



Monsoon intra-seasonal variability in a high-resolution version of Met Office Global Coupled model

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ABSTRACT

Intra-seasonal oscillation (ISO) is a key ingredient of the East Asia and western North Pacific (EAWNP) summer monsoon and particularly important for seasonal forecast. This paper evaluates the seasonal means and ISOs of the EAWNP summer monsoon simulated by the latest version of the Met Office Global Coupled Model (HadGEM3-GC2) with two different atmospheric model resolutions at ~ 130 and ~ 25 km coupled to a same $0.25^\circ \times 0.25^\circ$ resolution ocean model. Results show that the mean states of sea surface temperature (SST), low-level specific humidity and the western Pacific subtropical high are all improved in HadGEM3-GC2 with higher atmosphere resolution. Moreover, although ISO variance is overestimated over the western North Pacific, the model has good fidelity in characterising ISO basic features over the EAWNP including the dominant EOF structure, northward propagation and cycle evolution, as well as the zonal displacement of western Pacific Subtropical High and South Asian High associated with the northward propagating ISOs. Increasing atmosphere model resolution yields improvements in most aspects of the Monsoon ISO over the EAWNP, especially for its northward propagation. Further analysis indicates that this improvement is mainly due to the better description of ISO-related air–sea interaction in higher resolution experiment, as evidenced by the enhanced intra-seasonal SST variance and more coherent northward propagation of rainfall, SST, and the associated surface dynamic and thermodynamic variables in the higher resolution model.

Keywords: East Asia monsoon, intra-seasonal Oscillation, high-resolution modelling, HadGEM3-GC2

1. Introduction

The East Asian (EA) and the western North Pacific (WNP) summer monsoon is one of the most important land–atmosphere–ocean coupled climate system over the subtropics and tropics and exhibits substantial variability at seasonal and intra-seasonal time scales (Ding, 2007). During boreal summer (May–September), the rainfall fluctuations over the EAWNP region are manifested in the form of active-break cycles intimately associated with the monsoon intra-seasonal oscillations (ISOs) (Chen and Murakami, 1988; Wu, 1993; Sumathipala and Murakami, 2010). The monsoon ISO with periodicity between 10 and 90 days has a more complex structure compared to the wintertime MJO (Madden and Julian, 1972), in which eastward propagation dominates, by also exhibiting northward or northwest propagation of convective anomalies (Kayano and Kousky, 1999; Hsu and Weng, 2001). The monsoon ISO influences the timing of the onset and the withdrawal of monsoon and precipitation associat-

ed with the mei-yu in central China and the baiu in Japan (Hsu, 2005; Ding, 2007). It also modulates sub-seasonal variability of the subtropical high and tropical cyclone genesis and tracks over the WNP region (Chen et al., 2009; Mao et al., 2010; Ren et al., 2013). Therefore, the seasonal and the intra-seasonal variability of the EAWNP summer monsoon has significant influence on the socio-economic growth of East Asian countries. Correct simulation of space–time characteristics of monsoon ISO by a forecast system is crucial not only for the extended range prediction of the active-break spells but also for the long-range prediction of seasonal mean monsoon rainfall.

Despite the significant impacts of the ISO on the Asian climate system and the benefits afforded by improved forecasts of monsoon ISO events, the simulation of monsoon intra-seasonal variability continues to be an onerous burden for some climate models. Major deficiencies are observed in simulating its spatial structure, northward propagation and amplitude (Lin et al.,

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2008; Sooraj and Seo, 2013; Neena et al., 2017). Some important issues that affect ISO simulation have been investigated. For example, Waliser et al. (2003) and Sperber and Annamalai (2008) showed that the lack of the eastward propagating convection across the Maritime Continents is one of the major biases causing the unusual tilting of the rainband associated with the northward propagating ISOs in AGCMs. By analysing the ISO in 32 CGCMs that participated in the Coupled Model Inter-comparison Project phase (CMIP) 5, Sabeerali et al. (2013) found many of the models underestimate the boreal summer ISO variance over the equatorial Indian and Pacific Ocean, and they emphasised that the model mean state is an important factor for simulating the monsoon ISOs. Model deficiencies in the simulation of the ISO are also attributed to the uncertainty in the convective parameterisation (Maloney and Hartmann, 2001; Ajayamohan et al., 2014), seasonal mean easterly shear (Sperber and Annamalai, 2008) and moist processes of the model (Sooraj and Seo, 2013; Demott et al., 2014).

Many observational and diagnostic studies emphasised the importance of treating ISOs as a coupled phenomenon, and the realistic air–sea coupling is crucial in defining and maintaining the observed space–time characteristics of monsoon ISO in terms of the large-scale organisation, amplitude and meridional propagation (Hsu, 2005; Sharmlila et al., 2013). Some comparison studies between the stand-alone and coupled integrations confirm the coupled nature of ISOs and the use of CGCM in ISO simulation since the quadrature phase relationship between atmospheric convection (or precipitation) and SST cannot be simulated solely using an AGCM with prescribed observed intra-seasonal SST (Kemball-Cook et al., 2002; Seo et al., 2007; Demott et al., 2014), although the improvements due to air–sea coupling are limited and sensitive to the model.

Given that the monsoon ISO interacts with a variety of weather and climate systems including tropical cyclones and meso-scale convective systems (Chen et al., 2009; Satoh et al., 2011), emphasis is also placed on the higher-resolution model in representation of ISO/MJO in recent years (Rajendran et al., 2008; Liu et al., 2009; Oouchi et al., 2009; Abhik et al., 2015). These studies indicate that higher-resolution models resolving deep convective motions and topography explicitly simulate realistic behaviour of MJO and some aspects of the monsoon ISO in the Indian region. However, higher-resolution simulation of ISO is less well known over the EA summer monsoon (EASM) region, where complex topography, strong air–sea coupling, and greater heterogeneity of the underlying surface conditions dominate. Therefore, it is necessary to evaluate the performance of high resolution CGCMs in simulating the EAWNP summer monsoon ISO and to reveal its response to model resolution.

In this study, we analyse a series of long present-day coupled integrations using the latest Hadley Centre Global Environment Model version 3 – Global Coupled configuration 2 (HadGEM3-GC2) with horizontal atmospheric resolution of N96 (about 130 km) and N512 (about 25 km). By using combina-

tions of a high- and low-resolution atmosphere model coupled with the same high resolution ocean model, while keeping the basic model formulation, configuration, physics and dynamics settings constant, this study investigates the extent to which such models can reproduce aspects of the seasonal mean and ISO of the EAWNP summer monsoon, with a focus on the impact of enhanced resolution.

The description of the model is given in Section 2. Section 3 describes various observational data-sets and the methodologies used for the evaluation of the simulations. Section 4 examines ability of the model to simulate the mean-state of the EAWNP summer monsoon, as well as the temporal and spatial variability of the northward propagating ISO. The major conclusions and findings of the study are summarised in Section 5.

2. HadGEM3-GC2

The HadGEM3-GC2 coupled model and technical details of the coupling approach are described in detail by Williams et al. (2015). It is comprised of the component configurations Global Atmosphere 6.0 (GA6.0), the JULES land surface model Global Land 6.0 (GL6.0), the NEMO ocean model Global Ocean 5.0 (GO5.0) and the Los Alamos CICE model (GSI6.0), which communicate with each other via the OASIS3 coupler. Fluxes of heat, freshwater and momentum are passed between the atmosphere and ocean-ice components every 3 h while fluxes are passed between the ocean and ice models every ocean model time step (22.5 min).

The GA6.0 and GL6.0 configurations are fully described by Walters et al. (2017). There are many changes to the physics and dynamics of the atmosphere component consolidated in the global coupled model HadGEM3 since HadGEM2. These include a significant revision to the atmosphere dynamical core, an increase in entrainment rate for deep convection, and improvements to several other physical parameterisation schemes (Walters et al., 2017). A few new schemes are also implemented, including the PC2 cloud scheme and the Gravity Wave Drag scheme (Wilson et al., 2008; Vosper, 2015). It has 85 levels in the vertical with a model top at 85 km with at least 30 levels in or above the stratosphere. Similar to the previous versions of the MetUM configurations, the GA6 science can be run over a wide range of horizontal resolutions on a regular latitude–longitude grid with no explicit changes to model parameterisation. Some previous studies have shown that the seasonal forecast system GloSea5, which is based on high-resolution HadGEM3-GC2, can successfully predict the winter North Atlantic Oscillation, tropical cyclones, extreme weather events, the MJO and El Niño Southern Oscillation, despite some deficiencies in magnitude of the variability (MacLachlan et al., 2015; Williams et al., 2015; Senior et al., 2016).

The GO5.0 configuration based on a version of the NEMO (Nucleus for European Modelling of the Ocean) ocean model is described by Megann et al. (2014), whilst GSI6.0 is

documented by Rae et al. (2015). Relative to the coupled model HadGEM2, there are much updated ocean physics although the sea-ice physics remains essentially unchanged. The GO5.0 runs on a tri-polar grid at an eddy-permitting resolution of 0.25° , with 75 levels in the ocean (with a 1 m top level). Previous studies have demonstrated that eddy-permitting configurations of the NEMO model are useful tools for simulating variability of sea level (Penduff et al., 2010) and large-scale ocean dynamics (Roberts et al., 2013). The GSI6.0 has the same resolution as the ocean model. The model uses elastic-viscous-plastic ice dynamics, energy conserving thermodynamics and five sea ice thickness categories (Hunke and Lipscomb, 2010).

Two near present-day simulations with external forcings fixed at the year 2000 level have been run 460 years each at N512 (about 25 km) and N96 (about 130 km) atmospheric resolution with no explicit changes to other model components. Where relevant (e.g. for aerosols) emissions vary through the annual cycle. The year 2000 was chosen as it combined a well-sampled and recorded set of external forcings with relatively neutral conditions in major climate indices, such as El Niño. The atmosphere is initialised from September year 18 of the model state of a previous N512 GA6.0 forced atmosphere integration with forcing representative of the year 2000. The ocean is initialised from EN3 climatology (Ingleby and Huddleston, 2007). A few parameters have been changed to ensure numerical stability of MetUM GA6.0. These changes include the time step, the magnitude of polar filtering in the advection scheme, and the diffusion of vertical wind velocities in the upper five levels of the atmosphere. These dynamical adjustments were found not to impact the climatology of the simulations (Mizielinski et al., 2014). In this paper the last 15 years of two simulations were used for evaluating the simulation of monsoon ISO over the EAWNP region.

3. Data and methodology

The simulations are validated with various observed data-sets over the May–September period of 1998–2012. The fundamental characteristics of the monsoon ISO are convective anomalies associated with heavy rainfall and/or outgoing long wave radiation (OLR). Therefore, daily rainfall estimates for 1998–2012 from the Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall data-set with $0.25^\circ \times 0.25^\circ$ spatial resolutions (Huffman et al., 2007) and daily OLR data from the National Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith, 1996) are used for model evaluation of the simulated monsoon ISOs. The daily SST from NOAA optimum interpolation SST (OISST) version 2 (V2) (Reynolds et al. 2002) and the daily averaged zonal wind, temperature, geopotential height, specific humidity and surface net shortwave flux with the horizontal resolution of $1.0^\circ \times 1.0^\circ$ from European Centre for Medium-Range Weather Forecasts interim Re-Analysis (ERA-I) (Berrisford

et al., 2009) are utilised to analyse ISO-related variability. Vorticity is computed using u and v wind components from ERA-I and simulation results.

To focus on the intra-seasonal variability, the daily anomalies for both observations and simulations are calculated by removing the annual cycle, composed of the time mean and the first three harmonics. Then, Lanczos band pass filters (Duchon, 1979), with 200 weights and retaining periods of 20–70 days, are applied to the anomaly data-sets covering all the seasons. Finally, daily data corresponding to the boreal summer season (May through September) are extracted for analysis. Standard metrics, including estimation of variance, wavenumber-frequency spectra, lag regression, lag correlation and combined Empirical Orthogonal Function (EOF) analysis, are applied to the filtered series. Apart from these metrics, by incorporating the methods outlined in Lee and Wang (2016), ISO-related variability is analysed using composites of ISO events selected based on the two leading combined EOF modes of the intra-seasonal OLR and 850 hPa zonal wind anomalies. Section 4.2.3 describes the procedure in detail.

4. Results

4.1. Mean states

The capability of a model to simulate the realistic intra-seasonal variability is intimately associated with its ability to simulate the mean climate (Wang and Xie, 1997; Sabeerali et al., 2013). In view of such importance, we first investigate the simulation of the seasonal mean state of the EAWNP summer monsoon. Figure 1 shows the May–September mean rainfall and 850 hPa wind field in observation and model biases. The observations are characterised by a cyclonic low-level circulation associated with the monsoon trough that prevails over the South China Sea, a low-level anticyclonic circulation over the WNP, and the cross-equatorial flow over the Maritime Continent (Fig. 1a). The monsoon rainfall maxima are observed over the eastern shore of the Bay of Bengal, the South China Sea, east of the Philippines and the Meiyu front region. These features were generally reproduced by both the N96 and N512 simulations despite biases in the amplitudes. The major deficiency is that the rain bands are overestimated over the eastern South China Sea and WNP region. This may be related to the strong low-level westerlies and the associated strong water vapour transport, which is related to the Indian summer monsoon (Fig. 1b and c). Further examination on difference between N512 and N96 indicates that while the precipitation change is not significant over the EAWNP region as resolution increases, the low-level westerly over the EASM region is slightly enhanced (figure not shown), indicating an improvement relative to the observation.

Figure 2 gives the latitude-time diagrams of pentad rainfall averaged along $122^\circ\text{--}135^\circ\text{E}$. During the boreal summer, the

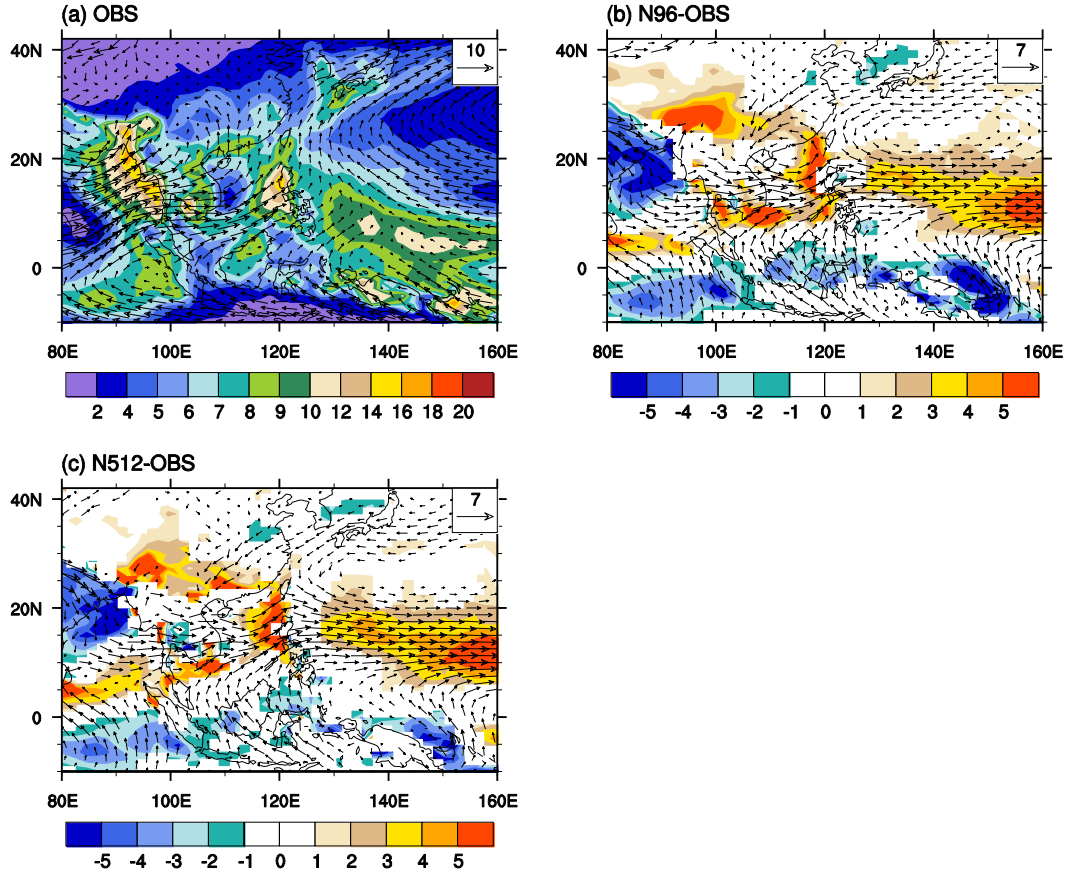


Fig. 1. May–September mean rainfall (shaded, units: mm day^{-1}) and 850 hPa wind vectors from the (a) Observation, (b) the difference between N96 and observations and (c) the difference between N512 and observations. Only the regions where the difference of precipitation and wind vectors are statistically significant at 5% level (Student's *t* test) are plotted in (b) and (c).

observations feature a northern rainband and a southern rainband. The northern rainband begin in mid-May, and exhibits with a stepwise northward propagation reaching 40°N in July, while the southern branch begins in June with a peak in August, and is located over the WNP region (Fig. 2a). These two rainbands are well reproduced in both simulations (Fig. 2b and c), but the north branch is underestimated, especially over the EASM region, whereas the south branch is overestimated and its onset seems to occur half a month earlier than the observations (Fig. 2d and e). The spatial pattern correlation coefficients of rainfall over $5\text{--}40^{\circ}\text{N}$ between simulations and observations are further shown in Fig. 3. It is clear that the model at both resolutions has a quite good skill in reproducing the spatial distribution of precipitation with correlation coefficient exceeding 0.7 for most of months. During the boreal summer, low skill is found in June, which may be associated with poor simulation of monsoon onset as shown in Fig. 2. High skill occurs in the following July, August and October, probably due to the better representation of the northward propagating monsoon rainbands (see Fig. 2). Improved skills occur during the spring and winter as resolution increases, but deterioration is seen in some

months such as June. This indicates that even the higher resolution model still struggle to correctly simulate the monsoon onset, consistent with other resolution sensitivity studies (Kitoh and Kusunoki, 2008; Johnson et al., 2015).

Figure 4 shows the spatial distribution of May–September mean SST and 500 hPa geopotential heights over the EAWNP region in observations and model biases. The observed warm pool, where SST exceeds 28°C , extends to north of 20°N (Fig. 4a). The broad observed features of SST are well captured in HadGEM-GC2, with a spatial pattern correlation coefficient of 0.95 and 0.98 for the N96 and N512, respectively (not shown). However, N96 tends to underestimate the SST over the warm pool and equatorial Indian Ocean, with the largest bias of approximately 1.5°C (Fig. 4b), which is a common bias in CMIP5 models (Li and Xie, 2014; Song and Zhou, 2014). In comparison with N96, the SST simulated by N512 is significantly enhanced with SST bias less than 0.5°C covering the coastal region of the East Asian continent and the WNP region (Fig. 4c), indicating an improvement in higher resolution model.

The model captures the gross pattern of 500 hPa geopotential heights, but the magnitude is underestimated, especially for

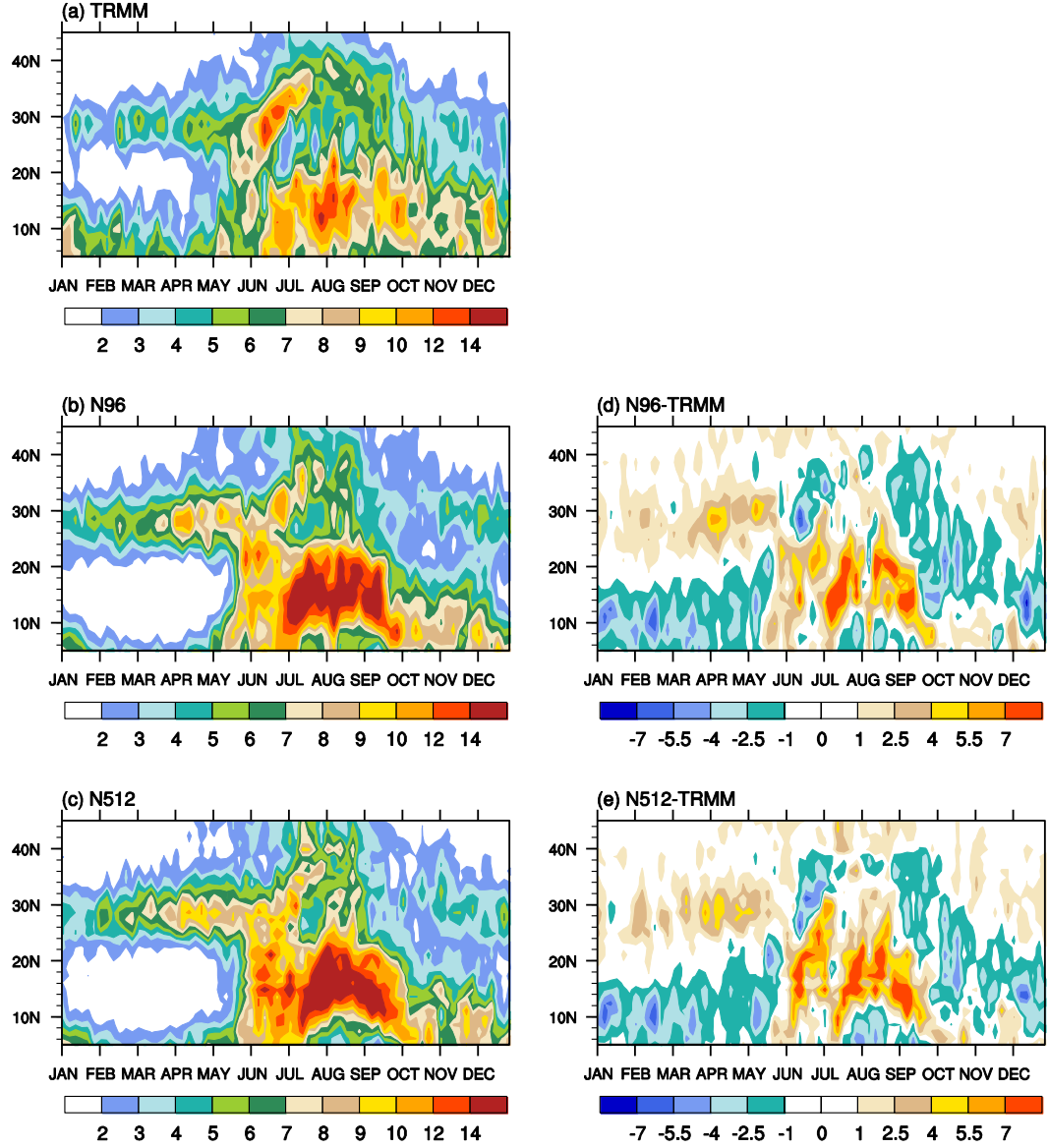


Fig. 2. Annual cycle climatology for rainfall rate (units: mm day⁻¹) averaged between 122 and 135°E from (a) TRMM 3B42, (b) N96, (c) N512, (d) the difference between N96 and observations and (e) the difference between N512 and observations.

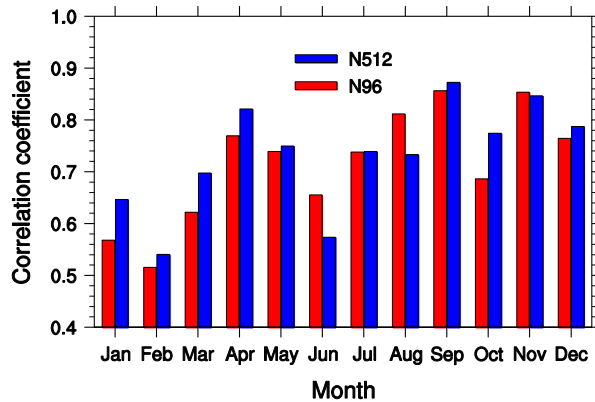


Fig. 3. Spatial pattern correlation coefficient of month mean precipitation between the observation and simulations over the EAWNP region.

WNP subtropical high (Fig. 4b and c). The largest bias is about 40 gpm. Compared with the N96, the intensity of WNP subtropical high simulated by N512 is significantly enhanced, thus comparing better with observation (Fig. 4c). Zhou et al. (2009) found that the intensification of the WNP subtropical high is related to atmosphere's response to the Indian Ocean–western Pacific warming. Therefore, the improvement in the WNP subtropical high simulation as resolution increases may be associated with the realistic representation of the SST over the equatorial Indian Ocean and western Pacific (Fig. 4c).

The mean easterly shear (200–850 hPa) and meridional gradient of mean low-level specific humidity are known to be key parameters for the northward propagation of the convection band

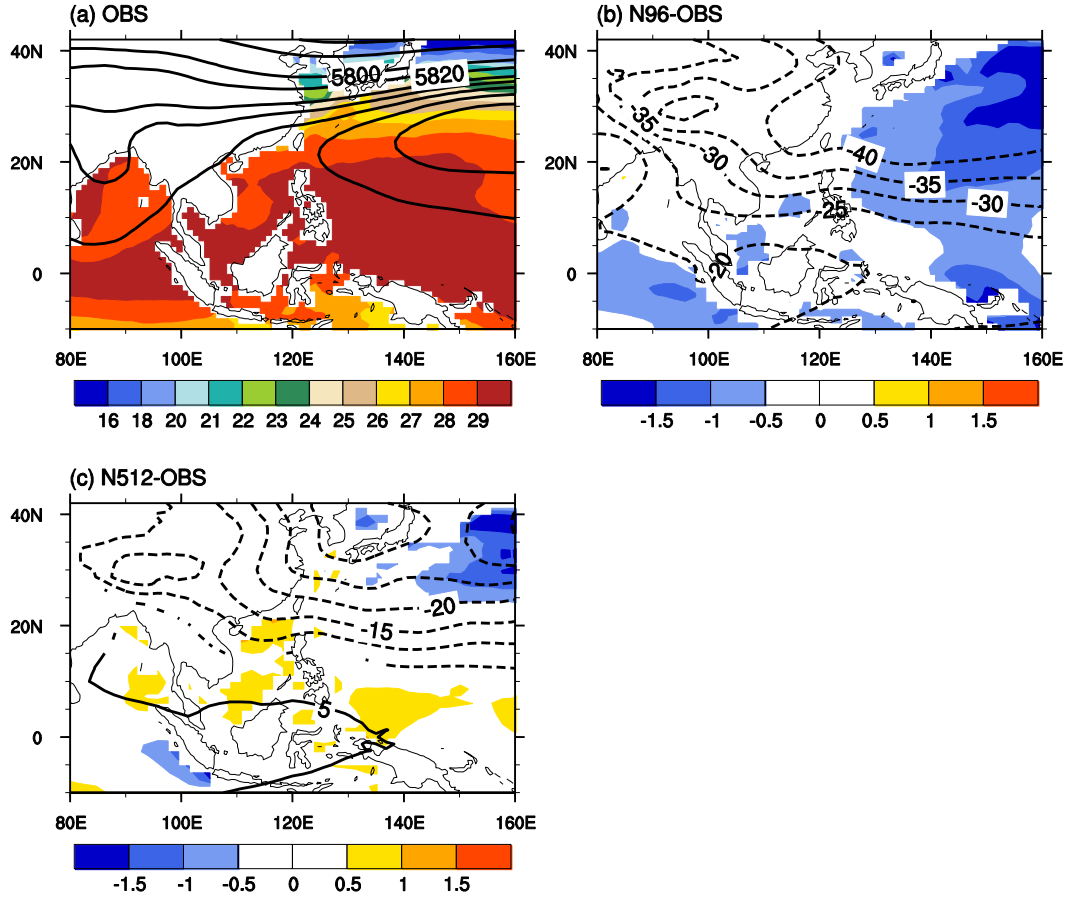


Fig. 4. May–September mean SST (shaded, units: $^{\circ}\text{C}$) and 500 hPa geopotential height (contour, units: gpm) from the (a) Observation, (b) the difference between N96 and observations and (c) the difference between N512 and observations. Only the regions where the difference of SST and 500 hPa geopotential height are statistically significant at 5% level (Student's *t* test) are plotted in (b) and (c).

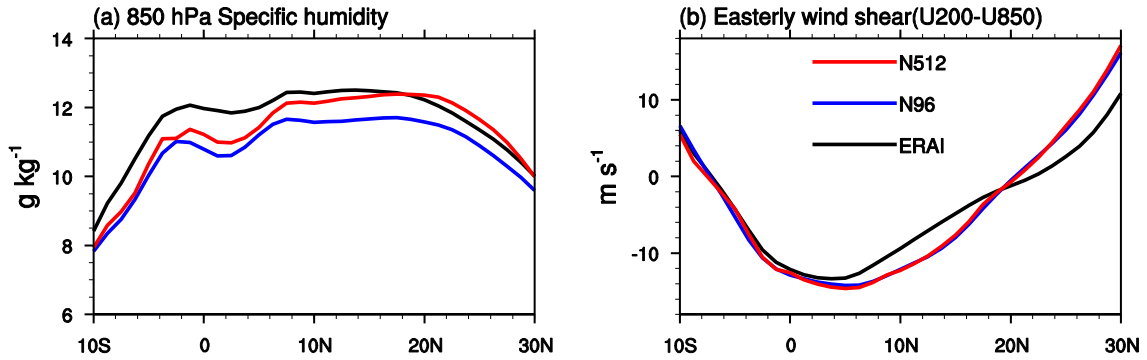


Fig. 5. Meridional distribution of May–September mean (a) 850 hPa specific humidity and (b) easterly wind shear between 200 and 850 hPa averaged between 122 and 135 $^{\circ}\text{E}$.

(Wang and Xie, 1997; Jiang et al., 2004). Figure 5 shows the easterly wind shear and low-level specific humidity averaged over 122–135 $^{\circ}\text{E}$ from ERAI, N96 and N512 simulations. From Fig. 5a, it is found that N512 simulation improves the magnitude of the surface specific humidity to the north of the equator, although

the meridional gradient of specific humidity over the WNP seems to be overestimated compared to the N96 and observations. From Fig. 5b, it is evident that both runs simulate the meridional variation of the vertical easterly shear with larger amplitude over the WNP region and lower amplitude over the EASM region.

4.2. Monsoon intra-seasonal variability

4.2.1. Wavenumber-frequency spectra and variance. The most significant character of monsoon ISO is the pronounced 20–70 day oscillation of northward propagating convection anomalies over EAWNP domain. Therefore, the meridional (north–south) wavenumber frequency spectrum analysis is carried out over the EAWNP region (125–140°E; 15°S–30°N) during boreal summer (May–September) to identify how well the model simulates such a dominant mode compared to the observations, following the methodology of Wheeler and Kiladis (1999) and Abhik et al. (2015). Figure 6 shows the summertime north–south space–time spectra of daily precipitation from TRMM and the model simulations from N96 and N512. A dominant northward propagating mode of 20–70 day period and wavenumber 1 with maximum power at 20 and 50 days is noted in TRMM (Fig. 6a). Comparing the model simulated spectrum to that of observations, it appears that both the runs could give ISO signal at wavenumber 1 with periods of 20–70 day. However, the power of the northward propagating ISO mode is underestimated and the 20 day peak is absent at N96 simulation (Fig. 6b). When increasing the horizontal resolution to N512, such biases are significantly reduced, although the power around 20–30 day is overestimated (Fig. 6c).

The 20–70 day filtered intra-seasonal variance of precipitation in observation and the model biases are shown in Fig. 7. The intra-seasonal variance of the observed precipitation shows

maxima located over the eastern Bay of Bengal, the South China Sea and the Philippine Sea. Additionally, a large belt of strong variance is observed over the EASM region that extends from the Yangtze River Valley and East China Sea to Japan and South Korea. The model at both horizontal resolutions captures the above active ISO centres, but the variance maximum over the eastern equatorial Indian Ocean is poorly simulated (figure not shown). Note that ISO variance is underestimated over most of the EAWNP region at N96 except for northern South China Sea and part of WNP region. Compared with the N96, N512 reduces the negative bias over the EASM and tropical Pacific (Fig. 7c), but the positive biases over the South China Sea and part of WNP region are strengthened. Earlier studies have shown that the intra-seasonal variability is associated with seasonal mean state (Sabeerali et al., 2013). In our study, these changes in ISO variance and power of northward propagating ISO mode (Fig. 6b and c) as resolution increases may be related to the significant enhancement of seasonal mean SST (Fig. 4b and c) and associated air-sea coupling (see Section 4.2.5).

4.2.2. Extraction of the leading modes. EOF analysis has been widely used to separate the phase structures of intra-seasonal variability from the filtered time series (Seo et al., 2007; Liu et al., 2008). A recent study by Lin (2012) and Lee and Wang (2016) applied the combined EOF analysis to fields of daily anomalies of intra-seasonal OLR and 850 hPa zonal winds (U850) over the EAWNP region. It was found that the first two EOF modes can reasonably well represent the

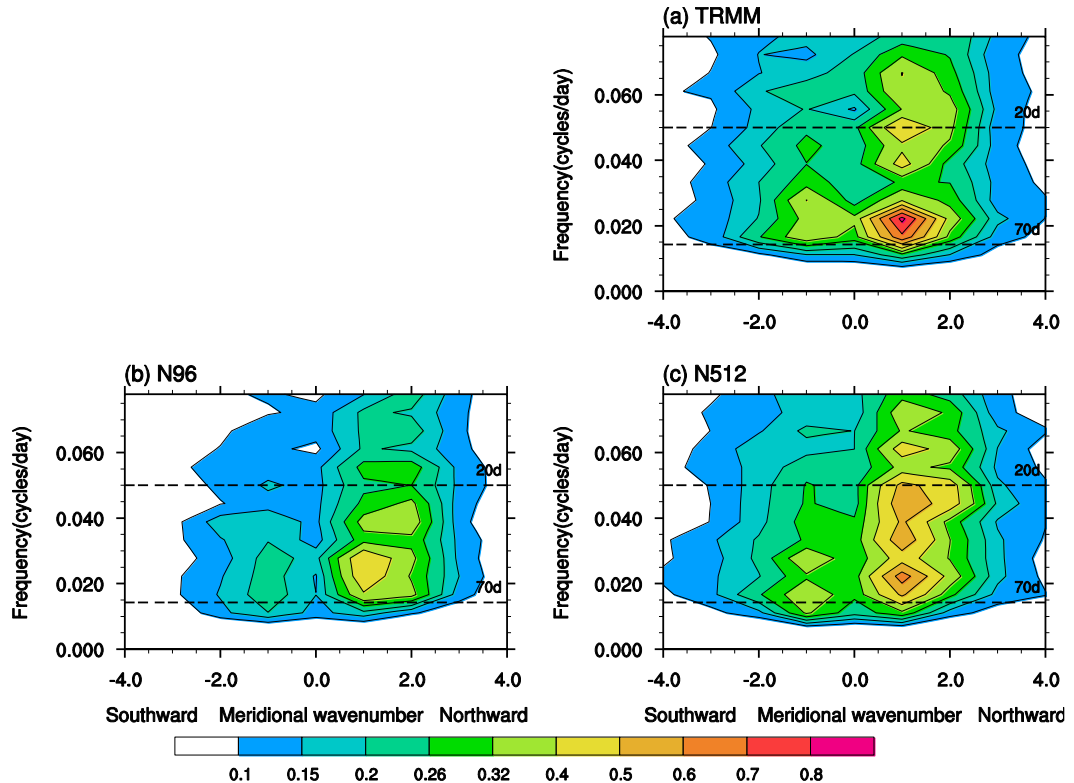


Fig. 6. Meridional wavenumber-frequency spectra during boreal summer over 15°S–30°N using precipitation (units: $\text{mm}^{-2} \text{day}^{-2}$) averaged between 122 and 135°E from (a) TRMM 3B42, (b) N96 and (c) N512.

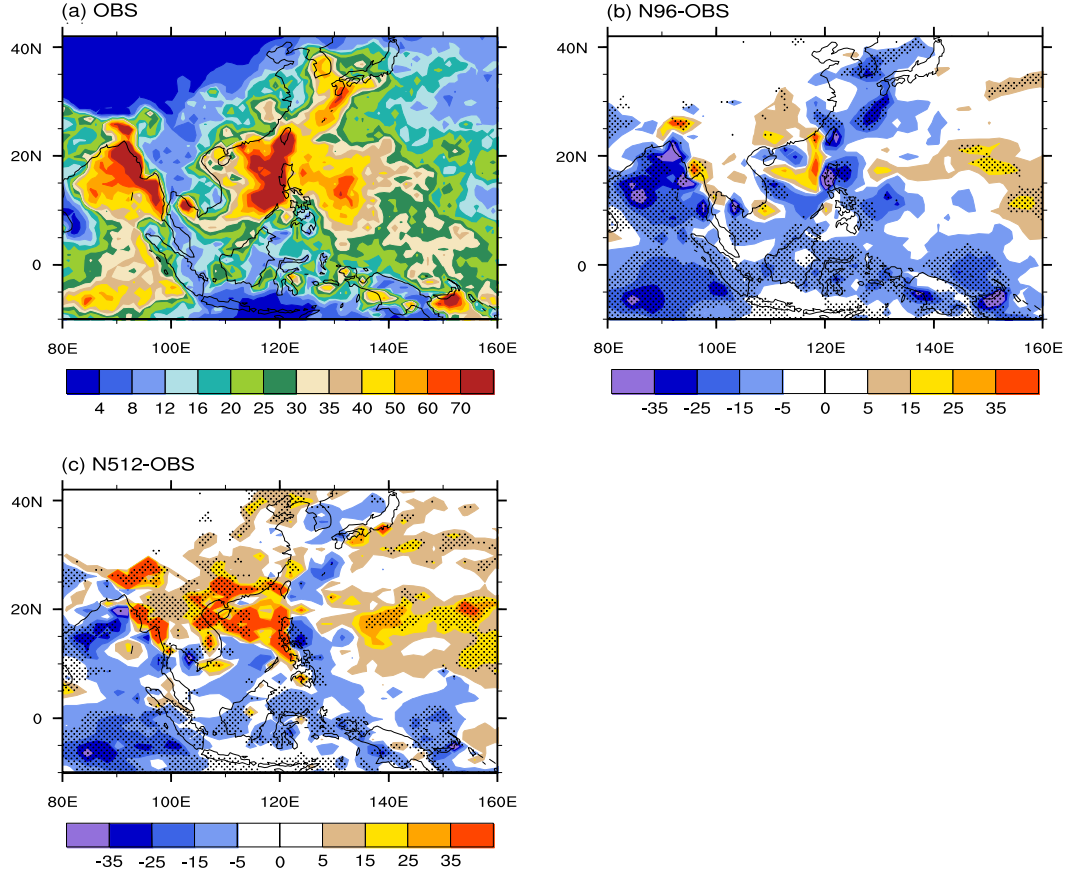


Fig. 7. 20–70 day filtered precipitation variance (units: $\text{mm}^2 \text{day}^{-2}$) during boreal summer (May–September) for the (a) Observation, (b) the difference between N96 and observations and (c) the difference between N512 and observations. The stippling in (b) and (c) denotes where the difference of the intra-seasonal precipitation variance is statistically significant at 10% level according to a F -test.

northward propagation of the ISO over the EAWNP summer monsoon region.

Figure 8 shows the spatial structure of the leading two EOFs of the combined fields of intra-seasonal OLR and U850 averaged over the EAWNP region. Following Lee and Wang (2016), the 850-hPa meridional wind was obtained by regressing onto each PC in order to show full horizontal wind field. For observations, the EOF1 is characterised by negative OLR anomaly dominating the South China Sea and Philippine Sea with an anomalous cyclonic circulation on its northwest side (Fig. 8a). The EOF2, almost out of phase to EOF1, exhibits a tri-polar OLR structure with an anomalous cyclonic and anti-cyclonic circulation located over the East China Sea and WNP, respectively (Fig. 8b). These two modes are also shown in Lee and Wang (2016) despite a small difference in the analysing domain size. Together these two modes constitute the northward propagating ISOs, and explain more than 33% of the total filtered variance.

The model at two different resolutions is able to reproduce the large loading located over the South China Sea and Philippine Sea in the first mode, as well as the meridional tri-polar pattern

in the second mode (Fig. 8c–f). These two leading modes, together accounting for 30.7% and 28.4% of the total explained variance for N96 and N512, respectively, have similar levels of statistical significance as the observed counterparts. However, the magnitudes of both OLR and 850 hPa wind anomalies are overestimated, and the locations of the anomaly centres shift northeastward relative to the observation, especially over the WNP region. Note that the cyclonic circulation anomaly over the East China Sea in EOF2 is absent at N96 but well simulated at N512 (Fig. 8d and f).

4.2.3. Monsoon ISO life cycle evolution. In this subsection, we analyse the life cycle of the monsoon ISO based on composites of ISO events. Following Lin (2012) and Lee and Wang (2016), we first divided an ISO event into eight phases based on the phase-space map of the PC1 and PC2 derived from Section 4.2.2. Then, ISO life cycle composites are constructed by averaging bandpass filtered anomalies across all days that fall within a given phase when the ISO amplitude (defined as $\text{PC1}^2 + \text{PC2}^2$) is greater or equal to 1 (the strong ISO area that lies outside the one unit circle on the phase-space diagram, see

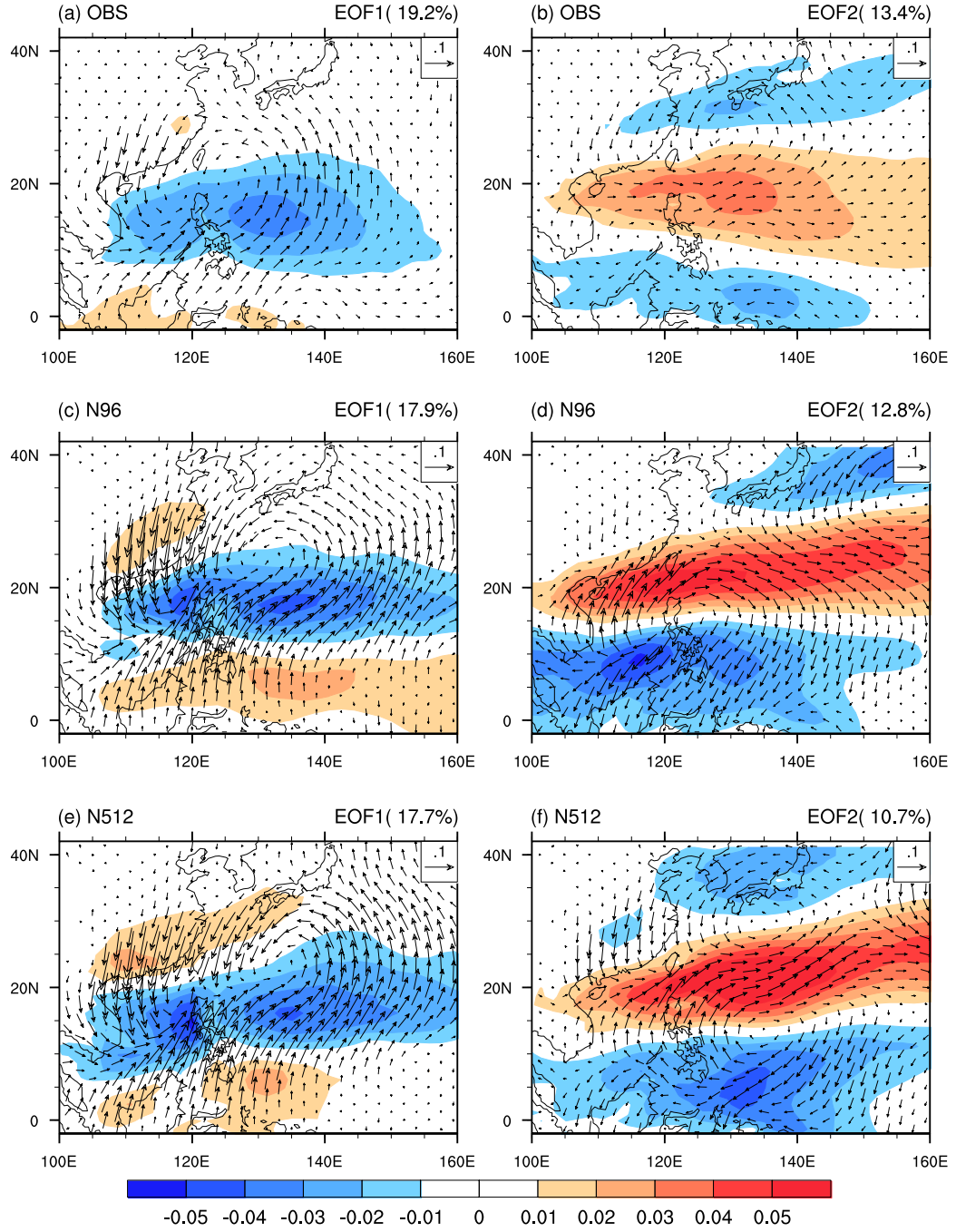


Fig. 8. First two leading combined EOF modes of daily OLR (shading) and U850 anomalies from the (a) Observations, (b) N96 and (c) N512. To display the full horizontal wind vector, the associated 850-hPa meridional wind was obtained by regressing 850-hPa meridional wind anomaly against each PC.

Table 1. Number of days for each phase of the monsoon ISO.

	Phase							
	1	2	3	4	5	6	7	8
Observation (1998–2012)	167	232	213	183	202	215	227	193
N96 (15 years)	117	166	198	134	132	148	193	145
N512 (15 years)	183	179	146	169	166	158	132	168

Fig. 7 in Lin 2012). Table 1 gives the number of days for each phase of the ISO for the observation and the two simulations. It is found that the both the simulations underestimate the number of days for most of phases.

Phases 1, 3, 5 and 7 from observations are shown in the left column in Fig. 9 to compare with the N96 (middle) and N512 (right) simulations. The observed monsoon ISO cycle is featured by enhanced (suppressed) convection coupled with anomalous cyclone (anticyclone) on their northwest side (Fig. 9a). This coupled circulation-convection system migrates northward and northwestward from the equator to the EASM region, consistent with analytical solution for the heating-induced circulation and an off-equator heating as shown in the theoretical study by Gill (1980). Such a Rossby wave-like behaviour of the intra-seasonal circulation–convection coupled system is also reported by Mao et al. (2010) and Lee and Wang (2016). These features are reasonably captured by both the N96 and N512 simulations, especially for the alternating development of the cyclone and anticyclone anomalies anchored over the South

China Sea and Philippine Sea, although the circulation and convection anomalies are overestimated at most of the phases (Fig. 9b and c). In addition, northwest-southeast tilted convection anomalies extending from the Bay of Bengal to the WNP in phase 1 and 5, which exhibits eastward propagation and closely connects to the northward monsoon ISO (Wang and Xie, 1997; Lawrence and Webster, 2002), is slightly better simulated at N512 when compared with the N96 simulation.

4.2.4. Structure of monsoon ISO-related anomaly fields. The structure of the monsoon ISO signal shown in Fig. 10 is investigated using composites of precipitation, 850 hPa vorticity, specific humidity and equivalent potential temperature, and 200 hPa divergence averaged along 122–135°E at phase 3, when the ISO-related rain bands propagate northward from the WNP to EASM region. It is found that the derived phase 3 of the ISO reaches convection maximum at 16°N in the observations, 20°N in N96, and 15°N in N512 (Fig. 10). The observed centres of positive low-level vorticity and specific humidity are 2–4°

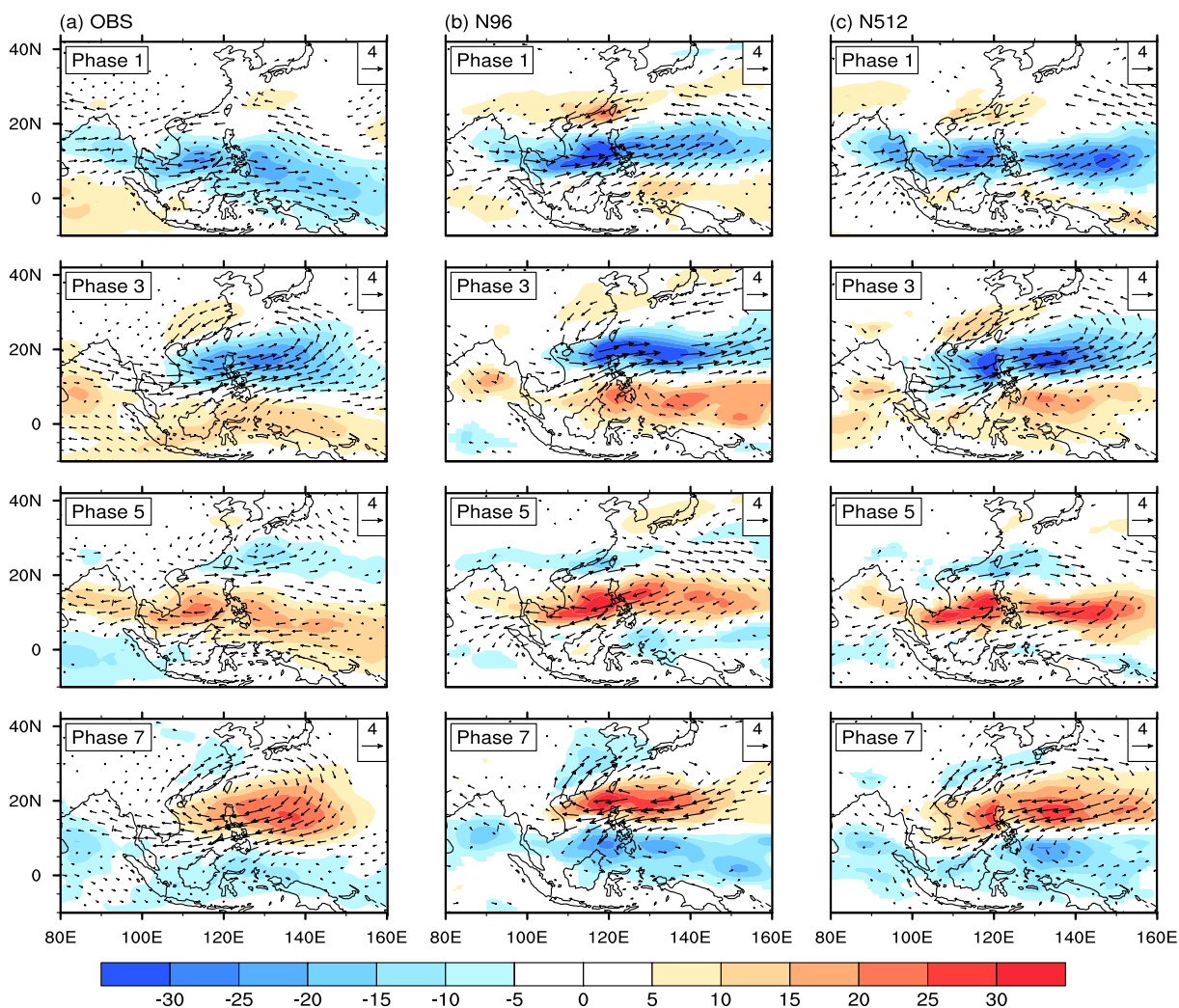


Fig. 9. Composites of OLR (shaded, units: W m^{-2}) and 850 hPa wind anomalies (vectors, units: m s^{-1}) for phase 1, 3, 5 and 7 from (a) NOAA and ERAI reanalysis (left), (b) N96 (middle) and (c) N512 (right) simulations. Only the values of wind and OLR that significantly exceed the 95% confidence level are shown.

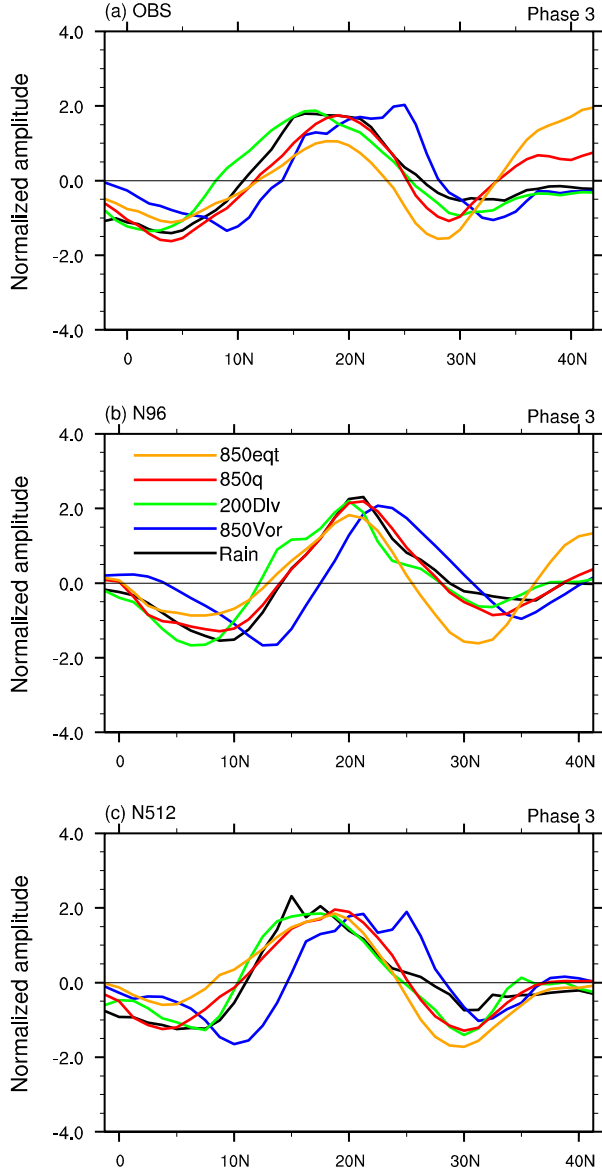


Fig. 10. Meridional distribution of composite rainfall, 200 hPa divergence, 850 hPa equivalent potential temperature, specific humidity and vorticity at phase 3 for (a) Observation, (b) N96 and (c) N512. All variables are averaged over the 122–135°E and normalised by their respective standard deviations.

north of the maximum convection centre (Fig. 10a). This contributes to the enhancement of the convective instability by enhancing the equivalent potential temperature (Fig. 10a). The asymmetric structure of these dynamic and thermodynamic parameters with respect to the maximum convection centre is key to the northward propagation of the monsoon ISO (Jiang et al., 2004). The upper-level divergence and low-level vorticity are generally in phase, showing a baroclinic structure of the ISO (Fig. 10a). While the observed characteristics of the ISO mentioned above are reasonably well simulated by N512 and

with similar magnitude (Fig. 10c), the asymmetric structure of low-level specific humidity and equivalent potential temperature is poorly simulated by N96 (Fig. 10b). These biases at N96 may be related to the absence of the northward propagating ISO signals in precipitation and SST over the EASM region (shown in Fig. 13b).

It is well known that the sub-seasonal migrations of the rain-band over the EASM region are strongly influenced by the zonal displacement of the WNP subtropical high through the modulation of the monsoon southwesterlies on its western flank (Mao et al., 2010; Ren et al., 2013). The zonal oscillation of the South Asian high also has great impact on the wet and dry phase of the WNP boreal summer ISO through the regulation of the upper-level atmospheric divergence (Liu and Lin, 1991; Ren et al., 2015). Therefore, in this section, the intra-seasonal variability of the WNP subtropical high and South Asian high is examined as shown in Fig. 11. For brevity, only phases 1 and 5, which correspond to the wettest and driest ISO phases of WNP summer rainfall, are shown here. Since the climatological WNP subtropical high and South Asian high are located over the WNP and Tibetan Plateau with ridge axes along 20 and 28°N, respectively (not shown), the observed anomalous patterns indicate a westward and eastward extension of the WNP subtropical high and South Asian high, respectively, during the wettest phase of the WNP rainfall, whereas they show opposite movement during the driest phase (Fig. 11a and b). Such intra-seasonal changes in zonal displacement of the two systems are properly simulated at both resolutions (Fig. 11c–f). However, the N96 fails to reproduce the north-south dipole structure of the anomalous 500 hPa geopotential height (Fig. 11c and d), while N512 shows an improvement, although the magnitude is overestimated (Fig. 11e and f). Note that increasing resolution also improves the simulation of 200 hPa geopotential height anomaly in terms of both the magnitude and spatial pattern, especially for the wettest phase of WNP rainfall (Fig. 11c and e).

4.2.5. Intra-seasonal SST variance and the associated air-sea coupling. Earlier studies suggest that the feedback of ocean plays an important role in maintaining the observed monsoon ISO, especially for its northward propagation (Sharmlila et al., 2013; Demott et al., 2014). This motivates a further check on the intra-seasonal SST variance and the air-sea coupled process associated with the northward propagation of ISO. The standard deviations of intra-seasonal SST are shown in Fig. 12. It is seen that strong intra-seasonal SST variance is observed over the Bohai Sea, the Japan Sea and the Kuroshio region extending from the north South China Sea to mid-latitude North Pacific. While the SST variance in both simulations displays spatial patterns consistent with the observations, the SST variances are obviously underestimated at N96 (Fig. 12b). Compared with N96, intra-seasonal SST variance at N512 is the significantly enhanced (Fig. 12d) over the EASM region, which is in better agreement with the observations.

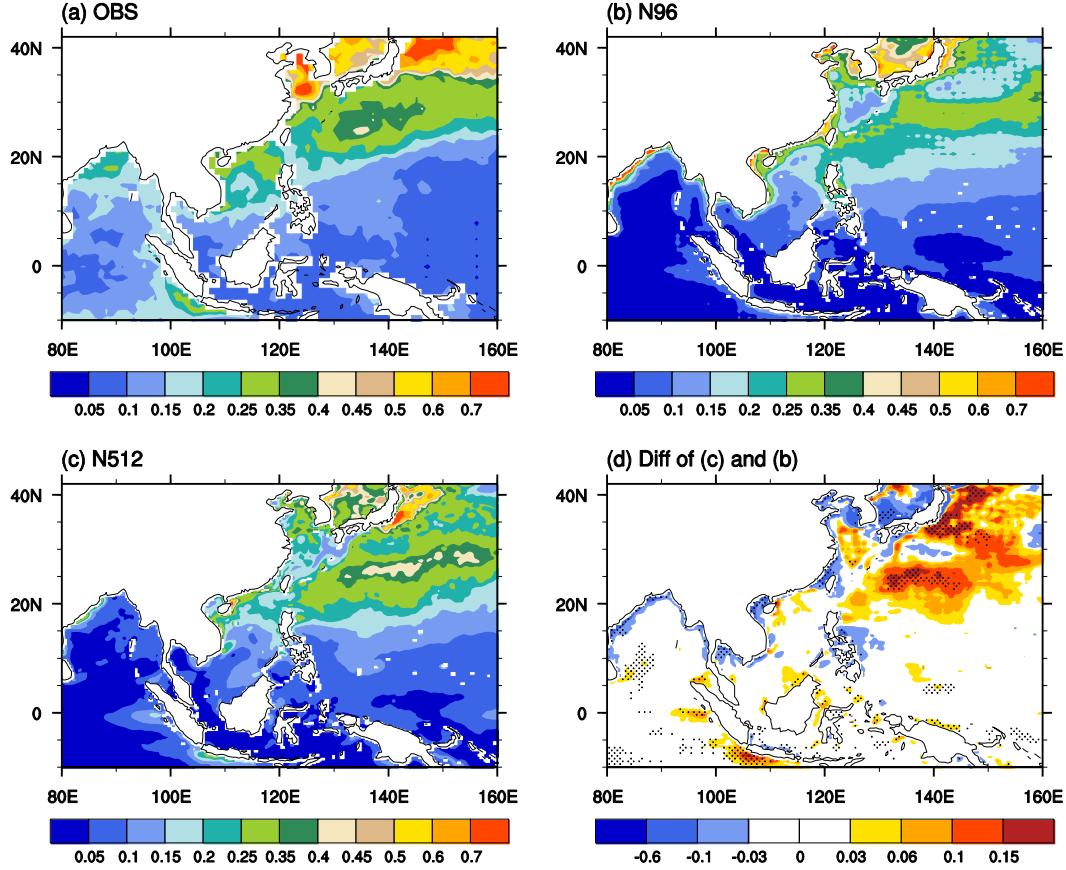


Fig. 11. Composites of 20–70 day filtered 500 hPa (shading, units: gpm) and 200 hPa (contour with an interval of 4 gpm) geopotential height over the EAWNP region at phase 1 (left) and 5 (right) for (a) and (b) ERAI reanalysis, (b) and (c) N96, and (e) and (f) N512.

The enhanced intra-seasonal SST variance might feedback to the atmosphere, resulting in the improved representation of northward propagating ISOs as model resolution increases. To confirm this, Fig. 13 further demonstrates the time lag-regression analysis of 20–70 day filtered precipitation, SST, and 850-hPa wind speed, and surface net downward shortwave flux, and 1000-hPa moisture convergence along 122–135°E correlated with a time series of intra-seasonal filtered precipitation averaged over the South China Sea and Philippine Sea (10–20°N, 110–130°E), where the monsoon ISO has a maximum variance (shown in Fig. 7). The observations feature a northward propagation of the ISO-related anomalies from equatorial western Pacific to the EASM region accompanied by a positive intra-seasonal air-sea coupling. To the north of the convection centre, the decrease of low level wind speed (Fig. 13d) and surface latent heat flux (figure not shown) associated with the wind-evaporation feedback, along with enhanced shortwave radiation (Fig. 13g) related to the cloud-radiation feedback may lead to positive SST anomalies (Fig. 13a). The positive SST anomalies favour enhanced low level moisture convergence to the north of the convection centre (Fig. 13j). This surface moisture convergence is regarded as one of the most important fac-

tors for the maintenance and propagation of the monsoon ISO (Fu and Wang, 2004; Seo et al., 2007).

Both the simulations capture the observed northward migration of ISO anomalies and the gross features of phase relationships among precipitation, SST, 850-hPa wind speed, surface net downward shortwave flux and 1000-hPa moisture convergence over the WNP region. However, there are still some differences as well. The observed northward propagation of precipitation anomaly is characterised by a northward jump between the 10–20°N with phase speed faster than other latitudes (Fig. 13a). While this feature is absent at N96 (Fig. 13b), it is partly captured by N512 (Fig. 13c). The precipitation and SST anomalies simulated by N96 exhibit southward propagation over the EASM region north of 25°N, while those signals show northward propagation in the observations and N512 simulation. Moreover, the 850 hPa wind speed, and surface net downward shortwave flux and 850 hPa moisture convergence anomalies leading the convection centre are underestimated over the EASM region at N96, while those at N512 are more realistic (Fig. 13d–l). It seems that northward propagation of rainfall, SST, and other surface dynamic and thermodynamic variables are more coupled and coherent as resolution increase.

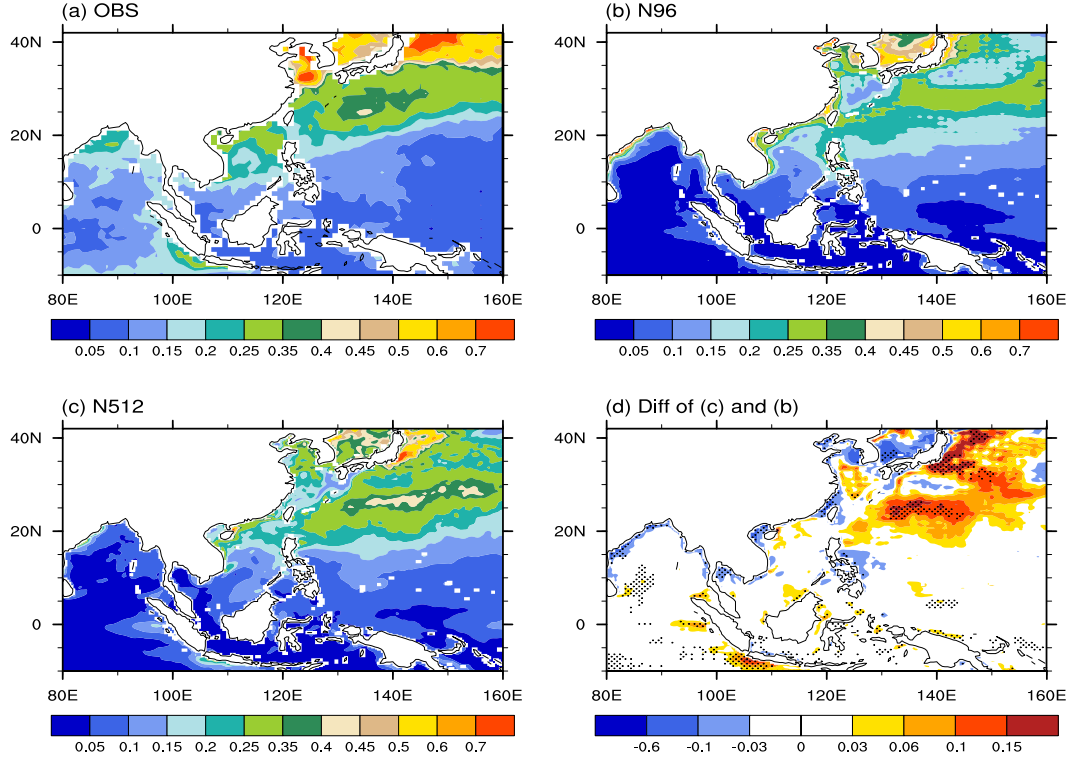


Fig. 12. 20–70 day filtered SST variance (units: $^{\circ}\text{C}$) during boreal summer (May–September) for the (a) OBS, (b) N96, (c) N512 and (d) the difference between N512 and N96. The stippling in (d) denotes where the difference of the intra-seasonal SST variance is statistically significant at the 10% level according to a F -test.

This indicates an intensified air-sea coupling, which might be responsible for the enhancement of the intensity (shown in Fig. 7) and northward propagation (shown in Fig. 6) of the monsoon ISO at N512 simulation.

5. Summary and discussion

ISO is one of the dominant forms of the EAWNP summer monsoon variability. The assessment of the current GCMs in simulating the monsoon ISO is important not only for detailed understanding of the physical processes that gives rise to ISO fluctuations, but also for further model development, which in turn will benefit the present prediction systems. In this study, we have analysed the fidelity of HadGEM-GC2, a relatively high resolution ocean–atmosphere coupled GCM, in simulating the boreal summer mean climate and the monsoon ISO over the EAWNP region. The effect of atmospheric resolution on model performance and the associated underlying physical mechanisms are further explored and discussed. The main results can be summarised as follows.

The HadGEM3-GC2 with two different resolutions has a reasonable seasonal cycle of EAWNP rainfall, and reproduces some of the mean features of EAWNP summer monsoon, e.g. seasonal mean easterly wind shear and low-level specif-

ic humidity. However, the model exhibits a wet bias over the WNP region during boreal summer, which is associated with the weak WNP subtropical high and strong westerlies over the South China Sea related to the Indian summer monsoon. While increasing the atmospheric model resolution does not lead to better performance in simulating the seasonal mean precipitation, it still overcomes some systematic biases in the early versions of this climate model, such as the underestimation of the WNP subtropical high and the cold SST bias over the WNP, which are common biases in many coarse resolution CMIP5 models.

Meanwhile, the spatio-temporal features of the monsoon ISO are examined in the model. Although the ISO variance is slightly overestimated over the WNP summer monsoon region, HadGEM3-GC2 with high resolution is able to produce the northward propagating ISOs around 20–70 days with dominant EOF structure and life cycle all resembling closely those derived from TRMM and ERAI reanalysis. The zonal displacements of the WNP subtropical high and South Asian high associated with the northward propagating ISOs are also well reproduced in the model despite some discrepancies in terms of the magnitude. Moreover, increasing atmosphere model resolution shows significant improvements in representing the aspects of monsoon ISO, especially for its northward propagation features. Marked improvements occur over the EASM region, where the variance

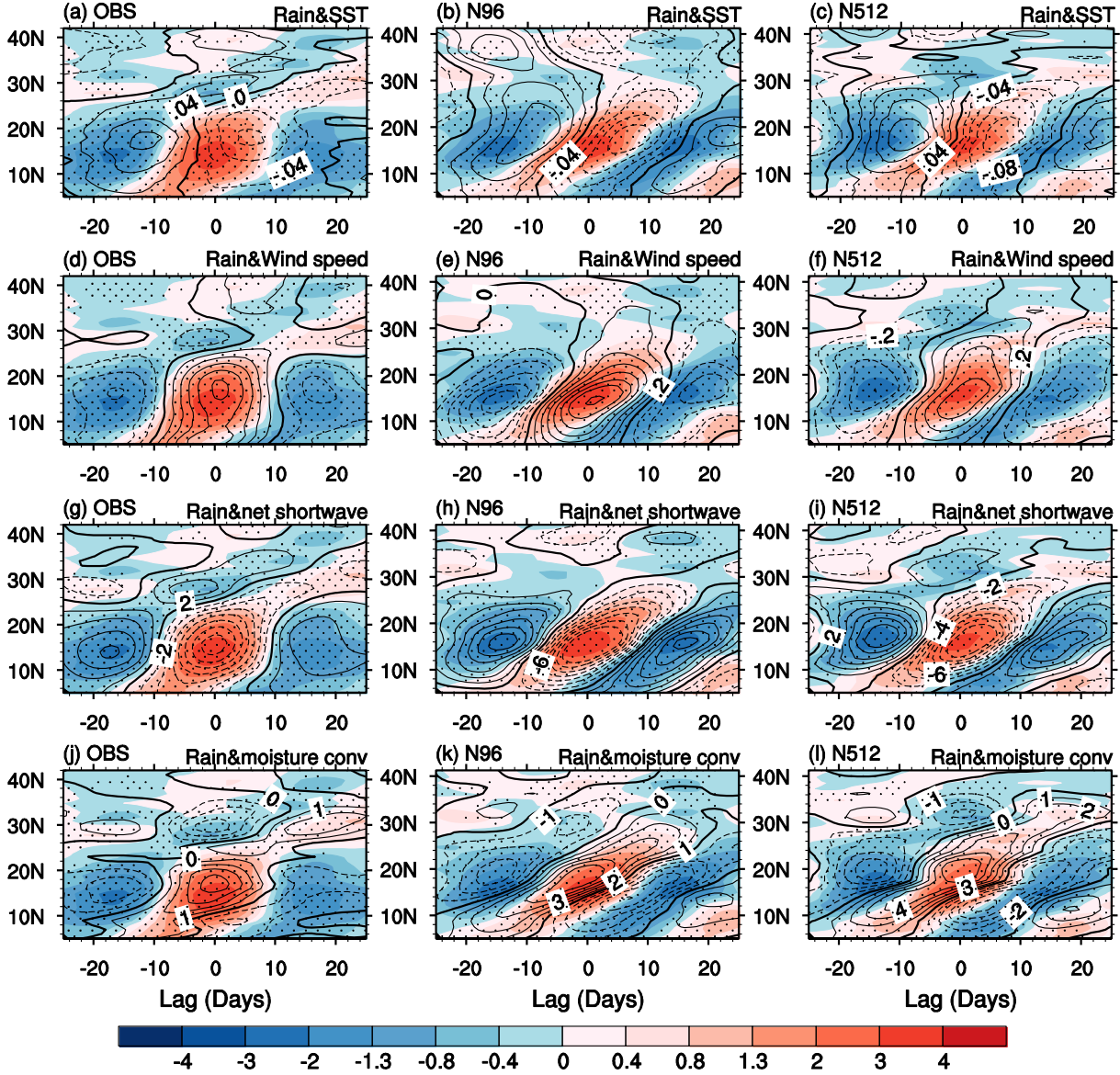


Fig. 13. Lag regression of the 20–70 day filtered precipitation (shaded, units: mm day^{-1}), SST (contours with an interval of 0.04°C), 850 hPa wind speed (contours with an interval of 0.2 m s^{-1}), surface net downward shortwave flux (contours with an interval of 2 W m^{-2}) and 1000-hPa moisture convergence (contours with an interval of $1 \times 10^{-9} \text{ kg s}^{-1} \text{ kg}^{-1}$) along $122\text{--}135^\circ\text{E}$ upon the filtered precipitation averaged over the South China Sea and Philippine Sea ($10\text{--}20^\circ\text{N}$, $110\text{--}130^\circ\text{E}$) for (a, d, g, j) observation, (b, e, h, k) N96 and (c, f, i, l) N512. The stippling indicates the regions where both regression coefficients are statistically significant at the 5% significance level.

of ISO and the northward power in precipitation spectrum around 20–70 days is underestimated, while those at N512 are more realistic. The simulated northward jump of the intra-seasonal rain band associated with EASM and the northwest-southeast tilted convection band structure extending from the Bay of Bengal to WNP related to the eastward propagation of the ISO are also slightly improved as resolution increases. Further analysis indicates that these improvements are related to stronger air–sea interaction when atmosphere model resolution increases, as evidenced by the enhanced intra-seasonal SST variance

and more coherent northward propagation of rainfall, SST, and the associated surface dynamic and thermodynamic variables as model resolution increases.

Many previous studies using atmosphere-only models show that increasing model horizontal resolution may allow more cloud processes to be resolved by the microphysics scheme rather than by the convection scheme, which results in less convective precipitation, especially over the equatorial tropical ocean (Liu et al., 2008; Kan et al., 2015). Resolution sensitivity studies in several versions of the MetUM Global Atmosphere

model (Demory et al., 2014; Johnson et al., 2015) also show similar results, which is found to be associated with better orographic representation in the tropics. However, in our study using the coupled model HadGEM3-GC2, very little resolution sensitivity is seen in the precipitation, but high SST sensitivity occurs over the equatorial tropical oceans. The possible reason is that the reduction of precipitation as the atmosphere model resolution increases from N96 to N512 enhances the downward solar radiation and reduces upward latent heat flux. This will warm the local SST and in turn increase the precipitation upon coupling with the ocean model, implying a negative feedback between the convection and SST. Therefore, a new equilibrium climate state is established in the coupled model system with reduced cold SST bias.

Previous studies have found that the evolution of monsoon ISOs is closely related to the tropical cyclone activity over the WNP region (Chen et al., 2009; Satoh et al., 2011). Benefiting from better represented meso-scale convection, more realistic simulation of favourable environment such as warm SST (shown in Fig. 3c) and increased relative humidity (shown in Fig. 4a), tropical cyclones may be better represented as resolution increases, which also contributes to the monsoon ISO simulation improvement. This will be examined in future work. Finally, although monsoon ISO simulations by the higher resolution model were more realistic, it still experiences large biases, such as the poor simulation of the monsoon onset, the overestimation of seasonal mean rainfall, power of the northward propagating ISO mode around 20–30 days, and ISO variance over WNP region, and the underestimation of the WNP subtropical high. Most of these biases can also be found in the lower resolution model. This indicates that only increasing the model horizontal resolution is not enough, further improving the model dynamics, cloud and radiation processes as well as cumulus convection parameterisations must also be considered in order to bring simulated monsoon ISO close enough to observations.

Disclosure statement

No potential conflict of interest was reported by the authors.

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