), the cloud feedback is not calculated directly from these radiative kernels, which represents one of the key limitations of the kernel method. Instead, the cloud feedback is estimated using the cloud radiative forcing ($\Delta\mathrm{CRE}$) corrected for non-cloud feedbacks as in Soden et al. (2004, 2008). After the calculation of non-cloud feedbacks for both all-sky and clear-sky (subscript cl) conditions, we thus estimate the cloud feedback (λ_c) as:

$$\Delta\mathrm{CRE} = \Delta R - \Delta R_{cl}$$
$$\Delta\mathrm{CRE}_k = (G - G_{cl})_{CO_2} - \Delta\overline{T}_{as}\sum_x (\lambda - \lambda_{cl})_x$$
$$\Delta\mathrm{CRE}_a = \Delta\mathrm{CRE} - \Delta\mathrm{CRE}_k$$
$$\lambda_c = \frac{\Delta\mathrm{CRE}_a}{\overline{T}_{as}} \quad (5)$$

Where, ΔR_{cl} is the clear-sky net radiation flux at TOA. Following Soden et al. (2008), $(G - G_{cl})_{CO_2}$ was considered being equal to 2x0.69 W m^{-2} . Finally, a 30-year mean relative to the period from 120th to 150th year of each scenario was used for all feedbacks estimation.

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3.3 Changes in the atmospheric circulation and precipitation

Monthly mean climatologies are computed for the last 30 years of piControl and abrupt4xCO2 runs, and the projected climate response to CO_2 increase is evaluated from the difference between these abrupt4xCO2 and piControl monthly mean climatologies. The statistical significance of this difference is calculated based on the t-Student test. The significance level used is of 90%. Furthermore, in order to evaluate how similar two spatial pattern are, we used the spatial inner product calculated as $\sum(A_i \cdot B_i)/(|A| \cdot |B|)$, where A and B are the 2-D variables and i is the spatial index related to their lat-lon coordinates.

4 Results

4.1 G, λ, ΔCRE and ECS estimated by Gregory method

Figure 1 shows the linear regressions of ΔR , ΔLW (clear-sky) and ΔSW (clear-sky) against $\Delta\overline{T}_{as}$ for BESM. These linear regressions based on all-sky data are used to estimate ECS, G and λ, here in Figure 1 the regressions are also based on clear-sky data to obtain ΔCRE (as mentioned in the previous section). BESM features G = 8.62 W m^{-2}, λ = -1.45 W m^{-2} K^{-1}, ΔCRE = -0.13 W m^{-2} K^{-1}, and ECS = 2.96 K.

The parameters G, λ, ΔCRE and ECS computed for all models are shown in Table 3. The results for ECS found here are similar to those of Andrews et al. (2012), which range between 2.07 to 4.74 K. G and λ vary from 5.01 to 8.95 W m^{-2} and from -1.66 to -0.60 W m^{-2}K^{-1}, respectively. Inter-model spread in G among the models are due to differences in the radiative codes used, as well as the rapid adjustment processes of the troposphere and surface (Collins et al., 2006; Gregory and Webb, 2008; Andrews and Forster, 2008). The spread in the ECS is more influenced by λ than G (Figure 2), as was also suggested by Andrews et al. (2012). The correlation coefficient between ECS and λ is -0.82, which is significant at 1% of confidence interval (Figure 2b). On the other hand, the correlation between ECS and G is -0.01, witch is not statistically significant (Figure 2a). Thus, the ratio of climate restoration (associated with λ) better explains the dispersion in ECS than the initial radiative imbalance triggered by the CO_2 increase (related to G). Despite BESM presenting one of the highest G among all the CMIP5 models, it shows a response to doubling CO_2, which is inside the warming range of 3.30$\pm$0.76 K presented by the models of the ensemble.

ΔCRE for BESM is -0.13, while CMIP5 models have ΔCRE varying from -0.50 to 0.70 W m^{-2} K^{-1}. This term does not consider the masking effects of clouds. Therefore, ΔCRE cannot be interpreted as a change in the cloud properties alone.

4.2 Climate Feedbacks estimated by Radiative Kernel method

Figure 3 shows the global-mean feedbacks for lapse-rate, water vapor, lapse-rate plus water-vapor, albedo, and cloud (SW, LW, and total) for each CMIP5 model. The radiative kernels are used to test whether the results are sensitive to the particular choice of radiative kernel, and whether inter-model differences are greater than the distribution of the radiatively active constituents of the base model. It is worth clarifying that positive/negative values of feedbacks contribute to the amplification/damping of global warming. The strongest positive feedback (Figure 3) is due to the water vapor (mean value: 1.39 W m^{-2}K^{-1}), followed

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by clouds (mean value: 0.96 W $m^{-2}K^{-1}$), and surface albedo (mean value: 0.32 W $m^{-2}K^{-1}$). The Planck feedback global-mean is negative with an average of -3.60 W $m^{-2}K^{-1}$ (not shown in Figure 3) followed by lapse-rate feedback with -0.77 W $m^{-2}K^{-1}$.

As described in Soden et al. (2008), both lapse-rate and water vapor feedbacks partially compensate each other. In the tropics, negative values of the lapse-rate feedback predominate, while in the Polar regions the signal is the opposite (Figure 4). The faster increase in upper troposphere temperature than near-surface temperature in all models (shown in Figure 4) results in a negative lapse-rate feedback. Considering the Clausius-Clapeyron relation, the upper troposphere with an increased temperature could allow more water vapor concentration, leading to a positive water vapor feedback. The opposite is also true, e.g. positive lapse-rate feedback could exist as a result of a lower warming and humidity at the troposphere than near the surface, which can be associated with a negative water vapor feedback. Hence, the lapse-rate and water vapor feedbacks can be combined as shown in Figure 3. Nevertheless, the water vapor feedback constitutes a strong positive feedback and the sum of them also results in a positive effect.

The albedo feedback is important in regions where there is a reduction in sea-ice and snow cover near the Polar Regions (Figure 4). The positive signal of the albedo feedback implies that the reduction in albedo corresponds to an increase in both the radiation budget at the TOA (due to the reduction of upward shortwave radiation) and temperature near the surface. The albedo feedback shows a large dispersion among models in northern high latitudes, as noted in yellow (standard deviation) and blue (limits between minimum and maximum) shaded areas in Figure 4. It is emphasized that not only the albedo feedback contributes to the Arctic Amplification. In fact, as discussed by Pithan and Mauritsen (2014), the albedo feedback is the second main contributor to Arctic Amplification, while the largest contributor is the temperature feedback. The explanation for the importance of temperature feedback during the surface warming, is in the fact that more energy is radiated back to space in low latitudes, compared with the Arctic.

Regarding cloud feedbacks, most of the inter-model spread arise from the SW component (figures 3 and 4). This dispersion is also noted in the standard deviation and in the limit between minimum and maximum of zonally averaged cloud feedback shown in Figure 4. The SW cloud feedback ranges from -0.28 to 1.40 W $m^{-2}K^{-1}$, while the LW cloud effect ranges from 0.10 to 0.96 W $m^{-2}K^{-1}$. The combined SW and LW cloud effects result in a positive cloud feedback ranging from 0.35 to 1.69 W $m^{-2}K^{-1}$. This result is similar to that found by Soden et al. (2008) for CMIP3 [IPCC AR4, IPCC (2007)] models, where they presented a near neutral and positive cloud feedback. ΔCRE computed by using the Gregory et al. (2004) methodology (Section 4.1) is related to the cloud feedback (estimated from corrected ΔCRE - Section 4.2), even though ΔCRE and λ_c could present opposite signals for some models. For instance, BESM shows -0.13 W $m^{-2}K^{-1}$ and 0.95W $m^{-2}K^{-1}$ for ΔCRE and λ_c, respectively.

Overall, BESM lies within the range of CMIP5 models, with global-mean values of 1.24 W $m^{-2}K^{-1}$, 0.95 W $m^{-2}K^{-1}$, 0.27 W $m^{-2}K^{-1}$, -3.57 W $m^{-2}K^{-1}$ and -0.71 W $m^{-2}K^{-1}$ for water vapor, cloud, albedo feedbacks, Planck and lapse-rate feedbacks, respectively. However, differences between BESM and the other models are found in the high latitudes, where BESM exhibit lapse-rate and humidity feedbacks marginally out of range of values set by the CMIP5 multi-model ensemble (Figure 4). It is also evident from figures 4 and 5 that BESM is an outlier for the cloud feedbacks. This is due to a strong

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shortwave component response over both the Arctic and the Southern Ocean near Antarctica. Even though BESM presents an acceptable radiation closure at TOA (less than 2 W m^{-2} bias), it is deficient in representing shortwave radiation over the Arctic and the Southern Ocean, as a result of negative biases of middle and high clouds in the extratropics as shown by Casagrande et al. (2016). Therefore, it is plausible that such a deficiency in cloud representation could cause the high positive values in SW cloud feedback. It is worth highlighting that the cloud feedback is one of the biggest causes of uncertainty in climate projections (IPCC, 2013). BESM has also a larger negative cloud feedback in the stratocumulus regions compared to the CMIP5 ensemble (figures 4 and 5). This, combined with its anomalous positive high latitude cloud feedback, is qualitatively consistent with the results presented in McCoy et al. (2016) showing an anti-correlation across models in the high latitude optical depth feedback and the lower latitude cloud amount feedback.

4.3 Changes in temperature, atmospheric circulation and precipitation

Figure 6 shows the annual mean for surface temperature change between the abrupt4xCO2 and piControl scenarios for the ensemble of 25 CMIP5 models and BESM. It is clearly seen in Figure 6 that despite the generalized increase of the air temperature over most of the globe in both panels, BESM shows a generally lower temperature increase, principally over the continental areas. The CMIP5 ensemble shows a mean continental temperature increase of 6.78 K, while BESM shows 5.57 K. Notwithstanding, the spatial pattern of temperature increase is similar, as measured by the spatial inner product (as described in the previous section) between the two upper panels in Figure 7, which results in the value of 0.96 (values near 1 mean that both variables have similar spatial pattern, whereas values near 0 mean that there are few spatial correspondences between variables). One point of interest of the scientific community is the relative low temperature increase over the subpolar North Atlantic, also refered as warming hole (Drijfhout et al., 2012). In the CMIP5 ensemble mean, the North Atlantic does not show a decrease of temperature, but it is the region with the smallest temperature increase globally; while BESM shows an area of temperature decrease in this region. Such a decrease is also present in other 6 analyzed models (CSIRO-Mk3-6-0, FGOALS-s2, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-R, and inmcm4). This results are consistent with Drijfhout et al. (2012), who showed that both observations and CMIP5 models present maximum cooling in the center of the subpolar gyre. Those authors argue that there are evidences that both subpolar gyre and AMOC adjust in concert with different time lags.

The regions with the largest temperature increase in the abrupt4xCO2 scenario are the Polar Regions, mainly over the North Pole. The equatorial Pacific shows an increase in temperature in the abrupt4xCO2 scenario when compared with the piControl, both in the CMIP5 ensemble and BESM. Such changes in the Pacific mean state is in line with the IPCC-AR5, in which it is shown that the Pacific Ocean becomes warmer near the equator as opposed to the subtropics in the CMIP5 projections (Liu et al., 2005; Gastineau and Soden, 2009; Cai et al., 2015). The scatter plot of global average of abrupt4xCO2 versus piControl presented in Figure 6 is an additional information that helps to understand the models dispersion around the mean value. It indicates a predominance of models in either quadrants 1 or 3 (top-right and bottom-left, respectively) and half of that in quadrants 2 and 4 (top-left and bottom-right, respectively). This is indicative of the general tendency for warmer/cooler mean climates in the piControl runs to present a corresponding warmer/cooler climate for the abrupt4xCO2 experiments; but not always. As it is the case for 1/3 of all the models considered, BESM falls out of quadrants 1 or 3.

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Figure 7 shows the precipitation changes between abrupt4xCO2 and piControl scenarios for multi-model ensemble and BESM. The results are approximately similar to Held and Soden (2006), with wet regions becoming wetter (near-equatorial and subpolar regions) and dry regions becoming drier (centered around 30° in both hemispheres). The precipitation pattern in the CMIP5 ensemble has increased precipitation over the equatorial Pacific, which can be related to the equatorial Pacific warming pattern shown in the temperature change (Figure 6). Also, the CMIP5 ensemble shows a decrease in precipitation in northern South America. BESM precipitation pattern is similar to the spatial patterns in the CMIP5 ensemble, yet with some notable discrepancies. For example, the decrease in precipitation over the South Pacific shown in the CMIP5 ensemble plot is extended into the Indonesian region in BESM. It is also worth noting in the BESM simulation that the South Pacific convergence zone (SPCZ) shifts southward in the abrupt4xCO2, compared to piControl. Over South America, the precipitation change pattern is similar to that which occurs during El Niño years (Kayano et al., 1988; Marengo and Hastenrath, 1993; Grimm and Tedeschi, 2009), with increased precipitation over southeastern South America and decreased precipitation over northern/northeastern South America, in both the multi-model ensemble and BESM. The scatter plot in Figure 7 suggests a linear relationship between experiments, meaning that models that have a larger (smaller) global average precipitation in piControl scenario show a larger (smaller) precipitation in abrupt4xCO2 scenario. In the scatter plot of Figure 7, BESM has value near the center, which means that it presents global averaged precipitation values similar to the average of all the models used in the ensemble.

Figure 8 depicts the scatter plot of ECS versus the change in precipitation between Abrupt4xCO2 and piControl (ΔPr), for all models considered. It is worth noting that all the models present increased global-mean precipitation for the quadrupling of atmospheric CO_2 with piControl pre-industrial CO_2 concentrations (positive values in y-axis in Figure 8). The apparent linear relationship between differences (abrupt4xCO2 minus piControl) in global-mean precipitation and ECS is also evident in Figure 8, in which warmest models tend to have highest changes in precipitation. This increase in precipitation with warming is governed by the increase in atmospheric radiative cooling (Allen and Ingram, 2002; Held and Soden, 2006; Thorpe and Andrews, 2014).

MRI-CGCM3, ACCESS1-0, and HadGEM2-ES show greater deviation from the linear fit shown in Figure 8. Also, BESM is marginally out of the residual standard error interval, with 9.5% increased precipitation (the error limit is 9.2%). ACCESS1-0 and HadGEM2-ES use the same atmospheric model (Bi et al., 2013; Dix et al., 2013), which could explain the lower increase in precipitation in both coupled models. Another reason could be that these two models present a better representation of the SW absorption by water vapor in their shortwave radiative transfer scheme, as shown in Figure 4 of DeAngelis et al. (2015), which leads to smaller precipitation response (per unit global warming).

As in the case of temperature and precipitation changes, we are also interested in understanding the alteration in the BESM atmospheric circulation (compared to other models) considering a quadrupling of CO_2 concentration. The sea level pressure (SLP) patterns shown in Figure 9 depict a poleward shift of the subtropical high pressure cells for both the CMIP5 ensemble and BESM. Furthermore, when the models are subjected to the increase of atmospheric CO_2 concentration, a decrease in SLP over the Polar regions is evident. This SLP decrease over the Polar regions and the increase in mid-latitudes indicate a positive trend of Arctic Oscillation (AO) and Antarctic Oscillation (AAO) episodes, which have already been reported in the studies of

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Fyfe et al. (1999), Cai et al. (2003), Miller et al. (2006). It is also interesting to note the statistically significant SLP decrease (increase) over the eastern (western) Pacific, a pattern that might be indicative of an ENSO-like pattern in scenarios with increased CO_2 concentration. This pattern is coherent with those depicted in Figure 6 for SST changes in a 4xCO_2 scenario. As for the case for near-surface temperature, the spatial inner product between multi-model ensemble and BESM has a high value (0.95) for SLP changes. This is an indication that BESM has a climate spatial response consistent with that presented by the other CMIP5 models ensemble.

Results for piControl scenario (contours in Figure 10) show that the Southern Hemisphere subtropical jet, depicted by the core of maximum eastward zonal wind, is localized around 35°S, 200-150 hPa, in both the CMIP5 ensemble and BESM. We note that regions with the strongest positive values (anomalous eastward wind) in all levels show a southward displacement in both panels of Figure 10 (BESM and the CMIP5 ensemble). This is consistent with the poleward displacement of high SLP center shown in Figure 9. Also, as the high-pressure centers experienced a poleward shift, the pressure gradients are intensified in subpolar areas, and consequently increased near-surface wind velocity is a result, following the geostrophic approximation $[u \approx -(1/f\rho)(\partial p/\partial y)]$, where f is the Coriolis parameter and ρ is the air density.

Figure 11 shows the average 5°N – 5°S (Walker circulation) differences between abrupt4xCO2 and piControl for omega (shades) and zonal wind and vertical velocity (vectors). According to the pattern of omega in piControl (contours), the multi-model ensemble and BESM show subsidence over an extensive area in the Pacific (150°E – 90°W), which intensity is reduced in the abrupt4xCO2 simulation, as indicated in Figure 11 (blue). This is coherent with near-surface temperature patterns (Figure 6), which show an equatorial warming pattern in the mean state (e.g. during El Niño years a weakening of the Walker circulation occurs). Furthermore, there are positive values in the difference between the two scenarios over South America (around 75°W), consistent with the decrease of precipitation in tropical South America, in both BESM and the CMIP5 ensemble (Figure 7).

5 Conclusions

piControl and abrupt4xCO2 scenarios for 25 CMIP5 models have been contrasted with those generated by the BESM-OA2.5 model. It is shown in this study that the abrupt increase in atmospheric CO_2 concentration is associated with the rise in the global-mean temperature and changes in atmospheric circulation and precipitation patterns.

Taking into account a quadrupling of pre-industrial CO_2 concentration, we demonstrate that BESM is in line with CMIP5 ensemble in terms of climate sensitivity as well as global and zonally averaged climate feedbacks. For instance, applying the Gregory et al. (2004) method for climate sensitivity estimation, we obtain ECS for the 25 CMIP5 models analyzed ranging from 2.07 to 4.74 K, with BESM showing 2.96 K, close to the ensemble mean value (3.30 ± 0.76).

To go further in the analysis, the radiative kernel method is used to separate the climate feedback into Planck, lapse-rate, water vapor, albedo and cloud feedbacks. BESM has shown zonally averaged feedbacks within the ensemble standard deviation of the other CMIP5 models. The exception being in the Arctic region and over the ocean near the Antarctic for cloud feedback. Over those regions, BESM-OA2.5 shows larger values than the zonal mean plus standard deviation for the analyzed models, mainly due to deficiencies noted in the shortwave radiation component of BESM-OA2.5. Despite BESM's good total

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(shortwave plus longwave) radiation closure at TOA, it shows deficiency in representing shortwave radiation over the Arctic and the ocean near the Antarctic (Casagrande et al., 2016).

Atmospheric circulation patterns in BESM-OA2.5 are similar to patterns in the multi-model ensemble and in other studies regarding near-surface temperature (IPCC, 2007, 2013). For precipitation, the thermodynamic component evidences the well-known 'wet-gets-wetter' and 'dry-gets-drier' pattern of precipitation changes (Held and Soden, 2006). However, BESM-OA2.5 along with the CMIP5 ensemble have consistent weakening of Walker circulation, principally in the Pacific and over northern South America, which has been reported in previous studies (Collins et al., 2010; DiNezio et al., 2012; Huang and Xie, 2015; Cai et al., 2015). Regarding SLP, both BESM and the CMIP5 ensemble indicate a poleward displacement of the subtropical high pressure systems, as shown in other studies (Fyfe et al., 1999; Cai et al., 2003; Miller et al., 2006). In line with such displacement, the subtropical jet is also shifted polewards, and it is more evident in the Southern Hemisphere.

The BESM (version 2.5) results show climate sensitivity and thermodynamical responses similar to the other CMIP5 ensemble, but it is not the aim for the BESM development. More than that, BESM has the objective of being an additional climate model with ability of reproduce changes that are physically understood in order to study the global climate system. In this sense, a new version of BESM is under development in order to overcome the present extra-tropical and tropical climate simulation deficiencies, as reported in Casagrande et al. (2016) and Veiga et al. (2018), respectively. Notwithstanding, the inter-model spread in climate sensitivity discussed here, mainly that regarding the cloud feedback, remains a scientific challenge for the future.

Code and data availability

The BESM-OA2.5 source code is freely available after signature of a license agreement. Please contact Paulo Nobre to obtain the source code and data of BESM-OA2.5.

Competing interests. The authors declare that they have no conflict of interest.

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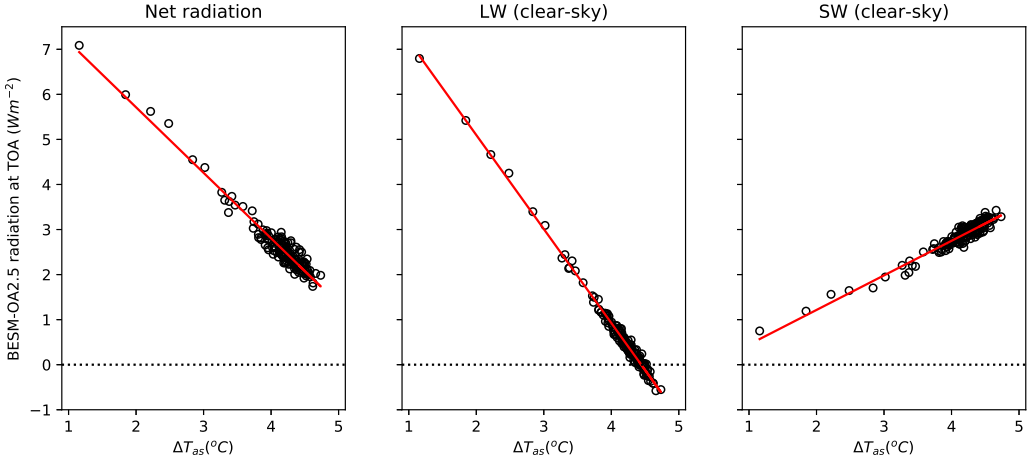

Figure 1. Annual global-mean linear regression between $\Delta\overline{T}_{as}$ and: (a) Net radiation, (b) ΔLW (clear-sky) (c) ΔSW (clear-sky) for BESM-OA2.5

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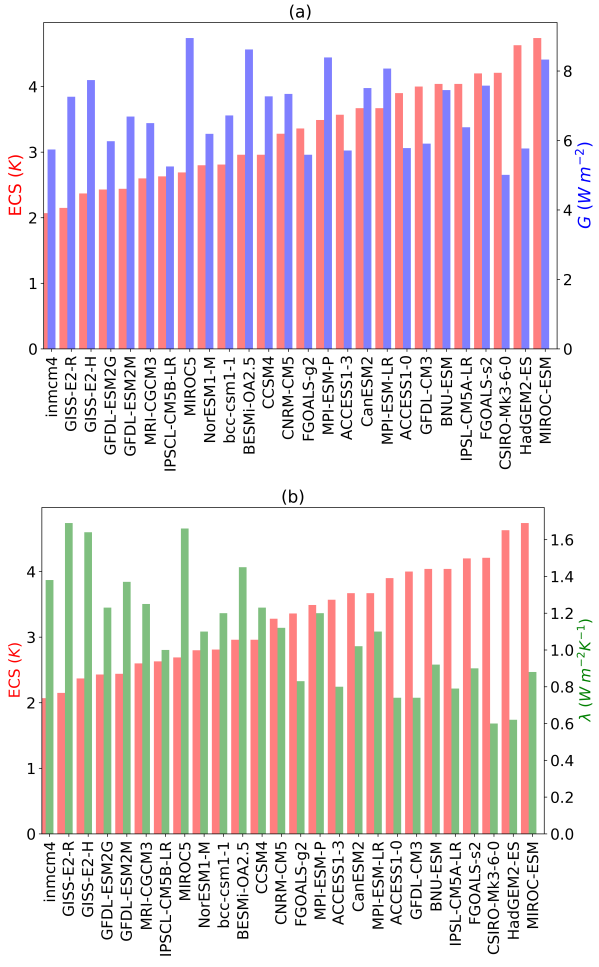

Figure 2. (a) ECS (red) and G (blue) values with ECS increasing from left to right; (b) ECS (red) and λ (green) with ECS increasing from left to right.

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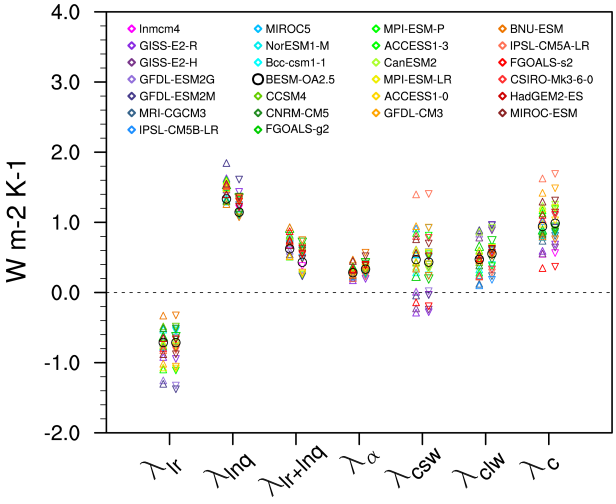

Figure 3. Global-mean feedbacks for 25 CMIP5 models and BESM-OA2.5 (circle). Changes in abrupt4xCO2 relative to piControl are averaged over years 120-150. The triangles mean estimated feedback values using NCAR radiative kernel whereas upside-down triangles mean estimated feedback values using GFDL radiative kernel.

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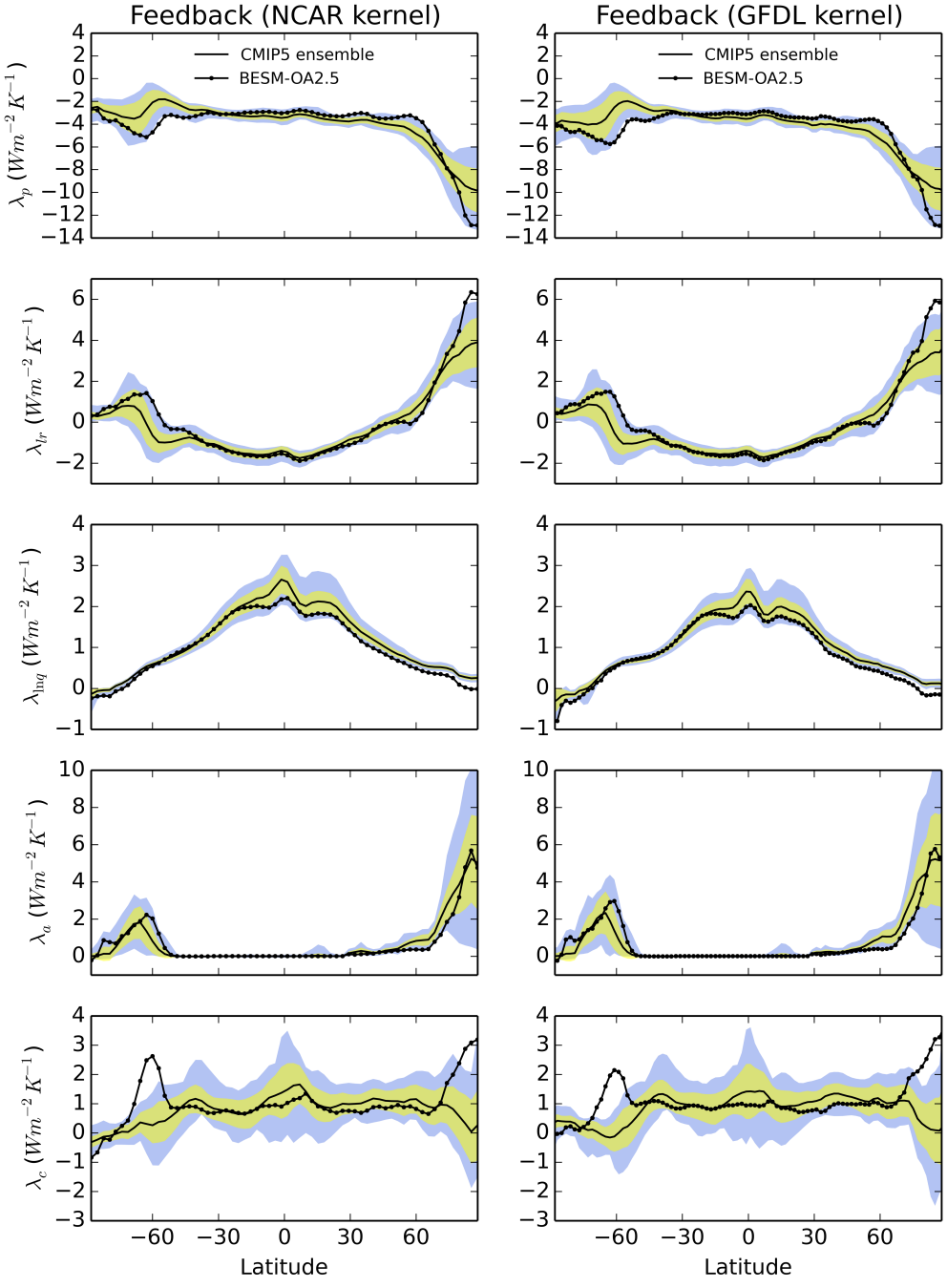

Figure 4. Feedbacks for the CMIP5 multi-model ensemble-mean (solid line) and BESM-OA2.5 (solid line with dots). Inter-model standard deviations for each latitude are in yellow. In blue are the feedback limits based on the maximum and minimum values for each latitude among the models, not including BESM-OA2.5. All feedbacks are based on the averaged over years 120-150.

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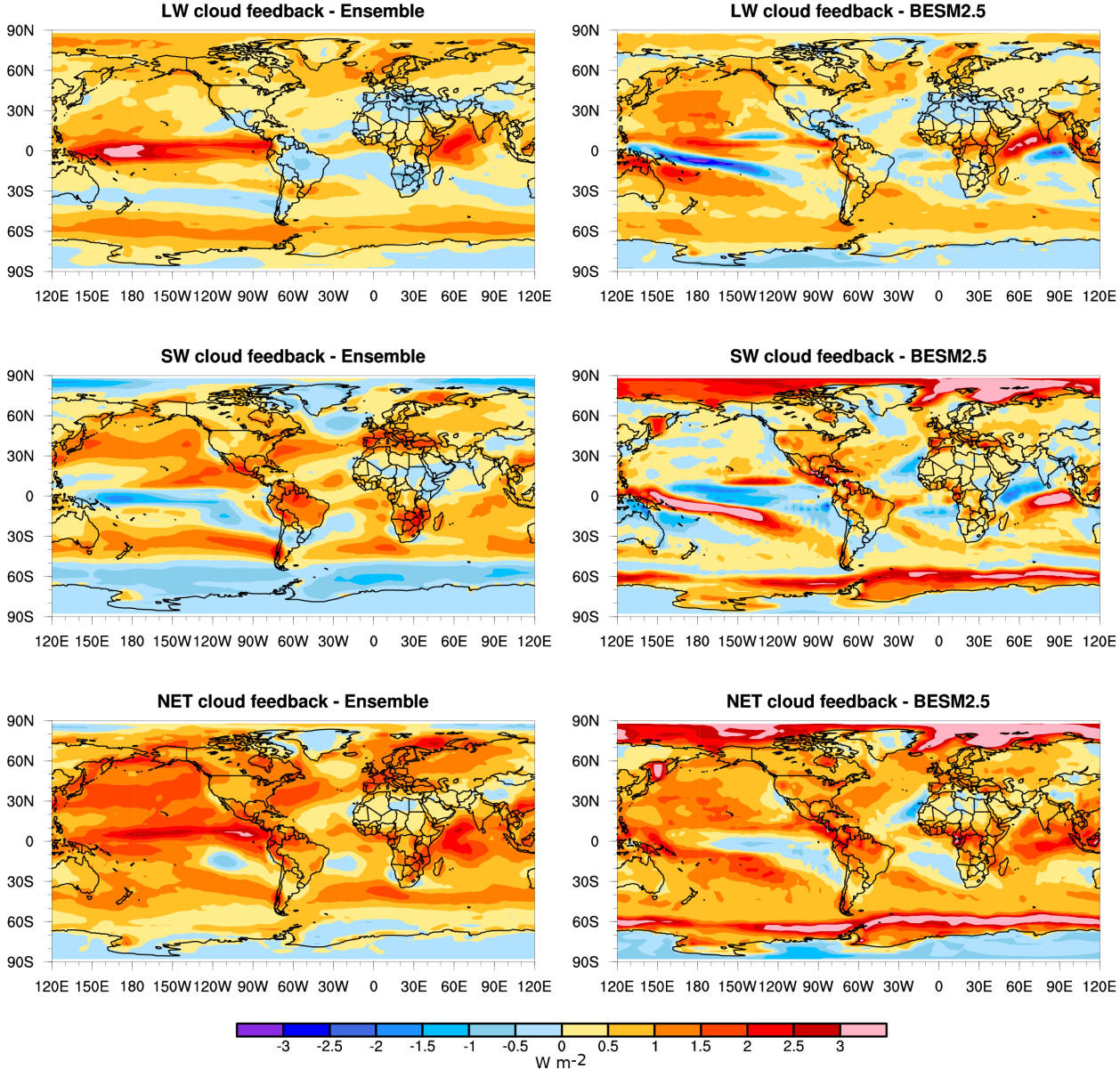

Figure 5. Cloud feedbacks using NCAR radiative kernel for CMIP5 ensemble (left column) and BESM-OA2.5 (right column). Those results are based on the averaged over years 120-150.

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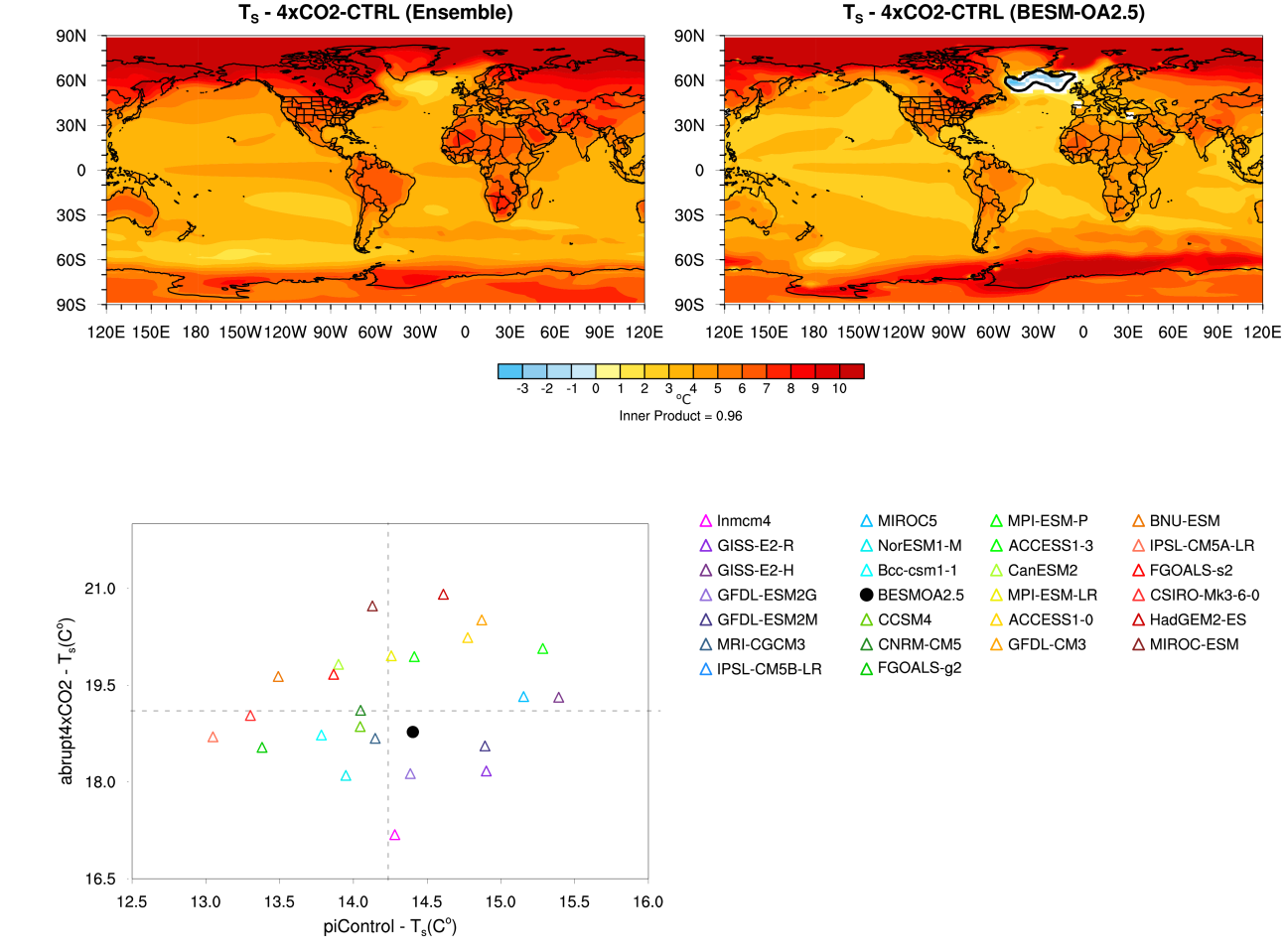

Figure 6. Difference (averaged over years 120-150) of surface temperature between abrupt4xCO2 and piControl simulations in (a) CMIP5 ensemble and (b) in BESM-OA2.5; and (c) scatter plot of global average of surface temperature for the CMIP5 models used in ensemble and BESM-OA2.5 (black dot). Shaded areas in (a) and (b) have level of confidence greater than 90%; the black line represents the isoline of zero temperature difference.

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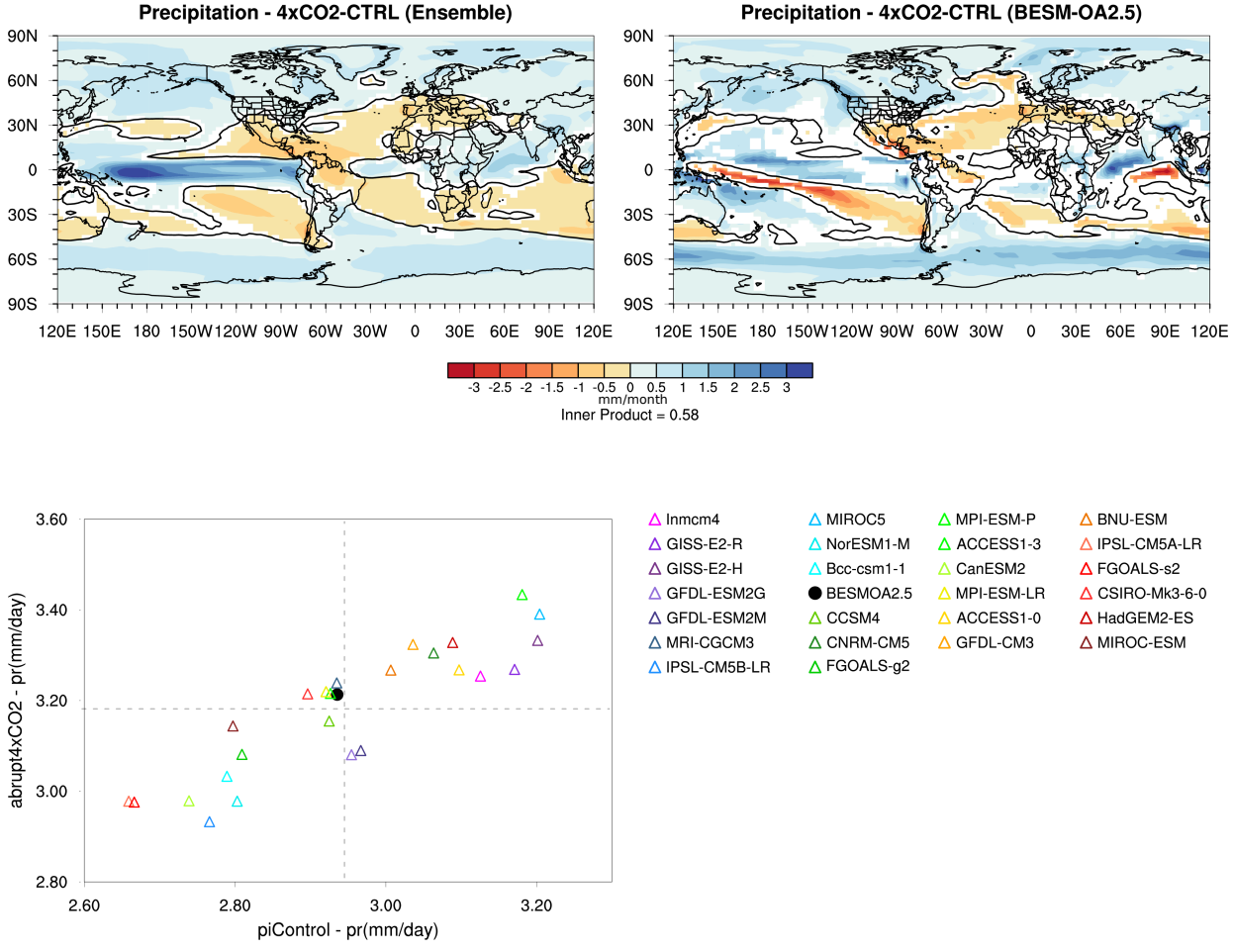

Figure 7. Difference (averaged over years 120-150) of precipitation (in mm/month) between abrupt4xCO2 and piControl simulations in (a) CMIP5 ensemble and (b) in BESM-OA2.5; (c) scatter plot of precipitation global average for CMIP5 models used in the ensemble and BESM-OA2.5 (black dot). Shaded areas in (a) and (b) have level of confidence greater than 90%; the black line represents the isoline of zero precipitation difference.

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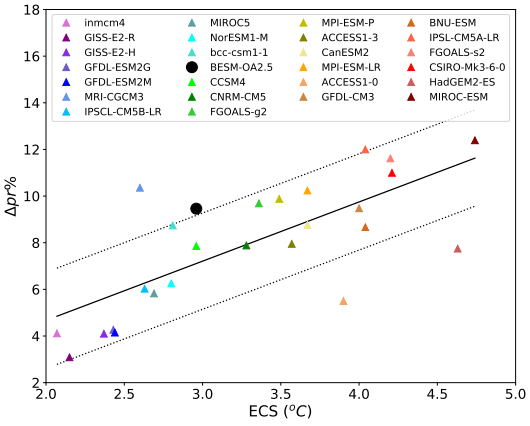

Figure 8. Scatter plot between ECS and $\Delta Pr(\%)$ for all models considered. The solid black line is the linear fit between ECS and perceptual change in precipitation. As in Figure 2, models are sorted according their ECS value. The dash lines represent the error limits considering the residual standard error.

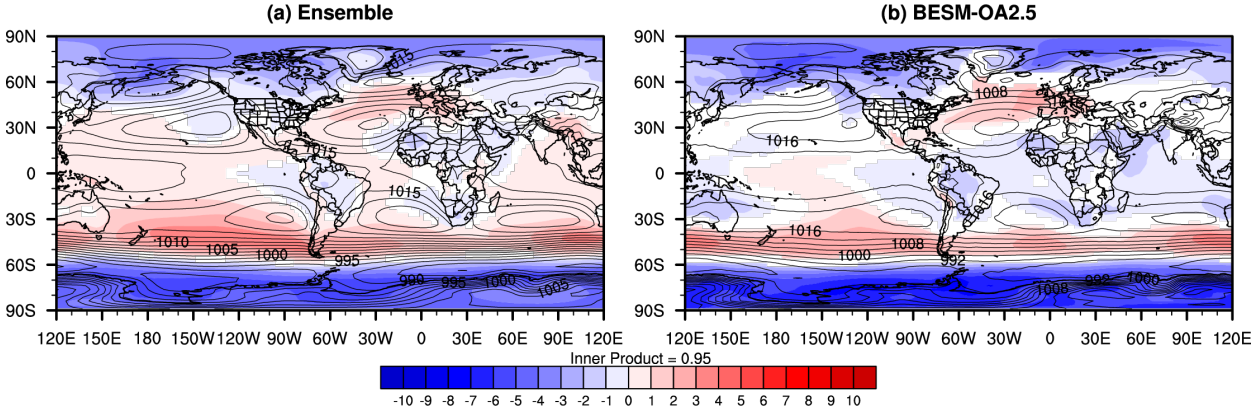

Figure 9. Difference (averaged over years 120-150) of sea level pressure (SLP) in hPa between two scenarios (abrupt4xCO2 minus piControl, shaded), and SLP during piControl (contours) in CMIP5 models ensemble (first column) and BESM-OA2.5 (second column). White areas have level of confidence less than 90%.

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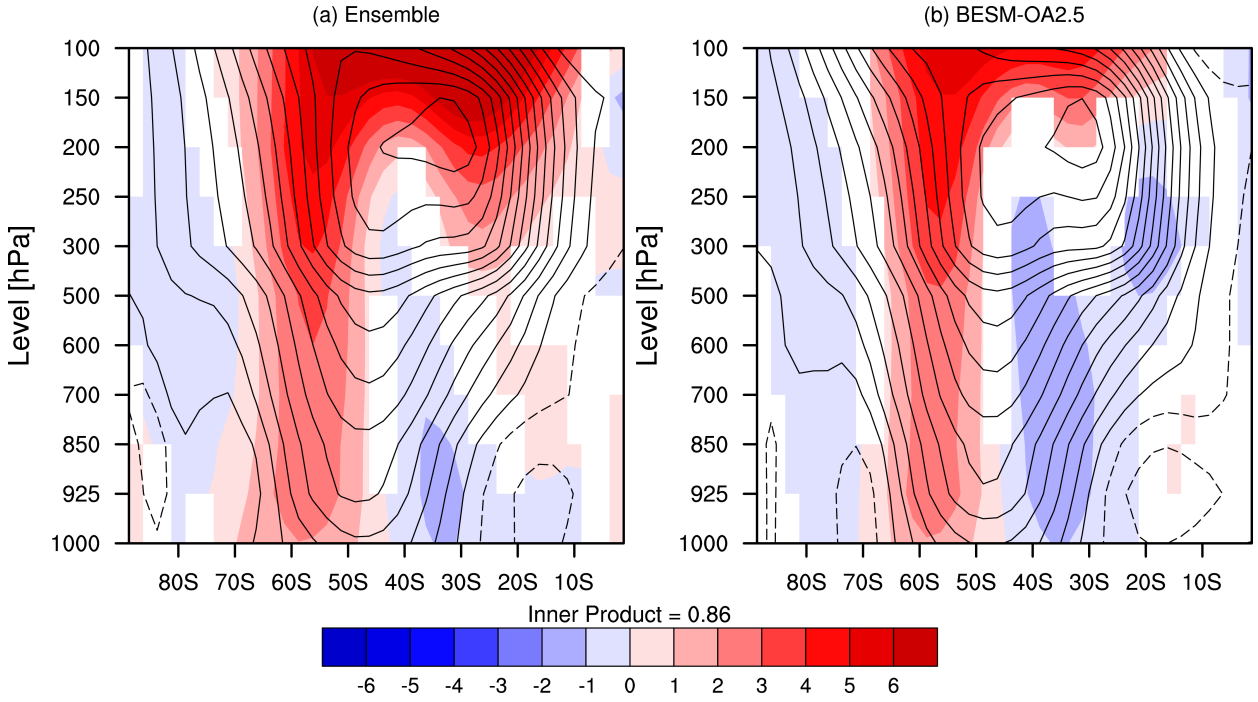

Figure 10. Vertical profile of the difference (averaged over years 120-150) of zonal mean wind (in m/s) between two scenarios (abrupt4xCO2 minus piControl, shaded), and piControl (contours) for (a) ensemble of CMIP5 models and for (b) BESM-OA2.5. White regions have level of confidence less than 90%.

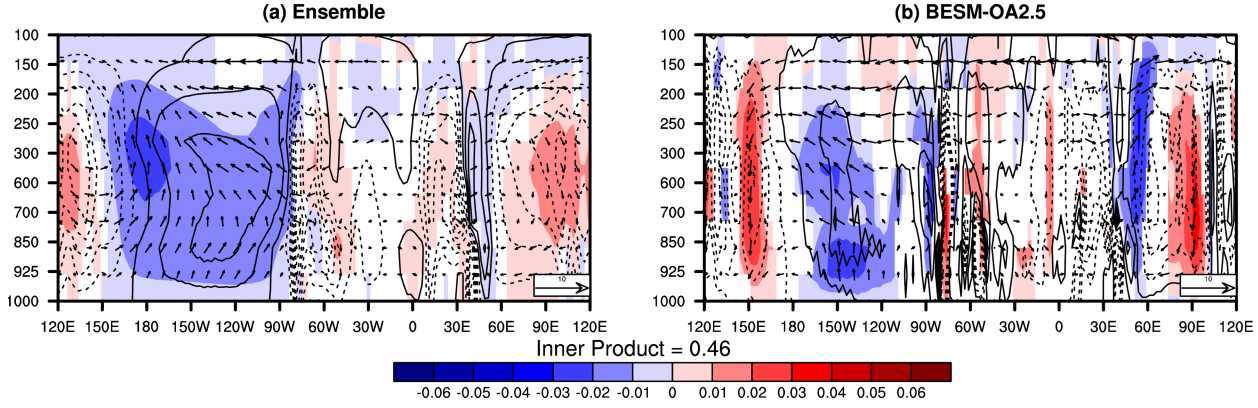

Figure 11. Difference (averaged over years 120-150) between abrupt4xCO2 and piControl for omega (shades) in Pa/s and zonal-vertical winds (vectors), averaged between 5°S and 5°N, for (a) CMIP5 ensemble and (b) BESM-OA2.5. Contours represents the averaged piControl omega in the same region. White areas have a level of confidence less than 90%.

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Table 1. Atmospheric physical parameterizations used in BESM-OA2.5 and BAM.

Physical Parameterization	BESM-OA2.5	BAM
Shortwave radiation	Clirad (Tarasova and Fomin, 2007)	RRTMG (Iacono et al., 2008)
Longwave radiation	Harshvardhan (Harshvardhan et al., 1987)	RRTMG (Iacono et al., 2008)
Cloud microphysics	Ferrier (Ferrier et al., 2002)	Morrison (Morrison et al., 2005)
Land surface model	SSib (Xue et al., 1991)	Ibis [Foley et al. (1996) modified by Kubota (2012)]

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Table 2. Models belonging to CMIP5 used in this study.

Number	Model	Institution, country
1	ACCESS1-0	CSIRO-BOM, Australia
2	ACCESS1-3	
3	bcc-csm1-1	BCC, China
4	BNU-ESM	BNU, China
5	CanESM2	CCCma, Canada
6	CCSM4	NCAR, USA
7	CNRM-CM5	CNRM-CERFACS, France
8	CSIRO-Mk3-6-0	CSIRO-QCCCE, Australia
9	FGOALS-g2	LASG-CESS, China
10	FGOALS-s2	LASG-IAP, China
11	GFDL-CM3	NOAA-GFDL, USA
12	GFDL-ESM2G	
13	GFDL-ESM2M	
14	GISS-E2-H	NASA-GISS, USA
15	GISS-E2-R	
16	HadGEM2-ES	MOHC, England
17	inmcm4	INM, Russia
18	IPSL-CM5A-LR	IPSL, France
19	IPSL-CM5B-LR	
20	MIROC-ESM	MIROC, Japan
21	MIROC5	
22	MPI-ESM-LR	MPI-M, Germany
23	MPI-ESM-P	
24	MRI-CGCM3	MRI, Japan
25	NorESM1-M	NCC, Norway

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Table 3. CO2 Forcing (W m^{-2}) (G), Net Feedback (W m^{-2} K^{-1}) (λ), Climate Response (W m^{-2} K^{-1}) (ΔCRE), and Equilibrium climate sensitivity (K) (ECS) values.

Model	G	λ	ΔCRE	ECS
ACCESS1-0	5.78	-0.74	0.11	3.90
ACCESS1-3	5.71	-0.80	0.27	3.57
bcc-csm1-1	6.72	-1.20	-0.06	2.81
BESM-OA2.5	8.62	-1.45	-0.13	2.96
BNU-ESM	7.45	-0.92	-0.27	4.04
CanESM2	7.51	-1.02	0.16	3.67
CCSM4	7.27	-1.23	-0.15	2.96
CNRM-CM5	7.34	-1.12	-0.19	3.28
CSIRO-Mk3-6-0	5.01	-0.60	0.25	4.21
FGOALS-g2	5.59	-0.83	-0.08	3.36
FGOALS-s2	7.58	-0.90	-0.45	4.20
GFDL-CM3	5.91	-0.74	0.49	4.00
GFDL-ESM2G	5.98	-1.23	-0.21	2.43
GFDL-ESM2M	6.69	-1.37	-0.31	2.44
GISS-E2-H	7.74	-1.64	-0.50	2.37
GISS-E2-R	7.26	-1.69	-0.46	2.15
HadGEM2-ES	5.77	-0.62	0.37	4.63
inmcm4	5.74	-1.38	-0.10	2.07
IPSL-CM5A-LR	6.38	-0.79	0.70	4.04
IPSL-CM5B-LR	5.25	-1.00	0.29	2.63
MIROC5	8.95	-1.66	-0.43	2.69
MIROC-ESM	8.33	-0.88	0.14	4.74
MPI-ESM-LR	8.07	-1.10	-0.06	3.67
MPI-ESM-P	8.39	-1.20	-0.04	3.49
MRI-CGCM3	6.50	-1.25	-0.05	2.60
NorESM1-M	6.19	-1.10	-0.08	2.80
Mean	6.84±1.09	-1.09±0.31	-0.03±0.30	3.30±0.76