Key process diagnostics for monsoon intraseasonal oscillation over the Indian Ocean in coupled CMIP6 models

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Abstract
The simulations of the monsoon intraseasonal oscillation (MISO) during the Indian summer monsoon (ISM) are evaluated with 19 atmosphere–ocean coupled general circulation models (CGCMs) from phase 6 of the Coupled Model Inter-comparison Project (CMIP6). The focus is on the northward propagation of MISO. The CMIP6 models have great improvement in simulating the mean rainfall, as 17 out of 19 models can reasonably simulate the mean rainfall. However, many models fail to reproduce the realistic patterns of the mean rainfall and the MISO amplitude, particularly over land in the monsoon region. The underestimation of the MISO amplitude is still a notable model bias in CMIP6. Moreover, 9 out of 19 models cannot generate realistic northward propagation features, and some even reproduce a stationary MISO pattern. Process diagnostics based on the seasonal mean vertical zonal wind shear, low-level mean moisture, and vortex tilting are also examined. It is found that the accuracy of model simulations of vortex tilting is strongly associated with the northward propagation of MISO. In contrast, the model fidelity in MISO is not dependent on the simulation skill for the seasonal mean state. In addition, decomposition analysis of vortex tilting illustrates that the meridional shear of the intraseasonal vertical velocity is crucial to the tilting simulation. The poor model fidelity in vortex tilting is caused by the weak convection, particularly the absence of downdraft to the north of the convection center. The coupling between the moisture in the boundary layer and the tilting in the free troposphere may be responsible for capturing the vertical motions. In summary, vortex tilting can be a useful metric for evaluating the northward propagation of MISO.

Keywords Monsoon intraseasonal oscillation · Vortex tilting · Model evaluation · CMIP6

1 Introduction
The intraseasonal oscillation (ISO) is the predominant atmospheric variability in the tropics. The main feature of the ISO is that it is characterized by the different propagation directions in boreal summer and boreal winter (Wang and Rui 1990). The eastward-propagating ISO, also known as the Madden–Julian Oscillation (MJO; Madden and Julian 1971, 1972), occurs mainly during boreal winter and its effects on the regional and global climate system have been investigated in many previous studies (such as Cassou 2008; Kessler and Kleeman 2000; Liu et al. 2022; Zhang 2013). However, during boreal summer, northward propagation becomes the prominent feature of the ISO and it is commonly known as the monsoon intraseasonal oscillation (MISO; Hoyos and Webster 2007). The MISO plays a prominent role in the onset of the Indian summer monsoon (ISM), tropical cyclone activity, ocean circulation, and the global hydrological cycle (Li et al. 2012, 2020; Meng et al. 2021; Webster 1983; Xie et al. 2018; Zhou and Murtugudde 2014). In particular, previous studies have proposed that the northward-propagating MISO has a significant influence on monsoonal precipitation variability (Goswami 2005; Krishnamurthy and Shukla 2008). It suggests that the accurate simulation and prediction of the northward-propagating MISO is tightly associated with the accurate prediction of the ISM.
The simulation of MISO depends on the understanding of MISO propagation dynamics. The mechanisms associated with MISO propagation have been examined in many previous studies, such as the Rossby wave emanation hypothesis (Lawrence and Webster 2001; Wang and Xie 1997), air-sea interactions (Fu et al. 2003; Kemball-Cook and Wang 2001), seasonal mean zonal and meridional winds (Bellon and Sobel 2008a; b; Drbohlav and Wang 2005; Jiang et al. 2004; Thual et al. 2015), the beta drift of the synoptic system (Boos and Kuang 2010), and convective momentum transport (Kang et al. 2010). In particular, the seasonal mean vertical zonal wind shear proposed by Jiang et al. (2004) has been used in many studies to explain the northward propagation of MISO (such as Sperber et al. 2013; Zhou et al. 2017). Jiang et al. (2004) proposed the mean vertical easterly shear mechanism based on a 2.5-layer model with the f-plane approximation. The positive barotropic vorticity is generated to the north of convection in the presence of the easterly wind shear, which triggers new convection with the aid of the moisture advection in the planetary boundary layer (PBL). This mechanism was further expanded in Drbohlav and Wang (2005). Subsequently, many studies have used the mean vertical easterly wind shear as a metric to explain MISO performance in the models (e.g., Kemball-Cook et al. 2002; Sperber and Annamalai 2008).

Although much progress has been made, simulation of MISO remains a significant challenge for state-of-the-art climate models. By evaluating 17 model simulations from phase 2+ and phase 3 of the Coupled Model Inter-comparison Project (CMIP2+ and CMIP3), Sperber and Annamalai (2008) pointed out that only 2 of the 17 models showed appreciable abilities to simulate the life cycle of MISO. Even so, Waliser et al. (2003) thought that the simulation skill with respect to the MISO had improved in CMIP3 when compared with the previous generation of models. Meanwhile, Sperber and Annamalai (2008) estimated the simulation relationship between seasonal mean easterly wind shear and MISO. They pointed out that the northward-propagating MISO is relatively better captured over the Indian Ocean than in other regions because the mean easterly wind shear is better represented there. This is consistent with the conclusion given by Kemball-Cook et al. (2002) based on the ECHAM4 general circulation model (GCM) coupled to a 2.5-layer intermediate ocean model. In comparison with the previous generation, the CMIP5 models show an improvement in simulating the northward propagation of MISO, but most models still have difficulties in accurately simulating a realistic MISO (Sabeerali et al. 2013; Sperber et al. 2013). More importantly, the underestimation of MISO variances has been attributed to the weak representation of mean vertical easterly shear. Furthermore, using the 27 GCMs participating in the year of Tropical convection MJO task force and global atmospheric system study (YOTC/MJOTF-GASS) program (Jiang et al. 2015), Neena et al. (2016) found that large discrepancies remain in model simulations of MISO propagation. In particular, the meridional extent of MISO propagation is misrepresented. Besides, the validity of the relationship between MISO propagation and the mean vertical easterly wind shear is disputed by Neena et al. (2016).

In addition, based on the models involved in the YOTC/MJOTF-GASS program, Jiang et al. (2018) concluded that the ability of a model to simulate the pattern of summer mean low-level moisture is closely related to its skill for MISO propagation. However, this relationship requires further examination using other models. Improving the poor representation of MISO propagation requires a focus on the specific process as well as the seasonal mean state. Li et al. (2021) was motivated to revisit the MISO mechanism with a focus on the multi-timescale interaction between the intra-seasonal and the seasonal components. They proposed the vortex tilting mechanism, in which the interaction between vorticity tilting and the mean easterly wind shear induces MISO to move northward. The vortex tilting mechanism is equivalent to the vertical shear effect presented by Jiang et al. (2004) but it explicitly shows that the MISO propagation is excited by the interaction of ISO winds and mean vertical wind shear.

In this study, we attempt to fully evaluate MISO performance in the CMIP6 models and test the relationships between model skill with respect to the seasonal mean vertical easterly shear, mean low-level moisture, vortex tilting, and the northward-propagating MISO. With a focus on the vortex tilting, we identify the key processes associated with MISO propagation according to the good versus poor simulations of MISO. The model outputs and reanalysis datasets used in this study are described in Sect. 2. The model evaluations with respect to the MISO and its key process diagnostics are presented in Sect. 3. Section 4 presents a discussion of the results and the main conclusions.

2 Model outputs and reanalysis datasets

Nineteen atmosphere–ocean coupled GCMs (CGCMs) are selected from the CMIP6, because these models provide all necessary variables for this study as of now. Daily historical simulations are selected, which are based on the first realization of all models, to assess the ability of the models to reproduce past climate variability. The specific model information is summarized in Table 1. More details regarding the CMIP6 models can be found at https://esgf-node.llnl.gov/projects/cmip6/. In addition to the model outputs, daily precipitation data are obtained from the Tropical Rainfall Measuring Mission (TRMM 3B42v7; Huffman et al. 2007). Other atmospheric variables, such as horizontal winds, specific humidity, and vertical velocity are selected from
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The fifth-generation ECMWF (ERA5) dataset is used, which has a horizontal resolution of 1.0° latitude × 1.0° longitude (Hersbach et al. 2020). To verify the robustness of the results, the ECMWF reanalysis-interim (ERA-interim; Dee et al. 2011) products are also applied to evaluate the model performances, but they are not shown here. The coupled models all shared the common period of 1998–2014 and the focus of this study is the ISM season. Hence, all analyses are performed for the period from June to September (JJAS) between 1998 and 2014. The intraseasonal component is defined as the signals with a period between 20 and 100 days. The Butterworth band-pass filter of 20–100-day is applied to obtain the intraseasonal component from the daily raw data and it is denoted with a prime. The background component is defined as the signals with a period over 100 days, and is obtained by using a 100-day Lanczos low-pass filter to the daily raw data. It is denoted with a bar.

In this study, model fidelity with respect to their representation of MISO and other variables is assessed using the pattern correlation coefficients (PCCs) and the normalized standardized deviations between the simulations and the observations. The PCC has been widely used in previous studies to determine the linear relationship between two spatial patterns (Clodman 1987; Li et al. 2021). The normalized standardized deviations indicate the relative amplitude of the model and observed variations. Because the comparison must have the same number of dimensions, the model outputs and reanalysis products are all interpolated onto a common horizontal resolution of 2.5° latitude × 2.5° longitude. Moreover, the statistical significance of the correlation coefficient is tested using Student’s t test. The effective number of degrees of freedom is determined following the modified Chelton method (Pyper and Peterman 1998).

3 Results

3.1 Individual performance of the coupled models

As the MISO is closely related to summer monsoon rainfall, the ISM mean rainfall simulated by the 19 CGCMs is assessed (Fig. 1b–t) and compared with the observations (Fig. 1a). The region of the tropical Indian Ocean bounded by 0°N–30°N and 70°E–110°E (Fig. 1) is defined as the MISO domain for this study. The observed mean summer rainfall is intense over the Indian peninsula and the Bay of Bengal (BoB), particularly over the northern BoB (10°N–25°N; 90°E–100°E) where the rainfall is greater than 14 mm day⁻¹. In CMIP6, 17 out of 19 models can reasonably simulate the mean summer rainfall. But only two models can simulate the mean

Table 1 The CMIP6 models used in this study

| Model name               | Modeling center/country                                      |
|-------------------------|-----------------------------------------------------------|
| ACCESS-CM2              | Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Bureau of Meteorology (BOM)/Australia |
| ACCESS-ESM1-5           |                                                            |
| BCC-CSM2-MR             | Beijing Climate Center, China Meteorological Administration/China |
| BCC-ESM1                |                                                            |
| CanESM5                 | Canadian Centre for Climate Modelling and Analysis (CCCMA)/Canada |
| CESM2-WACCM-FV2         | National Science Foundation, Department of Energy, NCAR/USA |
| CESM2                   |                                                            |
| EC-Earth3-Veg           | European Centre for Medium-Range Weather Forecasts         |
| GFDL-CM4                | NOAA Geophysical Fluid Dynamics Laboratory/USA              |
| IPSL-CM6A-LR            | Institute Pierre-Simon Laplace (IPSL)/France              |
| MIROC6                  | Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology/Japan |
| MPI-ESM1-1-2-HAM        | Max Planck Institute for Meteorology/Germany               |
| MPI-ESM1-2-HR           |                                                            |
| MPI-ESM1-2-LR           |                                                            |
| MRI-ESM2-0              | Meteorological Research Institute (MRI)/Japan              |
| NEMO                    | Nanjing University of Information Science and Technology/China |
| NorESM2-LM              | Norwegian Climate Centre/Norway                            |
| NorESM2-MM              |                                                            |
| SAM0-UNICON             | Seoul National University/South Korea                      |
rainfall pattern with a PCC over 0.8 (EC-Earth3-Veg in Fig. 1i and NorESM2-MM in Fig. 1s). Thereby, most models still show notable biases in their simulations of mean summer rainfall over the MISO domain, particularly over the maxima rainfall region. For example, the mean rainfall maximum over the northern BoB region is simulated too widely in the BCC models (Fig. 1d, e) and CESM2-WACCM-FV2 (Fig. 1h). Additionally, the maxima rainfall over the Indian land region (10°N–20°N; 70°E–80°E) is underestimated by ACCESS-CM2 in Fig. 1b, ACCESS-ESM1-5 in Fig. 1c, CanESM5 in Fig. 1f, MRI-ESM2-0 in Fig. 1p. Some models overestimate the rainfall over the Indian land region (e.g., BCC-CSM2-MR in Fig. 1d, BCC-ESM1 in Fig. 1e, and CESM2-WACCM-FV2 in Fig. 1h). In comparison with the simulations from CMIP5, the models have an improvement in simulating the mean rainfall intensity. However, as in CMIP5 (Sabeerali et al. 2013),

Fig. 1 Mean rainfall during the ISM (June–September) from a TRMM and b–t each CMIP6 model. The units are mm day$^{-1}$
the simulation biases of mean rainfall patterns still exist, particularly over land monsoon regions in CMIP6.

The standard deviation (STD) of the intraseasonal rainfall is always applied to estimate the MISO amplitude, such as in Sobel et al. (2008) and Neena et al. (2016). The observed and simulated STDs of MISO are shown in Fig. 2. Six models have the ability to simulate the reasonable intensity as their normalized standardized deviations are between 0.75 and 1.25 (ACCESS-CM2, ACCESS-ESM1-5, IPSL-CM6A-LP, MIROC6, MPI-ESM1-2-HR and SAM0-UNICON). The BCC-CSM2-MR and BCC-ESM1 overestimate the MISO amplitude in the simulations (Fig. 2d, e) by about 1.5 mm day$^{-1}$. Except for the BCC models, other models with lower normalized standardized deviations underestimate the MISO amplitude apparently. For example, ACCESS-ESM1-5 (Fig. 2c), CanESM5 (Fig. 2f),

Fig. 2 Standard deviation of intraseasonal rainfall during the ISM from a TRMM and b–t each CMIP6 model. The units are mm day$^{-1}$. 

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EC-Earth3-Veg (Fig. 2i), and MRI-ESM2-0 (Fig. 2p) largely underestimate the MISO amplitude over the BoB region by about 1.5 mm day$^{-1}$, which is almost half of the observed intensity. Particularly, the STD of MISO is largely underestimated in the equatorial Indian Ocean in these models. Thereby, these models have poor skills in depicting the MISO activity in the tropical Indian Ocean, and these model biases are also seen in CMIP5 (Sabeerali et al. 2013). In general, few models can reproduce the realistic pattern of the MISO amplitude, as many models have a PCC lower than 0.7. Corresponding to CMIP3 and CMIP5, the STD pattern of MISO is still being poorly depicted (Sabeerali et al. 2013; Sperber et al. 2013; Waliser et al. 2003). In addition, the PCC in the STD of MISO is in agreement with that in the mean summer rainfall, as their correlation coefficient is $\sim 0.68$ and is significant at the 95% confidence level. For example, EC-Earth-Veg is the model that shows superior simulation skill for the pattern of the MISO amplitude (Fig. 2i) and the mean rainfall (Fig. 1i). This suggests that simulation of the MISO amplitude is closely associated with mean rainfall patterns, which is corresponding to the simulations in Sperber et al. (2000) and Neena et al. (2016). Across the 19 models, the multi-model mean of the mean rainfall shows dry biases over the MISO domain. Similarly, the multi-model mean of the STD of MISO is marked by negative biases over the study region. The multi-model means are not shown here but were reported in our previous study (Li et al. 2021).

In addition to the MISO amplitude, the northward propagation becomes the dominant characteristic of MISO during the ISM season and it is more complex than the MJO (Wang and Rui 1990; Jiang et al. 2004; Wang et al. 2018). Consequently, we examine the ability of the models to capture the spatial pattern associated with the northward propagation of MISO using the regionally averaged intraseasonal rainfall within 5°N–15°N, 0°E–95°E, which is regarded as the MISO index (Sikka and Gadgil 1980; Li et al. 2021). As shown in Fig. 3, when the MISO index reaches its local peak and is greater than the value of the mean plus STD, the day is defined as Day 0 and marked by the red dot. All Day 0s (red dots) represent the significant MISO events as the pronounced convection center reaches the selected region of 5°N–15°N, 0°E–95°E. There are 31 significant MISO events from 1998 to 2014 in observations, which are used for the composite analysis hereafter. To demonstrate the whole process of northward propagation, 20 days before and after Day 0 are selected from all significant MISO events. Then, the Hovmöller diagram of intraseasonal rainfall from TRMM with respect to Day 0s is composited (Fig. 4a). It is notable that the intraseasonal rainfall propagates from 5°S to 20°N and beyond. We examine the performance of the models in simulating the northward propagation of MISO using the same method. For each model, the composite analysis is applied but its own Day 0 is defined using the model simulated rainfall, unlike for the observations. Accordingly, the composite Hovmöller diagram of MISO for each model is created with respect to its own Day 0 (Fig. 4b–t). The results do not change significantly with different selections of the reference box of the MISO index.

There is no doubt that the significant precipitation signal is most pronounced over the selected region of 5°–15°N. Ten models are able to capture the northward propagation features reasonably well. For example, ACCESS, MPI and NorESM2 show superior skills in simulating the northward propagation of MISO (Fig. 4b, c, m, o and r, s, respectively). In these well-simulated models, the simulated MISO pattern can propagate meridionally from 5°S to 25°N. In comparison to CMIP5, only 7 models (GFDL-CM3, GFDL-ESM2M, MPI-ESM-MR, MPI-ESM-LR, MPI-ESM-P, CMCC-CM, and CNRM-CM5) have a PCC over 0.8 as reported by Sabeerali et al. (2013). Thereby, the CMIP6 models show an improvement in simulating the northward propagation of MISO. MPI and GFDL are models that have a good representation in northward-propagating MISO in both CMIP5 and CMIP6. Conversely, the other half of the models have difficulty in representing the realistic northward propagation of MISO. For example, in BCC (Fig. 4d, e), CanESM5 (Fig. 4f), EC-Earth3-Veg (Fig. 4i), and IPSL-CM6A-LR (Fig. 4k), the MISO appears localized over the region of 5°N–15°N. In addition, a good association is observed between the PCCs of the MISO propagation (Fig. 4b–t) and PCCs of the STD of MISO (Fig. 2b–t), with a significant correlation coefficient of 0.54. This suggests that the simulation skill for the MISO propagation simulation is well linked to the simulation of the MISO activity pattern.
3.2 Simulations of key physical mechanisms

The ability of a model to simulate the MISO is limited largely by our understanding of the MISO propagation dynamics. One mechanism of MISO propagation is based on the vertical shear of background zonal winds (Jiang et al. 2004; Drbohlav and Wang 2005). This highlights the role of mean vertical easterly shear in inducing the propagation of MISO. Some studies have verified that a higher score for the mean vertical easterly shear improves model fidelity with respect to MISO propagation (Sperber and Annamalai, 2008; Yang et al. 2019). Correspondingly, we evaluate the performance of the mean vertical easterly shear during the ISM season in each model (Fig. 5). The pronounced mean vertical easterly shear over the BoB is well captured by most models. 95% (68%) of the models have a PCC higher than 0.8 (0.9). This suggests that the CMIP6 models have good skills in depicting the pattern of the background zonal winds. Moreover, the relationship between model simulation skill with respect to MISO propagation and the mean easterly wind shear is plotted in Fig. 6a. Although the models generally show reasonable simulations for the mean zonal winds, the simulations of MISO propagation are still unsatisfactory. Their correlation coefficient is only −0.03 and is not statistically

Fig. 4 Hovmöller diagrams of composite intraseasonal rainfall during the ISM from a TRMM and b–t each CMIP6 model. The rainfall is averaged within 80°E–95°E. The units for rainfall are mm day\(^{-1}\). All dotted areas are significant at the 99% confidence level
significant at the 95% confidence level. There is a poor association between model fidelity for the mean easterly
wind shear and that for MISO propagation. For example, BCC-CSM2-MR (Fig. 5d) and CanESM5 (Fig. 5f) show
superior simulation skills for the mean vertical easterly
shear pattern, with a PCC of 0.96 and 0.94, respectively.
However, they fail to simulate a reasonable
northward-propagating MISO, because the simulated
MISO propagation is almost localized over 5°N–15°N
(Fig. 4d, f). This suggests that we should reexamine the
role of the mean vertical easterly shear in the MISO the-
ory, and this will be considered below.

In addition to the dry dynamics discussed in this study,
moist processes were invoked to explain MISO in a series of

Fig. 5 Mean vertical shear of background zonal winds $\frac{\partial u}{\partial p}$ (the difference between $\bar{u}$ at 850 hPa and $\bar{u}$ at 200 hPa) during the ISM from a ERA5 and b–t each CMIP6 model. The units for $\frac{\partial u}{\partial p}$ are m s$^{-1}$.
The observed moisture increases with latitude and corresponds to the monsoon rainfall pattern (Fig. 7a). In addition, the mean moisture maximum greater than 10 g kg\(^{-1}\) is significantly located over the region within 15°N–25°N and 80°E–100°E in ERA5. 10 out of 19 models have the ability to reproduce the mean low-level moisture pattern, with the maximum moisture over the northern BoB. However, the other half of the models in CMIP6 has difficulty in simulating the realistic mean moisture. For example, the ACCESS models cannot simulate reasonably the latitudinal distribution of the mean moisture (Fig. 7b, c). Several models even fail to simulate the location of the moisture maxima, such as CanESM5 (Fig. 7f) and MRI-ESM2-0 (Fig. 7p). The simulation of low-level moisture is further evaluated using the pattern correlation between the ERA5 reanalysis (Fig. 7a) and the corresponding pattern for each model (each panel in Fig. 7b–t). As shown in Fig. 6b, the PCCs for the northward-propagating MISO do not have a strong dependence on the PCCs for low-level moisture, with a non-significant
correlation coefficient of –0.02. For example, in EC-Earth3-Veg (Fig. 7i), the simulated mean low-level moisture has a PCC of 0.91 with the observations (Fig. 7a). However, the simulated northward-propagating MISO (Fig. 4i) has a PCC of only 0.55 with the observations (Fig. 4a). Thus, as the impact of \( \frac{\partial 
abla}{\partial t} \), we hypothesize that the mean low-level moisture plays a similar role in the northward-propagating MISO. The models that reasonably simulate the background moisture are also likely to accurately represent the moisture.

Fig. 7 Mean specific humidity between 900 and 600 hPa during the ISM from a ERA5 and b–t each CMIP6 model. The units for mean specific humidity are g kg\(^{-1}\).
processes associated with the MISO. However, some other important details regarding the mean low-level moisture are also required. Some previous studies have emphasized that the advection of moisture by the intraseasonal winds plays a crucial role in the northward propagation of MISO (Qin et al. 2020, 2022; Wang et al. 2018). Thus, improved model simulation skills with respect to the advection process may be a breakthrough that can connect the background moisture to the MISO. The close relationship between moisture and MISO propagation requires further investigation. Nonetheless, the PCCs for low-level moisture are generally less than the performance of the mean vertical easterly shear. This indicates that the models are not yet as accurate for capturing the background moisture as the simulation of the background dynamic field. Despite that, the simulation of low-level moisture in most models does show an improvement compared with the CMIP5 simulations (Ahn et al. 2017).

Our previous study pointed out the vortex tilting processes play a crucial role in the MISO propagation by diagnosing the vorticity budget in observations (Li et al. 2021). The work fully demonstrated the vortex tilting processes with different timescale interactions. Vortex tilting is defined as $\frac{\partial \omega' \partial z}{\partial y}$, where $\omega'$ is the intraseasonal vertical velocity in an isobaric coordinate. $\frac{\partial \omega' \partial z}{\partial y}$ implies that the mean horizontal vortex, induced by the vertical shear of the background zonal wind, is tilted by the intraseasonal vertical velocity shear. It can cause a cyclonic vorticity anomaly to the north of the MISO convection, which further develops into new convection and leads the northward propagation. This multi-scale

**Fig. 8** Hovmöller diagrams of composite tilting $\frac{\partial \omega' \partial z}{\partial y}$ from (a) ERA5 and (b–t) each CMIP6 model. All terms are integrated from 850 to 200 hPa and averaged within 80°E–95°E. See text for the definition of Day 0 in the composite analysis. The units for vorticity tilting are kg m$^{-2}$ day$^{-1}$. All dotted areas are significant at the 99% confidence level.

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interaction plays a much more important role in the MISO simulation than does the mean state alone. Here, the Hovmöller diagrams of the composite \( \frac{\partial u}{\partial y} \frac{\partial p}{\partial y} \) with respect to Day 0 based on ERA5 and models are shown in Fig. 8. The vortex tilting is vertically integrated from 850 to 200 hPa and zonally averaged within 80°E–95°E. The observed tilting propagates significantly from the equator to 20°N (Fig. 8a). On Day 0, the positive tilting anomaly reaches around 15°N, when the convection center is located at nearly 10°N. Hence, the tilting leads the convection center and drives the MISO propagation. In CMIP6, the composite tilting structure can be reasonably captured by about half of the models as PCCs of nine models are higher than 0.8. Particularly, CESM2, MPI-ESM-1-2-HAM, and NorESM2-LM have a good model fidelity with respect to the northward-propagating vortex tilting (Fig. 8g, m, r, respectively). In general, these three models are able to reproduce a northward-propagating MISO pattern that resembles the observations reasonably well (Fig. 8g, m, r). In contrast, several models have a poor model fidelity in the vortex tilting propagation. For example, BCC-CSM2-MR, BCC-ESM1, CanESM5 and IPSL-CM6a-LR can only simulate the localized tilting without a propagation pattern (Fig. 8d, e, f, k). Consequently, the simulated MISO is confined to 5°–15°N (Fig. 4d, e, f, k).

For clarity, the PCCs between the simulated and the observed tilting propagation structures are also calculated and plotted against the PCCs for the MISO propagation (Fig. 6c). The significant relationship of simulation skill between the MISO propagation and vortex tilting is evident, and their correlation coefficient is 0.83. The linear regression line, fitted using least-squares means with respect to the PCCs, indicates that a better rendition of the tilting is associated with the MISO simulation. The Taylor diagram is applied to compare model performances on the northward-propagating MISO, as shown in Fig. 9. There are two statistics used in the Taylor diagram: the PCC and the normalized standardized deviations between model simulations and the observations. Accordingly, the performance of the CMIP6 models with respect to MISO is quantified and illustrated in Fig. 9. The model of EC-Earth3-Veg has the lowest normalized standardized deviation (about 0.54), which indicates that its simulation for the northward propagation of MISO (Fig. 4i) is the weakest when compared with the observation (Fig. 4a). Two other models have similarly low normalized standardized deviations; i.e., IPSL-CM6a-LR with 0.56 and CanESM5 with 0.59. In contrast, BCC-ESM1 has the highest normalized standardized deviation of 1.3 and significantly overestimates the intensity of the northward-propagating MISO (Fig. 4e). In addition, NorESM2-LM, MPI-ESM-1-2-HAM, and MIROC6 have the highest PCCs (>0.86) across the models. They can simulate the most realistic propagation pattern (Fig. 4).

Consequently, we select six models as the good (poor) simulation group, with respect to their PCCs and normalized standardized deviations for simulating the northward-propagating MISO. These two groups, with their different simulation capabilities, give us the opportunity to shed light on the key processes associated with the vortex tilting mechanism. The composite Hovmöller diagrams of the intraseasonal rainfall are created based on the good and poor simulation groups (Fig. 10a, b). All intraseasonal rainfall anomalies are zonally averaged within 80°–95°E. CESM2, CESM-WACCM-FV2, MPI-ESM-1-2-HAM, MPI-ESM1-2-HR, MIROC6, and NorESM2-LM are selected to represent models with superior simulation skills for MISO propagation. Significantly, the good simulation group can reproduce a realistic MISO propagation pattern (Fig. 10a). As in the observations (Fig. 4a), the MISO propagates from 5°S to 25°N. In comparison, the poor simulation group has difficulty in capturing the MISO propagation characteristics, as the pronounced rainfall is confined around 5°N–15°N (Fig. 10b). This is consistent with the individual poor performance of these selected models; i.e., BCC-CSM2-MR, BCC-ESM1, CanESM5, EC-Earth3-Veg, IPSL-CM6a-LR, and NESM3. The northward-propagating vortex tilting is composited with respect to Day 0 for the good and poor simulation groups (Fig. 10c, d). The tilting anomaly is zonally averaged within 80°E–95°E and vertically integrated from 850 to 200 hPa. Similarly, for models with a good MISO simulation capability, the simulation for tilting (Fig. 10c) is close to the observations (Fig. 8a). Meanwhile, the propagation of tilting breaks down around 10°N (convection center), and no complete propagation path is simulated in the poor simulation group (Fig. 10d). Hence, the groups display the
differences in simulation skills related to the MISO and vortex tilting explicitly.

The tilting \( \frac{\partial \omega'}{\partial y} \) denotes the interaction between the background vertical easterly wind shear \( \frac{\partial u}{\partial y} \) and the meridional shear of intraseasonal vertical velocity \( \frac{\partial \omega'}{\partial y} \). In Fig. 10e, f, \( \frac{\partial u}{\partial y} \) is shown for the good and poor simulation groups. This denotes that the mean vertical easterly shear can be well captured by these two groups. The PCC of \( \frac{\partial u}{\partial y} \) between the good (poor) simulation group and ERA5 (Fig. 11a) is high at 0.96 (0.95). There is no statistically significant difference in the representation of the vertical shear of mean zonal winds between the good and poor simulation groups. This is consistent with the above results in that the mean state is not the major factor affecting the MISO simulation. The composite Hovmöller diagrams of \( \frac{\partial u}{\partial y} \) are created with respect to Day 0 using the ERA5 data and the good and poor simulation groups (Fig. 11a–c). The composite \( \frac{\partial \omega'}{\partial y} \) is zonally averaged within 80°-95°E and vertically integrated from 850 to 200 hPa. The composite \( \frac{\partial \omega'}{\partial y} \) anomaly for the good simulation group (Fig. 11b) is generally the same as that for ERA5 (Fig. 11a), with their PCC of ~0.9 is significant at a 95% confidence level. However, the \( \frac{\partial \omega'}{\partial y} \) anomaly is much weaker and shows a broken structure around 10°N in the poor simulation group, which is similar to the tilting pattern in Fig. 10d. In the vortex tilting mechanism, it is highlighted that the vertical velocity is non-uniform in the meridional direction. Hence, the weak \( \frac{\partial \omega'}{\partial y} \) results in a lack of capacity for a non-uniform lifting of the vortex tube induced by \( \frac{\partial \omega'}{\partial y} \), which further leads to the poor simulation of tilting and the MISO.

Theoretically, there are two possible causes of a weak \( \frac{\partial \omega'}{\partial y} \).

1. One is that the vertical velocity is strong but uniformly distributed in the meridional direction. The other is that the vertical velocity itself is simulated very weakly. Next, we explore the simulation differences of the vertical velocity in the meridional–vertical domain (Fig. 11d–f). The composite \( \omega' \) is zonally averaged within 80°-95°E with respect to Day 0. As shown in Fig. 11d, the composite \( \omega' \) displays a dipole structure, with the updraft reaching its maximum at around 10°N and the downdraft at around north of 20°N. The updraft and the downdraft are significant throughout the troposphere and correspond to the height of the deep convection. In the good simulation group (Fig. 11e), the locations of the downdraft and the updraft throughout the troposphere are reasonably simulated. It induces that \( \frac{\partial \omega'}{\partial y} \) in the good simulation group is well constructed and closer to ERA5. However, in the poor simulation group (Fig. 11f), the simulated updraft is much less than that in either ERA5 or the good simulation group. In addition to the intensity, the poor simulation group fails to reproduce the positive–negative dipole along the latitudinal direction. This is partly because the updraft is not strong enough to stimulate the downward branch of the convective circulation to the north of convection. This substantially weakens the intensity of the vertical velocity shear in the meridional direction, leading to the failure to simulate reasonable \( \frac{\partial \omega'}{\partial y} \) (Fig. 11c). Thus, the well-simulated horizontal vortex \( \frac{\partial \omega'}{\partial y} \) cannot be effectively tilted by the weak \( \frac{\partial \omega'}{\partial y} \) in the poor simulation group, which further leads to the models failing to capture the realistic vortex tilting and MISO propagation. Basically, an updraft strong enough to cause sinking on its northern side is essential to the vortex tilting process. Nevertheless, convective downdrafts have been observed to significantly affect tropical convective systems (Cheng 1989; Jiang et al. 2010; Houze 1977; Mishra and Sahany 2011). For example, Maloney and Hartmann (2001) pointed out that a convection scheme with an unsaturated downdraft can produce realistic intraseasonal variability. In the coupled models of CMIP6, it implies that the simulation skill associated with the downdraft to the north of convection is also core for tilting and MISO simulations.

4 Conclusions and discussion

The MISO becomes the majority component during the Indian summer monsoon season over the Indian Ocean, which is characterized by the northward propagation. The
The evaluation of MISO presented here is carried out using 19 of the coupled ocean–atmosphere models from the CMIP6. A set of evaluation metrics is used to assess the simulation of mean summer rainfall, the intraseasonal rainfall variance, and the northward propagation of MISO in the summer monsoon domain. The validity of some reported relationships is also tested; i.e., the model simulation associations between the mean vertical easterly shear, mean low-level moisture, vortex tilting, and the northward propagation of MISO. Process diagnostics according to vortex tilting are applied to model simulations to test their usability with respect to the northward propagation of MISO.

Fig. 10 Hovmöller diagrams of composite intraseasonal rainfall (a, b) and vorticity tilting (c, d), and the mean vertical shear of background zonal winds \( u' \) (e, f) during the ISM for the good (left column) and poor (right column) simulation groups. The rainfall is averaged within 80°E–95°E. The units for rainfall are mm day\(^{-1}\). The vorticity tilting is integrated from 850 to 200 hPa and averaged within 80°E–95°E. The units for vorticity tilting are kg m\(^{-2}\) day\(^{-1}\). The units for \( \frac{u'}{p} \) are m s\(^{-1}\). See text for the classification of simulation groups used in the composite analysis. All dotted areas are significant at the 99% confidence level.
CMIP6 has an improvement in simulating the intensity of the summer mean rainfall as 17 out of 19 models have a reasonable normalized standardized deviation. However, the mean rainfall pattern is still a challenge to CMIP6 models. The dry biases in the mean summer rainfall are still observed over the Indian Ocean, particularly the monsoon land regions. The MISO amplitude, namely the intraseasonal rainfall variance, carries a similar dry bias to that seen in the mean rainfall. Most models cannot capture the observed MISO amplitude. Underestimation of the MISO amplitude is still a notable bias. Meanwhile, several models fail to simulate the MISO amplitude in the equatorial Indian Ocean, like the situation in CMIP5. The model skill with respect to simulating the mean rainfall agrees well with the simulation skill for the MISO amplitude. Composite analysis is used to estimate the northward propagation feature of MISO. 10 out of 19 models can represent the realistic MISO propagation in CMIP6. As in CMIP5, models from the MPI and GFDL always have a good performance in simulating the northward-propagating MISO. However, large discrepancies are evident in the model depictions of the northward propagation of MISO. Some models still simulate a stationary MISO, and the meridional extent near the equator and the northern BoB are misrepresented.

As the main focus of this study is on the northward propagation of MISO, some of the reported common metrics are also evaluated. The importance of simulating the seasonal mean vertical easterly shear and the seasonal mean low-level
(900–600 hPa) moisture pattern is examined as being a requisite condition for MISO northward propagation. Nearly all models have the ability to successfully simulate the mean vertical easterly shear. However, there is no significant relationship of simulation between the northward propagation of MISO and the mean vertical easterly shear. A poor association is also found between the mean low-level moisture simulation and the northward propagation of MISO. Hence, even in half of the models that show good fidelity in simulating the mean moisture, the northward propagation is still misrepresented. Meanwhile, a good association is evident between the simulation of vortex tilting and the northward propagation of MISO. Models from CMIP6 that are successful in simulating the observed vortex tilting generally can simulate the realistic northward propagation of MISO. Thus, the vortex tilting diagnostic is a useful metric for the northward-propagation of MISO.

To further evaluate model performance with respect to the northward-propagating MISO, two groups of six models are identified as generating good and poor simulations. Accordingly, vortex tilting, and the decomposed components (\( \frac{dp}{dr} \) and \( \frac{dq}{dr} \)) are generated for these two groups. Notable differences in the variables for these groups. The MISO and vortex tilting are generally the same as the observed propagation patterns for the good simulation group. However, the simulation of MISO is weak and does not show the observed meridional propagation structure in the poor simulation group. This group also has difficulty in simulating the vortex tilting, as the anomalies are poorly simulated in the convection center around 10°N. Further analysis shows that the poor tilting representation is caused mainly by poor simulation of \( \frac{dp}{dr} \) rather than \( \frac{dq}{dr} \). In the poor simulation group, the updraft is relatively weak and the downdraft to the north of convection is not reproduced. It results in the meridional shear of the intraseasonal vertical velocity being weaker in the poor simulation group than in the observations and in the good simulation group. Overall, this evaluation of MISO in the coupled CMIP6 simulations shows that the representation of some MISO features is better than that associated with CMIP5 (Sabeerali et al. 2013). However, the dry biases persist in the mean rainfall and intraseasonal rainfall variance simulations. Vortex tilting simulation skill shows a direct relationship with the simulation skill for the northward propagation of MISO. The meridional structure of vertical velocity at the intraseasonal timescale is crucial to the tilting simulation. In particular, the downdraft to the north of convection can influence the tilting intensity.

In addition, some studies pointed out that the convection parameterization scheme is strictly associated with moisture distribution (e.g., Hack 1994; Thomas et al. 2021; Zhang and Mu 2005). Thus, we further analyze the composite intraseasonal specific humidity in the meridional–vertical domain with respect to Day 0 (Fig. 11g–i). Clearly, a good relationship is evident between the specific humidity (Fig. 11g) and vertical velocity (Fig. 11d) in ERA5. The moisture anomaly also shows a dipole structure in the meridional direction, as the wet anomaly locates around 5°N–15°N and the dry anomaly locates around 25°N–30°N (Fig. 11g), which coincide with the updraft and the downdraft, respectively (Fig. 11d). Similarly, the dipole structure in moisture is well simulated in the good simulation group (Fig. 11h). However, the poor simulation group can only simulate the positive specific humidity anomaly. Given that previous studies demonstrate that the drying in front of convection during ISOs is associated with the downdraft processes (e.g., Kiladis et al. 2005; Fu et al. 2006; Tian et al. 2006), it may partly explain the lacking of the downdraft anomaly in Fig. 11f. Moreover, it is found that the moisture maximum locates in the PBL in the poor simulation group. Thereby, in the poor simulation group, the PBL moisture cannot effectively transport up to the free troposphere and supply the deep convection. It implies that the simulation for the coupling processes between the moisture in the PBL and the vorticity in the free troposphere may be responsible for the representation in simulations for vertical motions and tilting in CMIP6. However, the hypothesis may serve as our understanding of MISO and vortex tilting, and this needs to be explored with more work in the future.

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**Data availability statement** The ERA5 reanalysis products are provided by the European Centre for Medium-range Weather Forecast (ECMWF), which can be obtained from their Web site at [https://apps.ecmwf.int/datasets/](https://apps.ecmwf.int/datasets/). The TRMM precipitation data is publicly available from the National Aeronautics and Space Administration (NASA; https://disc.gsfc.nasa.gov/datasets/TRMM_3B42RT_Daily_V7?summar). The CMIP6 model outputs are produced by the Working Group on Coupled Modelling and climate modeling groups in the World Climate Research Programme ([https://esgf-node.llnl.gov/projects/cmip6/](https://esgf-node.llnl.gov/projects/cmip6/)).

**Declaration**

**Conflict of interest** The authors declare that they have no conflict of interest.

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