Asymmetry in the IOD and ENSO Teleconnection in a CMIP5 Model Ensemble and Its Relevance to Regional Rainfall

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ABSTRACT

Recent studies have shown that the impact of the Indian Ocean dipole (IOD) on southern Australia occurs via equivalent barotropic Rossby wave trains triggered by convective heating in the tropical Indian Ocean. Furthermore, the El Niño–Southern Oscillation (ENSO) influence on southern Australian climate is exerted through the same pathway during austral spring. It is also noted that positive phase [positive IOD (pIOD) and El Niño] events have a much larger impact associated with their respective skewness. These phenomena play a significant role in the region’s rainfall reduction in recent decades, and it is essential that climate models used for future projections simulate these features. Here, the authors demonstrate that climate models do indeed simulate a greater climatic impact on Australia for pIOD events than for negative IOD (nIOD) events, but this asymmetric impact is distorted by an exaggerated influence of La Niña emanating from the Pacific. The distortion results from biases in the Pacific in two respects. First, the tropical and extratropical response to La Niña is situated unrealistically too far westward and hence too close to Australia, leading to an overly strong impact on southeast Australia that shows up through the nIOD–La Niña coherence. Second, the majority of models simulate a positive sea surface temperature skewness in the eastern Pacific that is too weak, overestimating the impact of La Niña relative to that of El Niño. As such, the impact of the positive asymmetry in the IOD only becomes apparent when the impact of ENSO is removed. This model bias needs to be taken into account when analyzing projections of regional Australian climate change.

1. Introduction

Contemporary coupled general circulation models (GCMs) simulations conducted as a part of phase 5 of the Coupled Model Intercomparison Project (CMIP5) provide an opportunity for a more comprehensive examination of the impacts of Indo-Pacific climate variability on global rainfall and for climate projections. Analysis of CMIP3 (Meehl et al. 2007) simulations, for example, has shown that there have been significant improvements in simulating modes of variability like El Niño–Southern Oscillation (ENSO) (Joseph and Nigam 2006; Guilyardi 2006) and an equatorial zonal mode with spatial structures and seasonality similar to the observed Indian Ocean dipole (IOD) (Saji et al. 2006; Cai et al. 2009b; Liu et al. 2011). It is less clear how the models perform in terms of a rainfall teleconnection associated with these modes of variability, despite being studied extensively in observations with relevance to past Australian interannual rainfall variability and trends (Ashok et al. 2003; Saji and Yamagata 2003; Ummenhofer et al. 2008; Nicholls 2010; Risbey et al. 2009a; Cai et al. 2010, 2011, 2012).

Cai et al. (2011) detailed the observed mechanisms associated with the teleconnection pathways of the IOD and ENSO and their influence on Australian cool season rainfall based on linear statistics. They found that the impact of the IOD on southeastern Australia is conducted through equivalent barotropic Rossby wave trains in response to tropical Indian Ocean convection anomalies. A similar influence of the IOD via such propagating Rossby waves has also been demonstrated for South America (Chan et al. 2008). ENSO’s impact on extratropical (southern) Australian rainfall predominantly stems from the same tropical Indian Ocean pathway, coming through its coherence with the IOD. In a follow-up study, Cai et al. (2012) showed that there is an asymmetry between positive and negative events, with positive...
IOD (pIOD) and El Niño events reducing rainfall over southern Australia significantly more than the rainfall increase from the respective negative phase events, consistent with an amplitude asymmetry between the different phases of the IOD (Fig. 1a) (Saji and Yamagata 2003; Hong et al. 2008) and ENSO (Hoerling et al. 1997; Burgers and Stephenson 1999; An and Jin 2004). This asymmetry refers to the feature that the amplitude of pIOD and El Niño is far greater than their respective negative (nIOD) and La Niña.

It is important to note that the negative phase of ENSO (i.e., La Niña events) has a more pronounced rainfall impact across eastern Australia than El Niño. This is because the center of convection anomalies over the western Pacific and a center of the anomalous convection-induced equivalent barotropic Rossby wave train, the Pacific–South America (PSA) pattern, are both closer to Australia than those induced by El Niño and thus are able to have a greater influence on Australia (Cai et al. 2012). Cai et al. (2012) further suggested that an observed austral spring [September–November (SON)] rainfall reduction across southeastern Australia since the 1950s is because of a marked increase in pIOD (Cai et al. 2009c) more so than, or in addition to, the lack of nIOD events (Ummenhofer et al. 2009).

The purpose of this study is to assess and benchmark how well the CMIP5 generation of climate models simulates the IOD and ENSO-induced teleconnections/asymmetries that propagate to the extratropics in SON. This study follows on from Cai et al. (2011) and Cai et al. (2012), who documented the observed patterns, given their importance to past Australian rainfall trends and their importance for making confident projections of future regional Australian climate change associated with such modes of variability. The remainder of this study is set out as follows. Section 2 details the datasets used and methodology followed. Sections 3 and 4 describe the models’ ability in simulating the IOD and ENSO rainfall teleconnection to the extratropical latitudes, with a focus on whether an asymmetry in their downstream impact is evident over influenced regions such as the Australian continent. Section 4 also explores biases in the climate models that lead to unrealistic features of the simulated rainfall teleconnections and the climatic impact on the influenced regions, and section 5 summarizes the findings.

2. Data and methods

We analyze the output of one ensemble member from each of the currently available 36 climate models that have taken part in CMIP5 (Table 1) for a 56-yr period (1950–2005). Simulated sea surface temperature (SST), outgoing longwave radiation (OLR; a measure of convection), geopotential height at the 200-hPa level (Z200), and rainfall are first linearly detrended and then interpolated onto a common grid (1° × 1°). For observations,
we utilize SST from the Hadley Centre Global Sea Ice and SST reanalysis (HadISST; Rayner et al. 2003) and rainfall from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996). The outputs are stratified into seasons, although we focus on austral spring (SON), when IOD events tend to peak and show the strongest covariation with ENSO (Saji et al. 2006; Liu et al. 2011; Cai et al. 2011).

In each climate model, and the observations, the IOD is described through empirical orthogonal function (EOF) analysis on SST anomalies in the tropical Indian Ocean domain (25°S–25°N, 40°–120°E) (Figs. 2a,b). The IOD index is taken as the time series associated with the EOF spatial pattern, having a standard deviation of one. A pIOD value refers to a phase when SST anomalies are anomalously cold in the eastern tropical Indian Ocean. Similarly, the ENSO index is taken as the time series associated with the EOF spatial pattern of SST anomalies in the tropical Pacific Ocean domain (25°S–25°N, 120°E–80°W) (Figs. 2c,d). We use EOF analysis as opposed to standard indices such as the dipole mode index (DMI; Saji et al. 1999) and Niño-3.4 as it allows each model to exhibit their own patterns, as opposed to an imposed structure (Saji et al. 2006; Cai et al. 2009b; Liu et al. 2011). Several studies have identified a small number of models that do not simulate realistic IOD and ENSO patterns (e.g., van Oldenborgh et al. 2005; Cai et al. 2009a; Yu and Kim 2010; Liu et al. 2011). However, most of these models tend to have small IOD (and/or ENSO) amplitude and do not contribute much variance–signal when considering regression coefficients. Tests show that our results are robust to the use of standard climate mode indices (such as DMI and Niño-3.4) and/or the removal of the unrealistic models; however, we retain all available models in the following analysis to use a full spectrum of models.

The analysis techniques used in this study are linear regression (or equivalently correlation) and partial linear regression (partial correlation). Here we use partial regression to isolate the independent signals of IOD and ENSO that are independent of each other. Partial regression involves calculating the linear dependence of a climate mode (e.g., IOD) upon another mode or process (e.g., ENSO) after the linear relationship between the two has been removed (see Cai et al. 2011 for details). Hereafter we will refer to the IOD index (the first key predictor) after the linear relation with the ENSO index (the other key predictor) has been removed as \( \text{IOD}_{\text{ENSO}} \). Similarly, the ENSO index after the IOD index dependency has been removed is referred to as \( \text{ENSO}_{\text{IOD}} \). An anomalous circulation pattern associated with the IOD after removing the effects of ENSO may be described by a map of the partial regression, which is calculated by removing the ENSO-coherent variance from gridpoint anomalies of a field (e.g., rainfall) to obtain a residual field and then regressing the residual field onto \( \text{IOD}_{\text{ENSO}} \). Removing the influence of ENSO in this manner also removes the IOD signal that is coherent with ENSO; therefore, the resultant patterns can be considered as “pure” IOD (or “pure” ENSO) impacts. The regression anomalies are scaled by a one standard deviation anomaly of the predictor in each case for a comparison of the size of anomalies associated with typical variations of the predictor indices (i.e., per unit change of each “independent” climate mode index). Significance of the regression anomalies is estimated based on significance of the associated correlation coefficients, which is when \( p \) value < 0.05.

3. Simulated asymmetry in the IOD teleconnection pathway

Figure 1a highlights the relationship between the observed IOD index (taken as the time series associated with the tropical Indian Ocean HadISST EOF1) and rainfall anomalies from NCEP–NCAR reanalyses averaged over the east pole used to define the IOD index (e.g., \( 0°–10°S, 90°–110°E \), hereinafter IODE) during austral spring (SON). Using all samples, it is evident that there is a significant \( (p \) value < 0.001) linear relationship. Dividing the analysis into positive and negative IOD phases displays the positive asymmetry noted in previous studies. However, now the correlation of rainfall associated with nIOD events is not statistically significant \( (p \) value \( \approx 0.95 \)), suggesting that the majority of variance in the linear analysis using all samples arises from the anomalies associated with pIOD events.

Most climate models have been shown to simulate both dynamic and thermodynamic feedbacks involving anomalous SSTs, winds, and the thermocline in the eastern tropical Indian Ocean, essential for the development of an IOD event (Saji et al. 2006), although there is large diversity in their intensity (Cai et al. 2009b; Liu et al. 2011). Aggregated over the 36 CMIP5 models, a weaker asymmetry is produced over the IODE region (Fig. 1b). The relationship of rainfall anomalies associated with all samples, and both positive and negative phases, is statistically significant over the large model sample size; however, for the same one-unit change of the IOD index, the greatest anomalies are associated with the reduction in rainfall during pIOD events, similar to observations. Examination of individual model performance reveals that approximately 65% of models (23 of the 36) display this asymmetry. Does this tropical asymmetry that occurs in the models transmit from the tropics...
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and have an asymmetric impact in the extratropics such as
Australia, as has been documented to occur in the ob-
servations (Cai et al. 2012)?

The IOD teleconnection is examined by calculating
regression and correlation coefficients, as conducted in
Fig. 1b, for convection and circulation anomalies asso-
ciated with the IOD index for each grid point and each
model and then constructing a multimodel average
during SON. First, we construct the linear relationship
with respect to the full IOD index (Fig. 3a), obtained
using all samples in the time series. Results show a pos-
tive diabatic heating (convective) anomaly over the
IODE extending to Australia (Fig. 3a, left column),
highlighting the ability of the models to simulate the
impact pathway from the tropics to the extratropics. A
tropically trapped baroclinic response to diabatic heat-
ing anomalies over the eastern Pacific and western IOD
pole (hereinafter IODW) manifests itself as 200-hPa
positive height anomalies in the tropical atmosphere
(Fig. 3a, middle column). Additionally, in response to

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Fig. 2. EOF1 patterns of SST anomalies for austral spring (SON) in the Indian Ocean domain (25°S–25°N, 40°–120°E) for the (a) CMIP5 multimodel ensemble mean and (b) observed (HadISST). (c),(d) As in (a),(b), but for EOF1 patterns of SST anomalies for SON in the Pacific Ocean domain (25°S–25°N, 120°E–80°W).
the convective anomalies over the IOD poles, Rossby wave trains propagate into the extratropics, resulting in a positive height anomaly center south of Australia. The positive height anomaly center is consistent with observations and crucial for capturing the rainfall response over the Australian continent associated with IOD variability as this feature reduces the intensity and frequency of the eastward-moving weather systems or pushes them poleward (Risbey et al. 2009a,b; Ummenhofer et al. 2009; Cai et al. 2011). The longitudinal position of the positive height anomaly center varies between models (because of each model’s distinct IOD pattern, figure not shown), which ultimately causes diverse impacts across more than just the southern portion of the Australian continent in the ensemble. Consequently, significant rainfall anomalies (at the 95% level) cover the entire Australian continent in the model ensemble (Fig. 3a, right column).

To test whether the IOD in climate models displays an asymmetry in the extratropical impact pathway, we repeat the regression analysis for both positive (Fig. 3b) and negative (Fig. 3c) phases of the IOD time series (as shown in Fig. 1b). The models display a strong positive asymmetry in the diabatic (convective) heating anomalies over the tropical Indian Ocean, with significantly stronger and more widespread anomalies over the IODE and IODW regions. Consequently, the Rossby wave train forcing is stronger during pIOD events. Circulation anomalies reveal that the positive height anomaly simulated south of Australia is therefore largest and more significant for pIOD events and almost disappears in the nIOD events case. Surprisingly, although a positive asymmetry exists over the tropical Indian Ocean in terms of the rainfall anomalies (evident from Fig. 1b), it is difficult to ascertain any difference between the extratropical rainfall impact between the two IOD phases (Figs. 3b,c, right column). Given the larger response of the positive height anomaly south of Australia during pIOD events, this is an unexpected result and leads to the question of what causes the lack of extratropical asymmetry in the models’ rainfall response.

4. Influence of ENSO on the IOD impact pathway

To test whether the rainfall asymmetry signal, expected from the reasonably well simulated IOD asymmetry, as reflected in the OLR and geopotential height regression maps (Figs. 3b,c), is masked by other climate modes important for the Australian climate, we employ partial regression analysis to investigate pure IOD events (e.g., IOD_{ENSO}). Here we consider ENSO as it covaries with
the IOD during SON and is a major driver for Australian rainfall variability during this season as well (Nicholls et al. 1997; Power et al. 2006; Wang and Hendon, 2007; Risbey et al. 2009b; Cai et al. 2011, 2012). Examining the impact due to the IOD$_{ENSO}$, we find that the impact asymmetry from the IOD is even more prominent (Fig. 4). Without the influence of ENSO, it is clear that pure pIOD events account for the majority of the extratropical response in rainfall when compared to the pure nIOD events, with a significant impact covering much of the Australian continent. For pure nIOD events there is very little significant impact on Australian rainfall once the covarying ENSO signal has been removed. Therefore, the lack of asymmetry for the combined IOD/ENSO response is due to the feature that ENSO’s impact unrealistically dominates the IOD response.

Figure 5 examines the process whereby ENSO unrealistically modifies the IOD signals. This is carried out by firstly removing the influence of the IOD in the circulation fields and ENSO index through a linear regression (e.g., ENSO$_{IOD}$). ENSO$_{IOD}$ anomaly patterns are then constructed using the residual anomalies. Using an all-sample regression to remove the influence of the IOD (Fig. 5a), we see that in the Pacific, where ENSO is the dominant driver of the convection anomalies, an anomalously large rising motion over the tropical Pacific region forms part of the well-known Southern Oscillation. Without the coherent IOD anomalies, in addition to the strong tropical western Pacific anomalies, large anomalies over the IODE region still exist, implying that ENSO’s impact pathways emanate from both the tropical Indian and Pacific Oceans, consistent with observations (Cai et al. 2011, 2012). However, because of biases in the model simulation of the Pacific SST climatological structure (Zheng et al. 2012), SST anomalies in the Pacific associated with ENSO extend further westward compared to observations (Figs. 2c,d). This ultimately results in a westward displacement of the downstream climatic impacts due to ENSO through the Pacific impact pathway (Fig. 5), as discussed below.

The regression of OLR onto positive ENSO (i.e., El Niño) samples produces a pattern that shows stronger anomalies over the IODE than negative (La Niña) ENSO samples (cf. Figs. 5b,c, left column). The resulting positive height anomaly center in the extratropical Indian Ocean associated with all samples of ENSO$_{IOD}$ via the tropical Indian Ocean pathway is well situated to impact the eastward-moving weather systems vital for delivering rainfall to southern Australia in SON. However, the pure El Niño–induced positive height anomaly is considerably greater and more defined than that associated with the pure La Niña events. In the tropical Pacific, modeled convective anomalies associated with El Niño, although farther eastward than those associated with La Niña, are still too far westward when compared with observations (e.g., Cai et al. 2012) because of the westward bias in the SST anomalies associated with ENSO (Figs. 2c,d), leading to the

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**Figure 4.** As in Fig. 3, but for coefficients associated with IOD$_{ENSO}$.
larger impact associated with El Niño than that in the observed.

The PSA wave trains generated by the tropical Pacific SST anomalies associated with ENSO have been simulated well by the climate models (Fig. 5a, middle column). The PSA pattern is evident in both phases of ENSO in the west Pacific (Figs. 5b,c, middle column), being more westward during the La Niña phase. However, the positive height anomaly (blue shading) east of Australia during the La Niña phase is farther south and west than what is observed (Cai et al. 2012, their Figs. 2b,c) and thus has an impact on rain-bearing easterlies important for delivering rainfall to the eastern portion of the Australia continent (Risbey et al. 2009b; Cai et al. 2011, 2012).

Examining the impact on rainfall in the extratropics due to ENSO (Fig. 5a, right column) shows that the anomalies associated with ENSO are similar to those presented in Fig. 3a, highlighting the coherence between the IOD and ENSO during SON. In addition, although the coherence between the IOD and ENSO is weaker in the majority of models (an average correlation of 0.48 for the 36 CMIP5 models) compared to observations (correlation of 0.69), the impact of El Niño through the tropical Indian Ocean pathway is evident in the rainfall anomalies over the southern portion of the Australian continent (Fig. 5b, right column). This signal appears separate from the anomalies over the eastern portion of Australia associated with the direct tropical response and the tropical Pacific pathway. The exaggerated westward displacement of the La Niña convection response, and presumably the lack of a realistic representation of an orographic effect associated with the low model resolutions, results in significant rainfall anomalies associated with negative ENSO impacting the entire Australian continent (Fig. 5c, right column). This is in contrast to the observed La Niña impact through the Pacific pathway, where the impact is mainly over tropical northeastern and eastern Australian regions only. Overall, much impact on rainfall in the extratropics (over the Australian continent) in the negative phase presented in Fig. 5c is associated with pure La Niña events (Fig. 5c, right column), as opposed to pure nIODs (Fig. 4c, right column). It is this unrealistically large impact from the simulated La Niñas, showing up through the coherence with nIOD that gives rise to the comparable impact from nIOD events on Australian rainfall, as shown in Fig. 3c, giving the initial impression that the models do not simulate the asymmetry impact due to the IOD. Removing the covarying ENSO reveals that the models do indeed simulate an asymmetric impact over IOD-influenced regions in the tropics and the extratropics.

Another factor that contributes to the distortion by ENSO is related to the simulated ENSO skewness. A positive skewness in SST associated with ENSO is present in observations (Figs. 6a,c), meaning that the amplitude of El Niño is significantly larger than the amplitude of La Niña (Hoerling et al. 1997; Burgers and Stephenson...
Although the majority of the CMIP5 models examined here simulate a realistic negative SST skewness in the IODE associated with the IOD, very few models simulate the observed level of positive SST skewness associated with ENSO and approximately one-third of models simulate a negative skewness in ENSO (Figs. 6a,b). Comparing the decadal variability of the SST skewness in the observations since 1950 (red dots in Fig. 6a, calculated using a 30-yr sliding window, moving forward every 2 yr), the average CMIP5 SST skewness in the eastern Pacific (Fig. 6a, black square) is weaker than the weakest post-1950 skewness in the observations. The modeled weak ENSO positive skewness means that relative to El Niño, the amplitude of La Niña and its impact is overly large.

Figure 6a also shows that a significant relationship exists in the observations between the decadal variability of SST skewness in the IODE and Niño-3 regions; however, there is no intermodel relationship in the climate models, suggesting that there is less coherence between the IOD skewness and ENSO skewness in the models, which could have enhanced the impact of the IOD skewness in terms of the rainfall teleconnection. Therefore, although the models do simulate the asymmetric impact due to the IOD via the Indian Ocean pathway, the weaker asymmetry of the Pacific Ocean associated with ENSO reduces this impact.

5. Summary and conclusions

The present study assesses how well CMIP5 climate models simulate the Southern Hemisphere extratropical teleconnection pathways of the IOD and ENSO in the austral spring season (SON) and whether there exists an asymmetry in the IOD impact via the tropical Indian Ocean, as identified in observations. We show that the models do indeed simulate a greater impact on Australian rainfall for pIOD events than for nIOD events, despite the large diversity in their IOD intensity, as summarized in Fig. 7. Similarly, with regards to ENSO, the models also capture the realistic impact pathway of El Niño events, forcing an extratropical response via the tropical Indian Ocean (Fig. 7b, right column).

However, the asymmetry in the impact of the IOD is distorted by two factors (i.e., Fig. 7, left column). The distortion results from biases in the Pacific in two respects. First, the tropical and extratropical response to La Niña is situated unrealistically too far westward and, thus, too close to Australia (Fig. 7c, right column). This results from the tropical convection anomalies and the extratropical PSA pattern being situated too far westward during La Niña events, impinging on eastern Australia, leading to an overly strong impact on southeast Australia that shows up through the nIOD–La Niña coherence. Second, the majority of models simulate a positive SST skewness in the eastern Pacific that is too weak, overestimating the impact of La Niña relative to that of El Niño. The overly large impacts from La Niña again manifest through its coherence with nIOD. The lack of an orographic effect due to low model resolution may help generate a pan-Australia rainfall effect exacerbating the tropical bias. The asymmetry in the IOD becomes apparent only after removing ENSO (Fig. 7, middle column).
Climate projections using these models need to consider such bias and the associated impacts. For example, most models simulate a slower warming rate in the eastern tropical Indian Ocean than in the western tropical Indian Ocean, inducing a pIOD-like mean state change, in terms of zonal SST gradients. Since the mid-twentieth century, observations show that consistent mean circulation changes have emerged in the tropical Indian Ocean (Cai et al. 2009a), trending toward such a future warming pattern as projected by the models. Given that the mean state change will influence mean rainfall trends, rainfall projections are likely to be distorted by the biases in the Pacific as well, making it harder for the rainfall trends to emerge. Therefore, our result highlights the importance of reducing the distortion in future projections of rainfall changes in IOD-affected regions such as Australia.

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