



Development and evaluation of the GRIMs–NEMO fully coupled model v1.0 for simulating the East Asian Summer Monsoon

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Abstract. This study introduces the newly developed GRIMs–NEMO fully coupled model version 1.0 for the first time and
10 assesses its capability to simulate the boreal summer climate, with a particular focus on the East Asian summer monsoon
(EASM). The model couples the GRIMs atmospheric model, NEMO ocean, and SI3 sea ice models through OASIS3-MCT,
providing a computationally efficient framework for climate simulation. Benchmark experiments show that GRIMs–NEMO
requires substantially fewer computational resources than does CESM2, suggesting its potential utility for long-term
15 integrations and ensemble-based studies. The model reasonably reproduces the large-scale features of precipitation,
atmospheric circulation, and temperature, and its precipitation skill is broadly comparable to those of CMIP5 and CMIP6
models. Nevertheless, several systematic biases are identified during boreal summer, including excessive rainfall over the
equatorial western Pacific, cold surface temperature biases, weakened Tibetan Plateau heating, and circulation errors over
the western North Pacific. The model also captures key modes of climate variability associated with the EASM, including
20 the El Niño–Southern Oscillation, the Pacific–Japan pattern, and the boreal summer intraseasonal oscillation, despite
remaining biases in their spatial structure, amplitude, and periodicity. A comparison between the coupled and atmosphere-
only simulations indicates that air–sea coupling improves sea surface temperature–precipitation feedbacks and the seasonal
evolution of the EASM rainband. Overall, GRIMs–NEMO shows reasonable capability as a computationally efficient, fully
coupled climate model, while the identified biases highlight the need for further improvements in atmospheric physical
parameterizations and the ocean model component.

25 1 Introduction

The atmosphere and ocean are two major components of Earth’s hydrological system. Through the exchange of
momentum, heat, and moisture, their interactions considerably affect weather and climate. Prominent phenomena
exemplifying the critical role of air–sea interactions include the monsoon, tropical cyclones, and the El Niño–Southern
Oscillation (ENSO). Numerous studies have investigated the influence of air–sea interactions on these atmospheric
30 phenomena (Shukla, 1975; Bielli et al., 2021; Jin, 1997; Latif et al., 1998; Wang, 2018).



Among these, the East Asian summer monsoon (EASM) is a prominent example in which air–sea interactions play a critical role (Dai et al., 2018). The EASM is a dominant system influencing the hydrological cycle over East Asia, and precipitation in this region plays an important role in maintaining the global energy and hydrological cycles and driving monsoon climate variability. EASM precipitation is characterized by a distinct rainband that contributes substantially to summertime rainfall over East Asia. This rainband typically forms over the Indochina Peninsula and the Philippines in May and gradually shifts northward, traversing the Yangtze River basin, southern Japan, and the southwestern Philippine Sea, before extending to northern China, Japan, the northwestern Pacific, and the Korean Peninsula (Ding and Chan, 2005). As the rainband tends to stagnate in certain regions, it can produce prolonged and intense rainfall, often resulting in significant socio-economic impacts across East Asia. The meridional migration of the rainband is primarily driven by the westward extension of subtropical highs over the Indian Ocean and the western North Pacific. Over the ocean, air masses actively exchange heat, moisture, and momentum, particularly over the western Pacific, North Pacific, and Indian Ocean. These air–sea interactions exert a substantial influence on the East Asian rainband, and understanding these processes is key to improving the simulation and prediction of the EASM.

To analyze the influence of air–sea interactions, many studies have employed coupled atmosphere–ocean models. In contrast, atmosphere-only general circulation models typically prescribe sea surface temperature (SST) as an external forcing, accounting only for the heat and moisture fluxes from the ocean to the atmosphere. Coupled atmosphere–ocean models, on the other hand, enable a more accurate representation of air–sea interactions by allowing information exchange between the atmospheric and oceanic components at short time intervals, thereby capturing two-way fluxes. Accordingly, previous studies have investigated these interactions by comparing coupled and atmosphere-only models. Numerous studies have demonstrated that the use of coupled models leads to improved predictions of precipitation and monsoon systems. In particular, coupled atmosphere–ocean models have shown enhanced skill in simulating precipitation associated with the EASM (Hu et al., 2012; Song and Zhou, 2014; Shi et al., 2021). Wu and Kirtman (2005) demonstrated that coupled models can reduce the overestimation of atmospheric variability often associated with atmosphere-only models by including negative ocean feedback. In addition, previous studies highlighted the importance of air–sea coupling in reproducing realistic SST–precipitation relationships associated with monsoon variability. Wang et al. (2005) showed that atmospheric general circulation models fail to reproduce the negative correlation between SST and precipitation and suggested this as one of the causes of their poor simulation of the EASM. In contrast, coupled atmosphere–ocean models can realistically simulate the negative SST–precipitation relationship, implying that air–sea interactions are crucial in monsoon regions where atmospheric feedback on SST plays an important role.

In the present study, we developed a new fully coupled atmosphere–ocean model and present it for the first time. In addition, we evaluate its performance in simulating the EASM and investigate the influence of air–sea interactions on the EASM simulation. The developed coupled model employs the Global/Regional Integrated Model system (GRIMs; Hong et al., 2013) as the atmospheric component and the Nucleus for European Modelling of the Ocean (NEMO; Madec and the NEMO Team, 2012) as the oceanic component and includes the Sea Ice Modelling Integrated Initiative (SI³) as the sea ice



65 model. The GRIMs–NEMO coupled system is fully integrated and exchanges coupling variables at 1 h intervals, enabling the representation of short-timescale air–sea interactions. This study has two primary objectives. The first is to introduce the newly developed GRIMs–NEMO coupled model and evaluate its ability to reproduce the general climatological characteristics across different seasons, with a particular focus on its performance in simulating the EASM. The second is to examine the impact of air–sea interactions on the simulation of the EASM.

70 This study is organized as follows. Sect. 2 provides a brief overview of the Coupled GRIMs–NEMO system. Sect. 3 describes the experimental design and analysis methods. Sect. 4 presents the evaluation results of the coupled model’s simulation performance and analyzes the influence of air–sea interactions on the EASM. Finally, a summary and conclusions are provided in Sect. 5.

75 2 Coupled GRIMs–NEMO

We present a newly developed global atmosphere–ocean–sea ice coupled model, Coupled GRIMs–NEMO. The coupled model consists of the GRIMs atmospheric, NEMO ocean, and SI³ sea ice models, which are integrated through the OASIS3–MCT coupler (Craig et al., 2017). During integration, the atmospheric, oceanic, and sea ice components exchange variables such as SST, ice cover, snow depth, wind stress, evaporation, precipitation, radiation, and heat flux every hour
 80 through the coupler. These exchanged fields influence the circulation within each component model, thereby enabling the representation of air–sea interactions.

GRIMs is a unified global and regional atmospheric prediction model developed for applications in numerical weather prediction, seasonal forecasting, and climate research. Currently, the GRIMs-based Global Model Program (GMP) is operationally used by the Republic of Korea Air Force for medium-range weather forecasting. The dynamical core of the
 85 GMP employs the spherical harmonics and double Fourier Series methods, providing an efficient and numerically stable modelling framework. The physical parameterization schemes in the GRIMs version 3.2 configuration include updated treatments for deep convection and the planetary boundary layer. Specifically, the model employs the longwave radiation scheme of Chou et al. (1999), the shortwave radiation scheme of Chou and Suarez (1999), the KSAS deep convection scheme (Han et al., 2020), the GRIMs shallow convection scheme (Hong et al., 2018), the WRF single-moment 3-class
 90 microphysics scheme (Hong et al., 2004), the cloudiness scheme of Hong et al. (1998), the Yonsei University boundary layer scheme (Hong et al., 2006) with enhanced mixing under stable conditions (Hong, 2010), the Noah land surface model version 2.7 (Ek et al., 2003; Chen and Dudhia, 2001), and parameterizations for convective and orographic gravity wave drag (Chun and Baik, 1998; Kim and Arakawa, 1995). The horizontal resolution corresponds to T126 (approximately 100 km), and the coupled model is configured with 28 vertical levels.

95 NEMO is widely used for research and prediction in oceanography and climate science and is also employed operationally by the European Centre for Medium-Range Weather Forecasts (ECMWF). NEMO includes components for the ocean, sea



ice, and biogeochemistry (TOP–PISCES); however, the biogeochemical module was excluded in the coupled configuration. The sea ice component is represented by the SI³ model. In Coupled GRIMs–NEMO, SI³ is integrated within NEMO, and the exchange of coupling variables is performed through the coupler. For vertical ocean physics, vertical mixing is represented by the TKE turbulent closure scheme (Blanke and Delecluse, 1993). Convection processes are represented using the enhanced vertical diffusion scheme (Lazar et al., 1999), while double-diffusive mixing is parameterized following Merryfield et al. (1999). The Coupled GRIMs–NEMO system employs NEMO version 4.2.2, configured with a horizontal resolution of approximately 25 km and 75 vertical levels.

The Coupled GRIMs–NEMO system enables computationally efficient integration with relatively low resource requirements, owing to the lightweight nature of the GRIMs atmospheric model. To evaluate its computational performance, a comparison was conducted between the Coupled GRIMs–NEMO system and the widely used Community Earth System Model version 2 (CESM2; Danabasoglu et al., 2020), using CESM2 version 2.2.2. Both models were executed in the same computing environment with identical horizontal resolutions: 200 km for the atmospheric component and 1° for the ocean component. In this comparison, CESM2 was configured without the atmospheric chemistry and wave components. Using a total of 108 CPUs, a 30-day integration was performed. Under this configuration, CESM2 required approximately 64 min to complete the simulation, whereas the Coupled GRIMs–NEMO system completed the same integration in about 16 min. The time profiling of each coupled model component showed that CESM2 required approximately twice the computational time of Coupled GRIMs–NEMO in both the atmospheric and oceanic components, while Coupled GRIMs–NEMO was faster across all components (Table 1). Given the high computational cost of long-term coupled climate simulations, these results demonstrate that the newly developed Coupled GRIMs–NEMO provides an efficient framework for air–sea interaction experiments under limited computational resources.

Table 1: Computational time according to model components. (Unit: minutes).

Component	Coupled GRIMs–NEMO	CESM2
ATM (Land)	7.13	14.91 (7.86)
OCN	15.6	33.29
ICE	Included in OCN	3.02
Coupler	8.45	27.36
Total	15.8	64.45



120 3 Methods

3.1 Evaluation of model performance

Before examining the impact of air–sea interactions on the EASM rainband, the simulation performance of the newly developed Coupled GRIMs–NEMO model was assessed using the Program for Climate Model Diagnosis and Intercomparison Metrics Package (PMP; Lee et al., 2024). PMP is an open-source Python software package that provides
125 observational datasets and objective diagnostic analyses, enabling the intercomparison of multiple Earth system models. In this study, PMP was used to quantitatively evaluate the performance of Coupled GRIMs–NEMO and compare it with CMIP5 and CMIP6 coupled models. The reference datasets provided by PMP, including ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2020) and the Global Precipitation Climatology Project (GPCP; Huffman et al., 2023a), were used to compare model results. To ensure consistency with the simulation periods of the CMIP models provided in PMP, Coupled
130 GRIMs–NEMO was integrated from 1970 to 2005, and the simulation results for 1980–2005 were used for the analysis. Historical simulations were conducted by prescribing external forcing datasets from input4MIPs (input datasets for Model Intercomparison Projects), including the solar constant (Matthes et al., 2017), greenhouse gas concentrations (Meinshausen et al., 2017), and ozone concentrations (Hegglin et al., 2016). ERA5 and Ocean Reanalysis System version 5 (ORAS5; Zuo et al., 2019) were used as initial conditions for model integration.

135 3.2 EASM experiments

To investigate the impact of air–sea interactions on the simulation of the EASM, three experiments were conducted: CPL, using the coupled model; ATM, using the atmosphere-only model forced by prescribed reanalysis SSTs; and ATM_CSST, in which SSTs simulated by the coupled model were prescribed to the atmosphere-only model. The
140 comparison between CPL and ATM_CSST enables isolation of air–sea interaction effects, independently of the SST biases in the coupled model. The experiments were conducted from 20 May to 31 August during each summer season from 2014 to 2023. The analysis was based on the June–August mean of the 10-year simulations. All experiments used the same atmospheric physical parameterizations and input datasets, including the Global Ocean Ensemble Physics Reanalysis product (E.U. Copernicus Marine Service Information, 2026) from the Copernicus Marine Service (CMEMS) and ERA5. ERA5 and the Integrated Multi-satellite Retrievals for GPM version 7 (IMERG; Huffman et al., 2023b) were used as reference datasets
145 for the analysis.



4 Result

4.1 Evaluation of Coupled GRIMs–NEMO performance

4.1.1 Climate fields

As an initial assessment of the newly developed Coupled GRIMs–NEMO, climatological simulation characteristics were analyzed to evaluate its overall performance, with particular emphasis on boreal summer, the main focus of this study. Figure 1a shows the seasonal root mean square error (RMSE) of precipitation, calculated using PMP based on results from the CMIP5 and CMIP6 models and Coupled GRIMs–NEMO. The precipitation RMSE of Coupled GRIMs–NEMO is comparable to those of the CMIP models in all seasons, with the smallest RMSE occurring in September–November (SON). The precipitation bias of Coupled GRIMs–NEMO model is approximately -0.4, opposite in sign to the positive biases observed in most CMIP models, although its magnitude is comparable. The pattern correlation coefficients (PCs) are 0.74 in December–February (DJF), 0.61 in March–May (MAM), 0.76 in June–August (JJA), and 0.84 in SON. These results indicate that Coupled GRIMs–NEMO exhibits simulation performance comparable to that of CMIP models.

Figure 1b–e shows the spatial patterns of precipitation in DJF and JJA. In DJF, Coupled GRIMs–NEMO reproduces a spatial pattern broadly similar to that of GPCP. The southeastward-extending precipitation band over the South Pacific is simulated as extending farther southeastward in Coupled GRIMs–NEMO, accompanied by a slight overestimation of precipitation. Although precipitation is relatively underestimated in high latitudes, the overall spatial pattern is well reproduced compared with that in GPCP. In JJA, a marked overestimation of precipitation is found over the equatorial western Pacific warm pool, with a general overestimation of precipitation near the equator. In contrast, precipitation is generally underestimated in mid- to high latitudes. Similar features are also observed in other CMIP models. Nevertheless, the location of the main precipitation cores is reasonably well simulated, as reflected in the PC of 0.76.

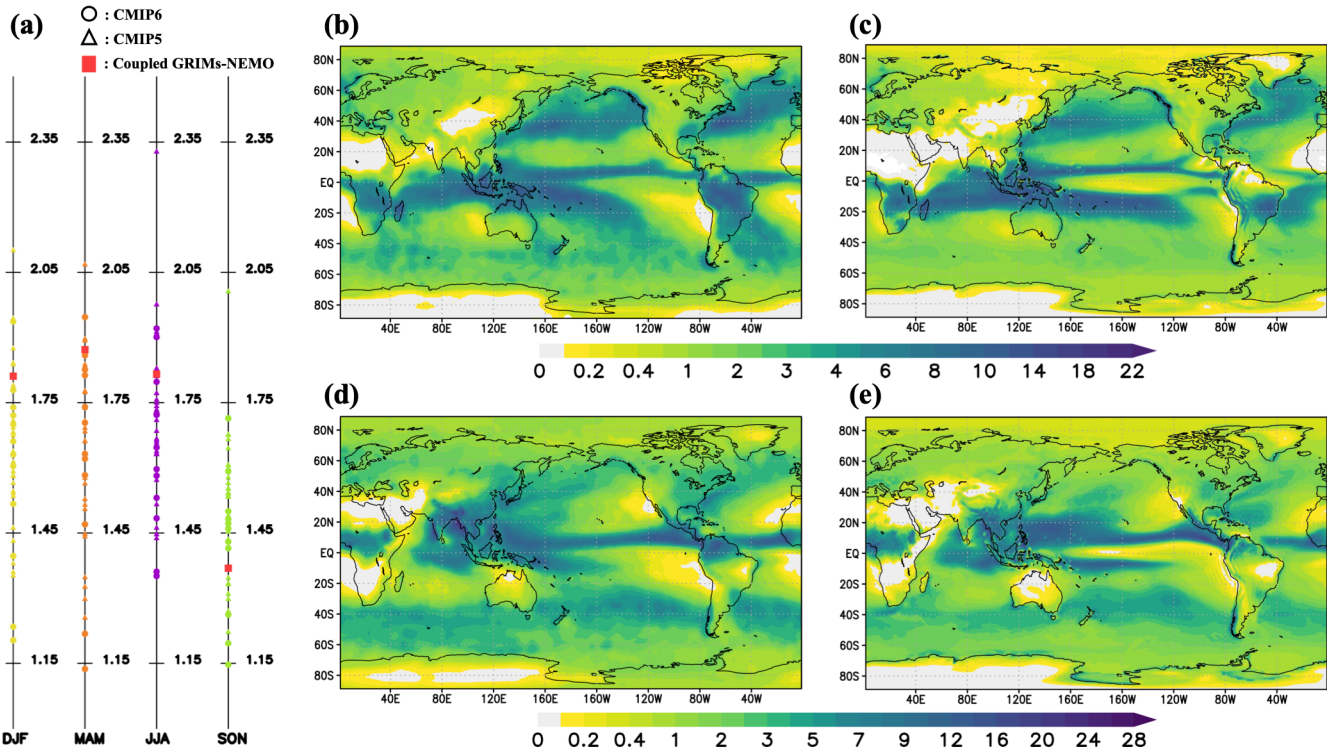


Figure 1: (a) Precipitation RMSE of the Coupled GRIMs–NEMO and CMIP models. DJF mean precipitation (mm day⁻¹) from (b) GPCP and (c) Coupled GRIMs–NEMO, and JJA mean precipitation (mm day⁻¹) from (d) GPCP and (e) Coupled GRIMs–NEMO. GPCP precipitation data © NASA.

Figure 2 shows the JJA atmospheric fields from ERA5 and Coupled GRIMs–NEMO. At both 850 and 500 hPa, Coupled GRIMs–NEMO exhibits lower geopotential heights than ERA5 over much of the globe. The global cold bias shown in Fig. 2e suggests that the cold bias throughout the atmospheric column reduces atmospheric thickness, contributing to the negative geopotential height biases. In the 850 hPa geopotential height field, the North Pacific High does not extend sufficiently westward toward the western Pacific, and a cyclonic circulation appears over the western Pacific in Coupled GRIMs–NEMO. This pressure-field bias over the Pacific likely affects the JJA precipitation pattern shown in Fig. 1, particularly the precipitation biases over the equatorial Pacific and the EASM rainband. This influence is discussed further in Sect. 4.2. At 500 hPa, the geopotential height over the Tibetan Plateau is underestimated, suggesting that the mid-tropospheric high over this region is not sufficiently developed. This feature is associated with the surface cold bias over the Tibetan Plateau (Fig. 2f), which indicates insufficient summertime heating of the plateau and weakened upper-level anticyclonic circulation. Such a thermal bias may weaken low-level convergence associated with the Indian monsoon, thereby contributing to the underestimation of precipitation over India. This bias in the simulation of lower-boundary



temperature is likely associated with the use of the relatively old Noah land surface model version 2.7 in Coupled GRIMs–
185 NEMO, and improvements to the land surface model are expected to enhance overall model performance. Although Coupled
GRIMs–NEMO exhibits systematic biases in JJA climatology, it reasonably reproduces the large-scale spatial patterns. The
PCs are high, with values of 0.99 for the 500 hPa geopotential height, 0.79 for the 850 hPa geopotential height, and 0.97 for
both upper-level and surface temperature.

Based on the PMP comparison with the CMIP models, the newly developed Coupled GRIMs–NEMO exhibits
190 competitive performance in simulating climatological fields. Regardless of season, precipitation is generally overestimated
near the equator and underestimated at high latitudes. This feature is likely associated with the model's cold temperature bias,
which affects the geopotential height field and, in turn, the simulated precipitation distribution. Nevertheless, despite these
systematic biases, Coupled GRIMs–NEMO reproduces the climatological atmospheric patterns reasonably well compared
with the reference data. These results suggest that Coupled GRIMs–NEMO has sufficient capability for use in climate- and
195 weather-related studies.

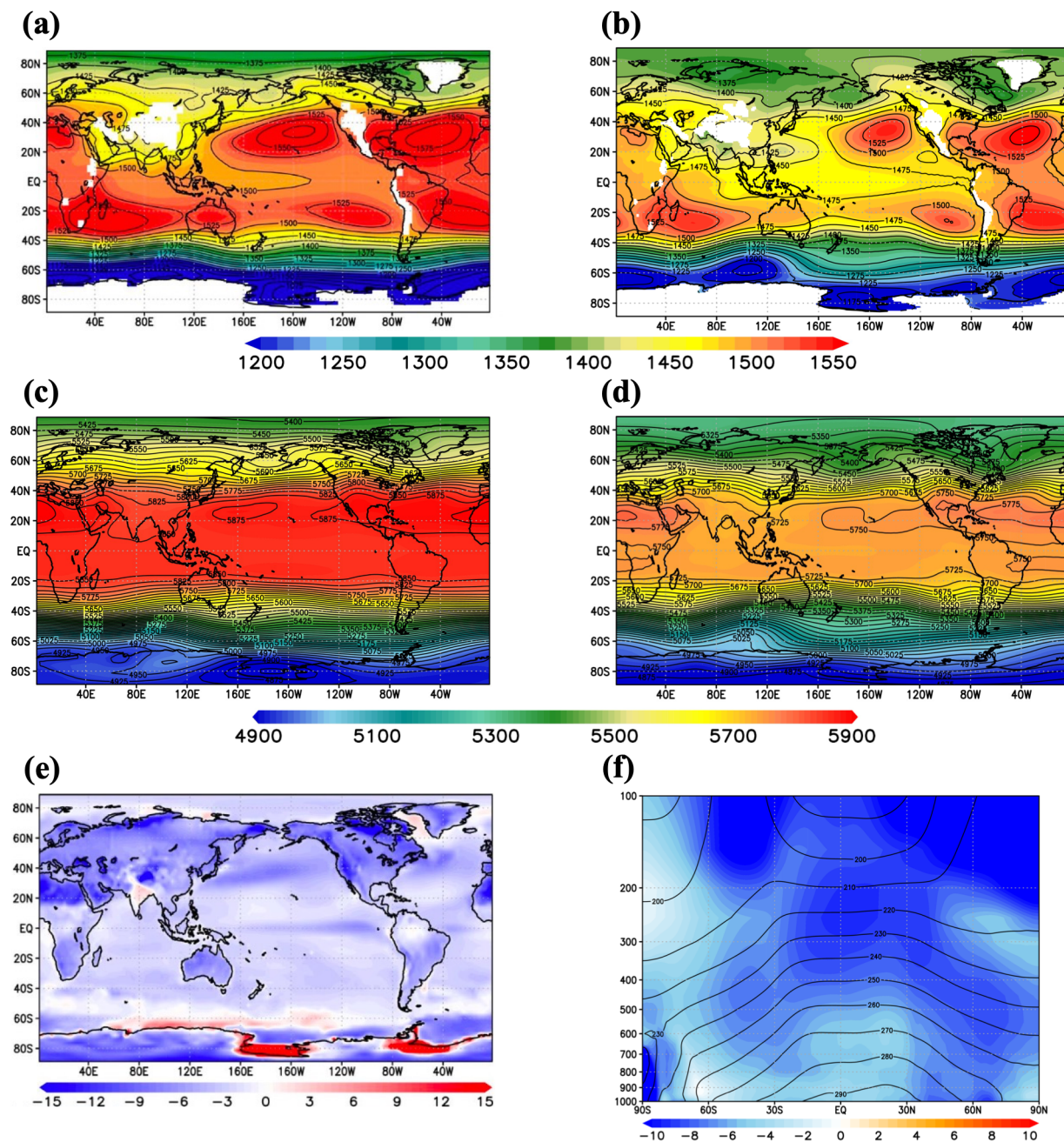


Figure 2: JJA mean 850 hPa geopotential height (gpm) from (a) ERA5 and (b) Coupled GRIMs–NEMO, and 500 hPa geopotential height (gpm) from (c) ERA5 and (d) Coupled GRIMs–NEMO. Difference in (e) surface temperature (K) and (f) zonal mean temperature (K, shaded), with Coupled GRIMs–NEMO temperature (K, contours). ERA5 data © Copernicus Climate Change Service (C3S).

4.1.2 Climate variability mode

In this section, we evaluate the performance of Coupled GRIMs–NEMO in simulating major climate variability modes. Among various modes of climate variability, we focus on ENSO, the Pacific–Japan (PJ) pattern, and the Boreal Summer Intraseasonal Oscillation (BSISO), all of which influence the EASM. Figure 3 shows the spatial patterns and time series of the first and second empirical orthogonal function (EOF) modes derived from DJF SST anomalies. The coupled model reproduces ENSO variability as the first EOF mode, consistent with Extended Reconstructed Sea Surface Temperature (ERSST) (Huang et al., 2017). However, the region of large variability over the eastern Pacific extends farther westward in the coupled model than that of ERSST, indicating that SST variability over the western Pacific warm pool is stronger in the model than in the observations (ERSST). The coupled model also reproduces the spatial pattern of the second EOF mode reasonably well compared with that of ERSST. In ERSST, the first and second EOF modes explain 66% and 14% of the total variance, respectively, whereas the corresponding values in the coupled model are 68% and 11%. However, the associated time series differ. For the first EOF mode, ERSST displays a dominant periodicity of 3–5 years, whereas the coupled model simulates a longer periodicity of approximately 7–8 years. These results indicate that, although Coupled GRIMs–NEMO has biases in simulated ENSO periodicity, it reasonably captures the ENSO signal and reproduces spatial patterns similar to those of ERSST.

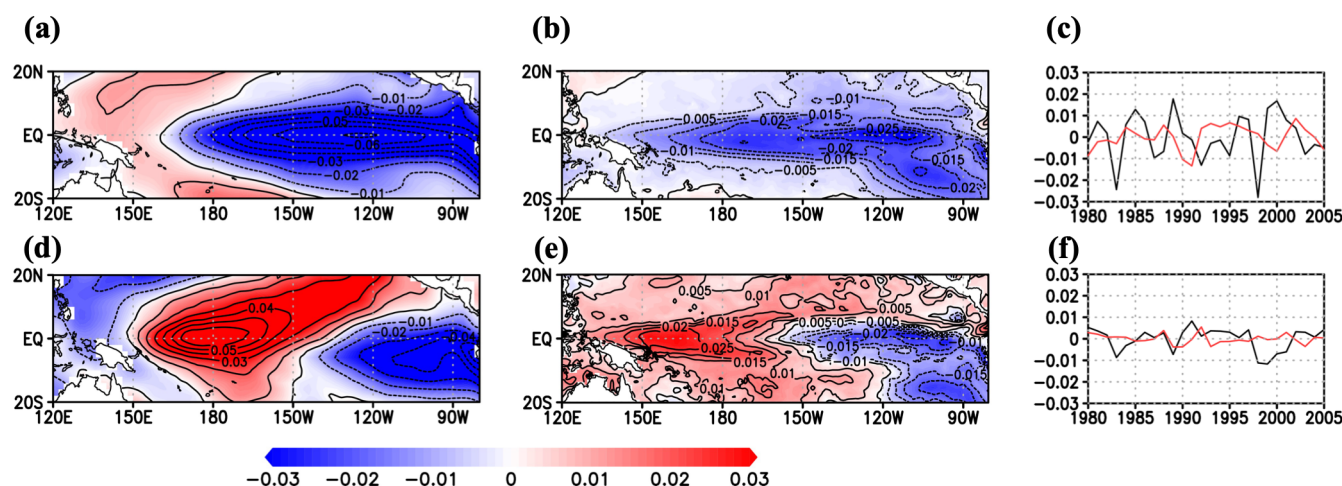


Figure 3: First EOF mode of DJF mean sea surface temperatures from (a) ERSST and (b) Coupled GRIMs–NEMO, and second EOF mode from (d) ERSST and (e) Coupled GRIMs–NEMO. Principal components time series for (c) EOF mode 1 and (f) EOF mode 2 are represented by black and red lines for ERSST and Coupled GRIMs–NEMO, respectively. ERSST data © NOAA.



Figure 4 shows the first EOF mode of JJA 850 hPa relative vorticity, which represents the PJ pattern. Compared with ERA5, Coupled GRIMs–NEMO simulates the overall pattern with a southward displacement. The first EOF mode explains 21.3% of the total variance in ERA5, whereas the corresponding mode in the coupled model accounts for a larger fraction, 31.4%. This feature is associated with cyclonic circulation over the western Pacific warm pool in the coupled model, as shown in Fig. 2b. The center of this cyclonic circulation is located farther south than that in ERA5, resulting in a southward shift of the relative vorticity pattern. In addition, the stronger development of this cyclonic circulation enhances convective activity over the western Pacific, which contributes to the larger fraction of 850 hPa relative vorticity variability explained by the first EOF mode in Coupled GRIMs–NEMO than in ERA5. These results indicate that Coupled GRIMs–NEMO exhibits a positional bias in simulating the PJ pattern, similar to biases observed in some CMIP models.

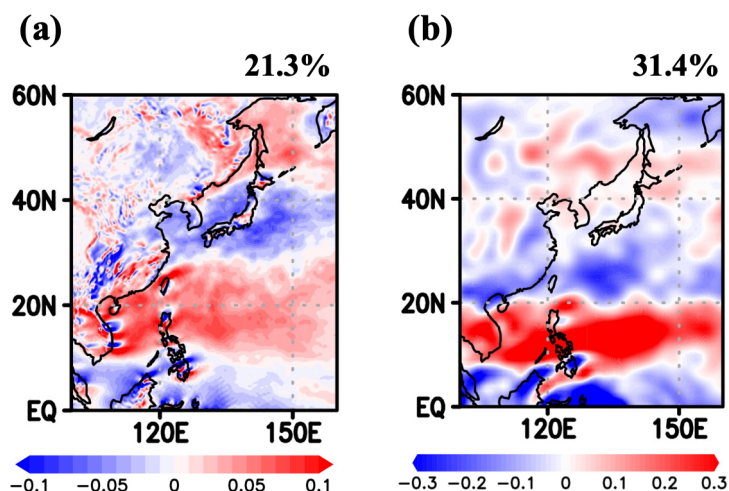


Figure 4: First EOF mode of JJA mean 850 hPa relative vorticity from (a) ERA5 and (b) Coupled GRIMs–NEMO. ERA5 data © Copernicus Climate Change Service (C3S).

We further evaluate model performance in simulating BSISO, which represents the intraseasonal variability of the monsoon. Figure 5 shows the composite fields for each phase of the BSISO life cycle. During phases 1–4, ERA5 shows that the precipitation band over the Indian Ocean propagates northwestward and eastward toward the Pacific. Coupled GRIMs–NEMO reasonably reproduces this propagation. However, the northwestward-propagating precipitation band from the Indian Ocean toward inland India is weaker in the coupled model than that in ERA5. This feature is attributed to the warm SST bias over the Indian Ocean in the coupled model, which reduces the land–sea thermal contrast and weakens the Indian monsoon. During phases 5–8, ERA5 displays the northwestward propagation of the precipitation band over the northwestern Pacific. The coupled model captures this propagation well and simulates the precipitation intensity more realistically than during phases 1–4. Overall, Coupled GRIMs–NEMO reproduces the BSISO life cycle in a manner similar to that of ERA5.

Although differences in precipitation intensity remain, the model shows reasonable performance in simulating monsoon intraseasonal variability, particularly the propagation of the precipitation band.

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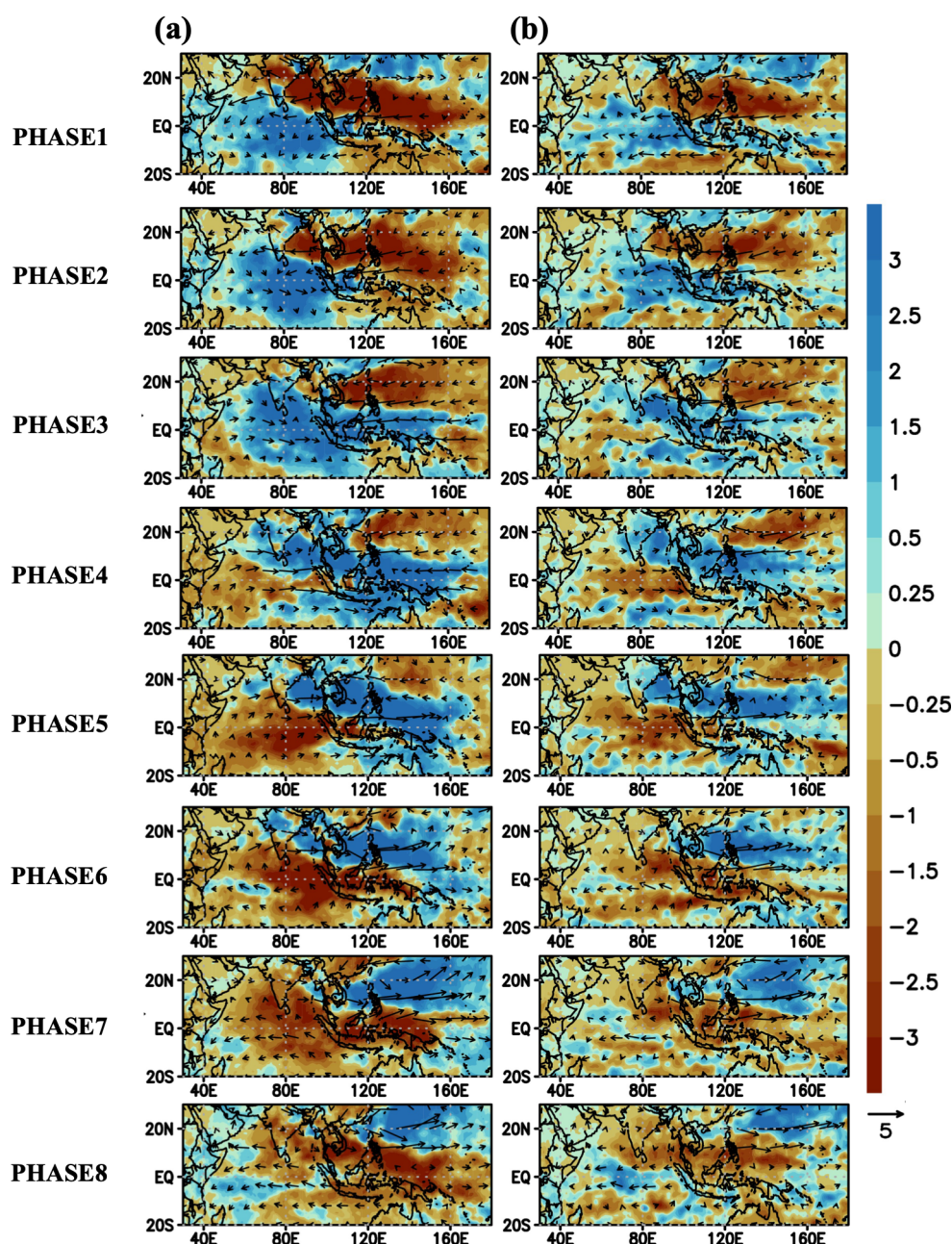
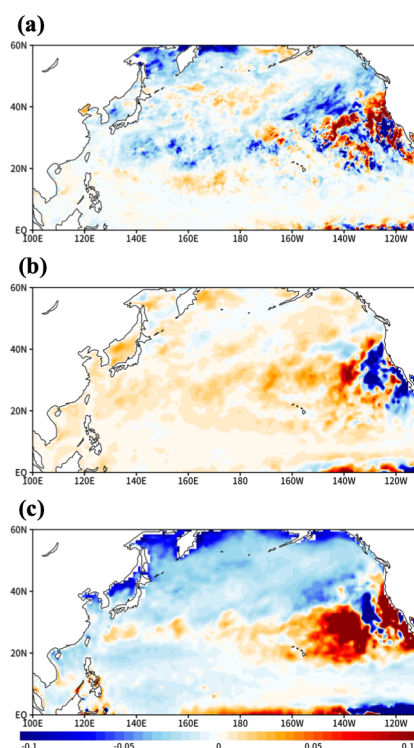


Figure 5: BSISO life cycle composite fields of daily precipitation anomalies (mm day⁻¹, shaded) and 850 hPa zonal wind (m s⁻¹).

4.2 The influence of air–sea interaction on the EASM

255 In this study, we investigated the influence of air–sea interactions on the simulation of the EASM using the Coupled GRIMs–NEMO model. Before this analysis, we examined whether air–sea interactions were adequately represented over the East Asian region in the coupled model. Figure 6 shows the grid-point regression coefficients of daily SSTs onto daily precipitation during JJA. In ATM (Fig. 6b), the negative relationship apparent in the observations (Fig. 6a) is not reproduced. In contrast, CPL (Fig. 6c) reasonably captures the negative relationship between precipitation and SSTs, although some positional differences remain due to systematic biases in the simulated precipitation region. In ATM, the atmosphere-only experiment, SSTs are prescribed as a one-way forcing on the atmosphere. Consequently, ATM does not account for SST cooling due to cloud-induced reductions in shortwave radiation associated with increased precipitation. Therefore, the negative relationship between precipitation and SSTs can be reproduced in a coupled model that includes ocean dynamics and accounts for air–sea interactions, and this feature is clearly represented in CPL. These results indicate that Coupled
 260 GRIMs–NEMO adequately represents air–sea interactions and is therefore suitable for investigating the influence of these interactions on EASM simulations.



270 **Figure 6: Grid-point regression coefficients of daily sea surface temperature onto daily precipitation during JJA, calculated for each year and averaged over the 10-year period: (a) observations (CMEMS and IMERG), (b) ATM, and (c) CPL. CMEMS data © Copernicus Marine Environment Monitoring Service (CMEMS). IMERG precipitation data © NASA.**



Figure 7 shows the JJA mean daily precipitation from IMERG and each experiment. In ATM (Fig. 7b), which was conducted using the GRIMs atmospheric model, a component of Coupled GRIMs–NEMO, precipitation is overestimated near the equator compared with that in IMERG (Fig. 7a). This overestimation is particularly pronounced over the western Pacific warm pool, whereas precipitation tends to be underestimated in the midlatitudes. In addition, ATM generally underestimates precipitation over the Indian Ocean. Nevertheless, the overall precipitation pattern is similar to that observed, indicating that the GRIMs atmospheric model broadly reproduces the large-scale spatial distribution of EASM precipitation. In CPL (Fig. 7c), SSTs are predicted using the ocean model; therefore, systematic biases in the ocean model can be reflected in the SST field, and air–sea feedbacks further influence precipitation distribution. Similar to ATM, CPL exhibits an overestimation of precipitation near the equator and an underestimation in the midlatitudes. Over the Indochina Peninsula, precipitation is somewhat overestimated over inland regions. However, the precipitation band along the western coast is simulated more similarly to that in IMERG, and the precipitation amount is improved compared with that in ATM. In addition, the precipitation pattern over the Indian Ocean is also improved in CPL relative to that in ATM. These improvements in precipitation simulation in CPL, compared with those in ATM—where SSTs are prescribed from reanalysis data—suggest that air–sea interactions play an important role in the predictability of the EASM. ATM_CSST (Fig. 7d) exhibits a precipitation pattern very similar to that of CPL, as the SSTs simulated by the coupled model are prescribed in this experiment. However, ATM_CSST exhibits larger precipitation amounts near the equator than those of CPL. This difference can be partly attributed to the air–sea interactions represented in CPL. In CPL, enhanced precipitation is accompanied by increased cloud cover, which reduces downward shortwave radiation at the sea surface and leads to SST cooling. The resulting SST cooling suppresses precipitation, thereby acting as a negative feedback between SSTs and precipitation. In contrast, ATM_CSST cannot represent this feedback because SSTs are prescribed as a lower boundary condition. Consequently, the precipitation response to the prescribed SSTs is likely overestimated in ATM_CSST.

To examine whether air–sea interactions also affect the seasonal evolution of the EASM rainband, a Hovmöller diagram of precipitation averaged over 120°E–140°E is analyzed. In IMERG (Fig. 8a), an organized rainband migrates northward from early June to mid-July, followed by a weakening of precipitation intensity and a subsequent southward retreat. This seasonal evolution is similarly reproduced in CPL (Fig. 8b). In early June, ATM_CSST (Fig. 8c) shows a strong precipitation core near the equator but fails to represent the organized precipitation band around 30°–40°N, whereas CPL captures this feature more realistically. This suggests that the pronounced overestimation of equatorial precipitation in ATM_CSST affects the meridional distribution of moisture available for northward transport. In CPL, air–sea interactions partially suppress excessive precipitation near the equator, thereby providing a more favourable environment for the organization of the northward-migrating EASM rainband. These results indicate that the representation of air–sea interactions positively influences the simulation of the seasonal evolution of EASM precipitation.

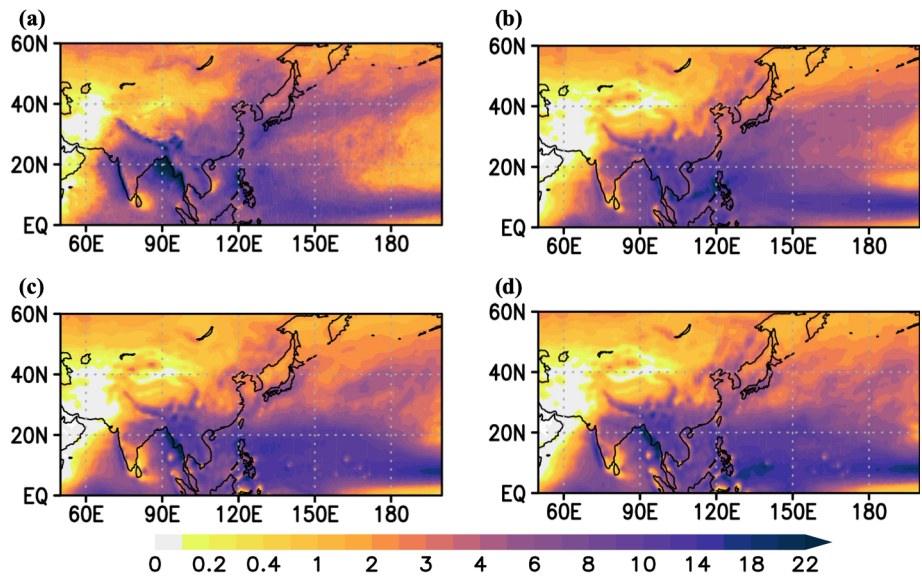


Figure 7: JJA mean precipitation (mm day⁻¹) for (a) IMERG, (b) ATM, (c) CPL, and (d) ATM_CSST. IMERG precipitation data

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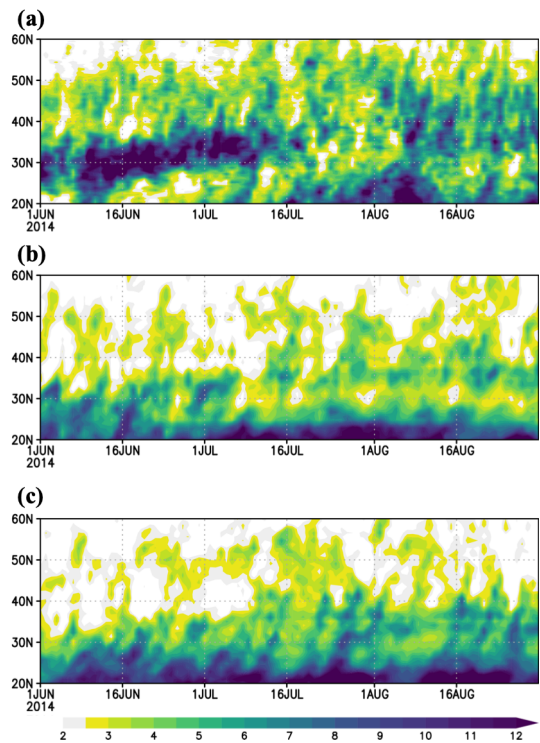


Figure 8: Hovmöller diagram of precipitation averaged over 120°E–140°E (mm day⁻¹): (a) IMERG, (b) CPL, and (c) ATM_CSST. IMERG precipitation data © NASA.



310 We further analyzed the factors contributing to the precipitation characteristics described above in each experiment. Figure 9a–d show the JJA mean integrated water vapour transport (IVT) from 1,000 to 300 hPa in ERA5 and in each experiment. In ATM (Fig. 9b), IVT is overestimated over the warm pool region, where precipitation is also overestimated. Consequently, the moisture transport pathway extending from the equatorial region toward Japan and the Korean Peninsula is weakened compared with that of ERA5 (Fig. 9a). This feature is more distinct in CPL (Fig. 9c). In particular, a large amount of moisture is transported from the Indian Ocean across the Indochina Peninsula and reaches the western Pacific, resulting in an overestimation of IVT near the western Pacific warm pool. Consequently, the amount of moisture transported toward the midlatitudes is further reduced, contributing to the underestimation of precipitation in the midlatitudes. In addition, moisture transport into inland India is underestimated compared with that of ERA5. This suggests that the moisture transported from the Indian Ocean is not sufficiently depleted through precipitation over inland India, leading to excessive moisture transport toward the western Pacific warm pool. A similar feature is also observed in ATM_CSST. The overestimation of IVT over the western Pacific can be further explained by biases in the low-level pressure field. Compared with that of ERA5 (Fig. 9e), CPL and ATM_CSST display an expanded low-pressure system over the western Pacific in the 850 hPa geopotential height field (Figs. 9g–h). This expansion of the low-pressure system suppresses the westward extension of the North Pacific High, thereby weakening the convergence zone formed south of the Korean Peninsula and Japan and reducing moisture transport toward the midlatitudes. In addition, the low-pressure system provides a favourable environment for the convergence of moisture transported across the Indochina Peninsula. As a result, the region of overestimated IVT extends toward the centre of the low-pressure system. CPL (Fig. 10b) exhibits larger surface heat fluxes over the equatorial region than those in ATM (Fig. 10a), while ATM_CSST (Fig. 10c) displays even larger surface heat fluxes than those in CPL. This is likely because the SSTs simulated using the coupled model are prescribed as a one-way lower boundary condition in ATM_CSST, allowing the warm SST bias in the coupled model to exert stronger thermal forcing on the atmosphere. In CPL, the enhanced surface heat fluxes near the equator increase lower-tropospheric heating and strengthen upward motion (Figs. 10d–f). This strengthened upward motion, particularly over the warm pool region, contributes to the development of a local low-pressure system, thereby influencing the precipitation bias in CPL.

Overall, these results demonstrate that atmosphere–ocean coupling plays an important role in reproducing the negative relationship between precipitation and SSTs and in regulating the spatial distribution of EASM precipitation. The comparison between ATM_CSST and CPL indicates that air–sea interactions can reduce precipitation overestimation near the equator, suggesting their influence on EASM simulation. However, the warm SST bias near the equator in CPL enhances surface heat fluxes over the western Pacific warm pool, thereby strengthening upward motion. Consequently, CPL exhibits excessive precipitation in the lower-latitude EASM region, while reduced moisture transport toward the midlatitudes leads to an underestimation of precipitation in the midlatitudes.

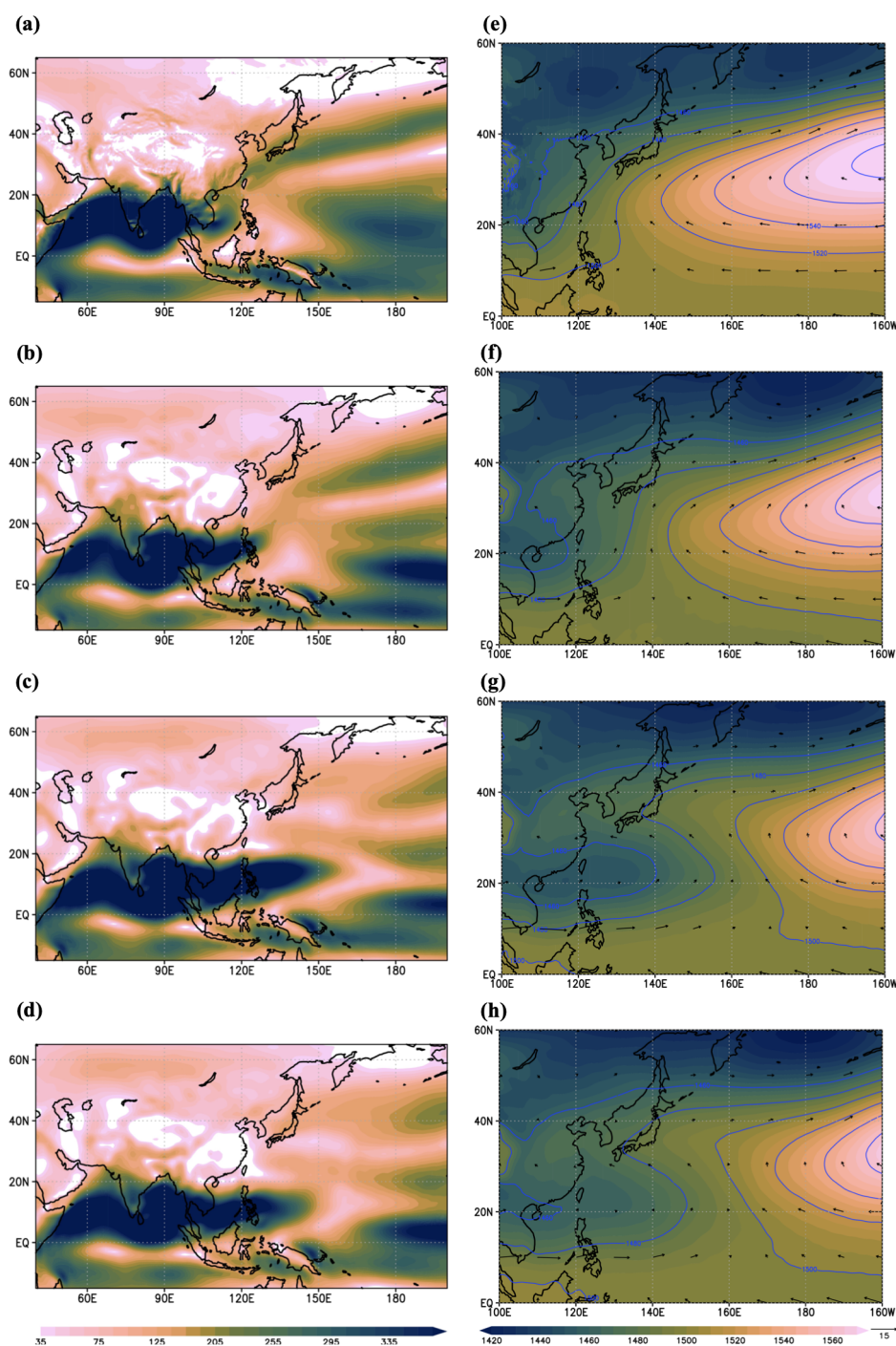


Figure 9: JJA mean fields of IVT (integrated from 1,000 to 300 hPa, $\text{kg m}^{-1} \text{s}^{-1}$) for (a) ERA5, (b) ATM, (c) CPL, and (d) ATM_CSST, and 850 hPa geopotential height (gpm; shaded and contours) with horizontal wind vectors for (e) ERA5, (f) ATM, (g) CPL, and (h) ATM_CSST. ERA5 data © Copernicus Climate Change Service (C3S).

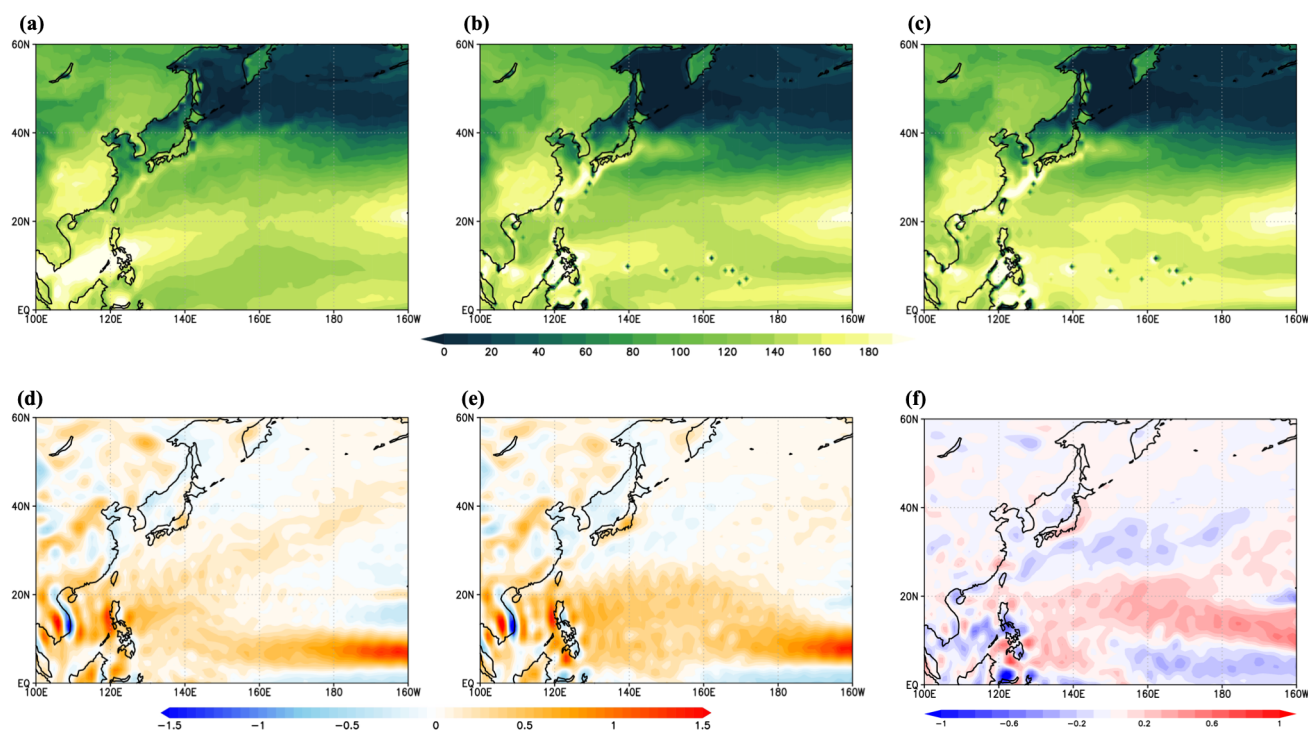


Figure 10: JJA mean surface heat flux, defined as the sum of latent and sensible heat fluxes (W m^{-2}), for (a) ATM, (b) CPL, and (c) ATM_CSST, and vertical velocity ($\times 10^{-1} \text{ Pa s}^{-1}$) for (d) ATM, (e) CPL, and (f) the difference (CPL – ATM).

350 5 Conclusion

This study introduced the newly developed Coupled GRIMs–NEMO model v1.0 and presented its overall simulation performance, with particular emphasis on its ability to simulate the EASM. We also investigated the influence of air–sea interactions on the simulation of the EASM. Coupled GRIMs–NEMO comprises the atmospheric model GRIMs, the ocean model NEMO, and the sea ice model SI³, which are fully coupled through OASIS3-MCT. A key advantage of this coupled model is its low computational cost, suggesting it can provide a substantial advantage for climate studies that require substantial computational resources.

The climatological performance of Coupled GRIMs–NEMO was evaluated with particular emphasis on boreal summer. The PMP-based comparison showed that the precipitation simulation performance of Coupled GRIMs–NEMO is comparable to that of the CMIP5 and CMIP6 models. Although the model showed a negative global precipitation bias, in contrast to the positive biases found in most CMIP models, the magnitude of the bias and the seasonal RMSE values were within a range similar to those of the CMIP models. In JJA, the model generally overestimated precipitation near the equator, particularly over the equatorial western Pacific warm pool, and underestimated precipitation in the mid- to high latitudes. These JJA precipitation biases were associated with biases in atmospheric fields, including a global cold bias, negative



geopotential height biases, a weakened westward extension of the North Pacific High, and a cyclonic circulation bias over
 365 the western Pacific. In addition, the surface cold bias over the Tibetan Plateau was linked to weaker summertime heating,
 which likely contributed to the underestimation of precipitation over India. This surface temperature cold bias is considered
 to be associated with the use of the Noah land surface model version 2.7, an older land surface model implemented in
 GRIMs. Therefore, updating the land surface model is currently planned as a high-priority improvement for Coupled
 GRIMs–NEMO. Such improvements are expected to reduce the surface cold bias, thereby enhancing the model's overall
 370 simulation performance. Despite these systematic biases, Coupled GRIMs–NEMO reasonably reproduced the large-scale
 climatological patterns of precipitation, geopotential height, and temperature, indicating its basic capability for climate and
 weather-related applications.

Additionally, Coupled GRIMs–NEMO was evaluated for its performance in simulating major climate variability
 modes that influence the EASM, including ENSO, the PJ pattern, and BSISO. The model reasonably reproduces the spatial
 375 structures of the leading ENSO-related EOF modes, although it simulates a longer ENSO periodicity of approximately 7–8
 years compared with the 3–5-year periodicity in ERSST. For the PJ pattern, the model captures the overall structure of the
 leading 850 hPa relative vorticity mode but shows a southward displacement and a larger explained variance than ERA5,
 which is associated with the cyclonic circulation bias over the western Pacific warm pool. The model also reproduces the
 overall BSISO life cycle, particularly the propagation of precipitation bands from the Indian Ocean to the Pacific and across
 380 the northwestern Pacific, although precipitation intensity over inland India is weaker than in ERA5. Overall, Coupled
 GRIMs–NEMO reasonably captures the major climate variability modes related to EASM variability.

The results demonstrate that air–sea interactions play an important role in simulating EASM precipitation in
 Coupled GRIMs–NEMO. CPL reproduces the negative relationship between precipitation and SSTs, which is absent in
 ATM, indicating that ocean dynamics and air–sea feedbacks are necessary to represent SST cooling associated with
 385 increased precipitation and cloud cover. Compared with ATM and ATM_CSST, CPL improves the spatial distribution of
 precipitation over the Indochina Peninsula and Indian Ocean and better captures the seasonal evolution of the EASM
 rainband. Hovmöller analysis shows that CPL more realistically reproduces the northward migration of the organized
 rainband, whereas ATM_CSST exhibits excessive equatorial precipitation and fails to organize the rainband around 30°–
 40°N. Moisture transport analysis indicates that precipitation biases are closely related to biases in IVT and low-level
 390 circulation. In CPL and ATM_CSST, excessive IVT over the western Pacific warm pool is associated with an expanded low-
 pressure system over the western Pacific, which weakens moisture transport toward the midlatitudes and contributes to
 underestimating precipitation over the midlatitude EASM region. Warm SST biases near the equator also enhance surface
 heat fluxes, strengthen upward motion, and contribute to excessive low-latitude precipitation. Overall, although atmosphere–
 ocean coupling improves key aspects of EASM precipitation simulation, the coupled model still exhibits systematic SST,
 395 circulation, and moisture transport biases that affect the regional distribution of precipitation.

This study is significant in that it introduces a newly developed fully coupled GRIMs–NEMO and provides potential
 users with a comprehensive assessment of its characteristics by evaluating its simulation performance from multiple



perspectives. In particular, for the boreal summer season, this study not only examines the simulated precipitation distribution and associated atmospheric circulation features, but also identifies the systematic biases of the model and
400 investigates the underlying causes of these biases. These analyses provide useful insights into future directions for model development. Based on these findings, future work will focus on improving the atmospheric component by updating its physical parameterization schemes and upgrading NEMO to a more recent version.

Code and data availability

The GRIMs-NEMO fully coupled model v1.0 source code and the model outputs used in this study are publicly available at
405 <https://doi.org/10.5281/zenodo.22712970> (Yoo and Chang, 2026) [Software]. For additional information or technical support, please contact E.-C. Chang (echang@kongju.ac.kr) or S. Yoo (soojin9608@gmail.com). The ERA5 reanalysis datasets and ORAS5 global ocean reanalysis monthly data are accessible from the Copernicus Climate Change Service through the Climate Data Store portal: <https://doi.org/10.24381/cds.bd0915c6> (Hersbach et al., 2020; last access: 8 September 2026) and
410 <https://doi.org/10.24381/cds.67e8eeb7> (Zuo et al., 2019; last access: 20 May 2026). The CMEMS global ocean ensemble reanalysis product can be obtained from Copernicus Marine Service marine data store portal: <https://doi.org/10.48670/moi-00024> (last access: 18 August 2026). The NASA's IMERG product can be accessed from
https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGDF.07, last access: 9 September 2026. The prescribed datasets used for the historical simulations are available through input4MIPs on ESGF, at <https://metagrid.esgf-west.org/> (last access: 11 Jun 2026). The PCMDI Metrics Package (PMP) are available from
415 https://github.com/PCMDI/pcmdi_metrics (last access: 8 August 2025).

Author contributions

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420 and editing)
Lee, J. : Investigation, Methodology, Software, Writing (review and editing)

Competing interests

The authors declare that they have no conflict of interest.



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