https://doi.org/10.5194/egusphere-2026-2024
Preprint. Discussion started: 21 July 2026

cSINGV v1.0: Development and evaluation of a 1.5 km coupled atmosphere-ocean-wave modelling system for the Western Maritime Continent

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Abstract. This study presents cSINGV v1.0, a high-resolution (1.5 km) regional coupled atmosphere–ocean–wave modelling system developed for the Western Maritime Continent (WMC). The system integrates a convection-permitting atmospheric model (SINGV) with newly configured ocean (NEMO) and wave (WAVEWATCH III) components within a unified coupling framework based on the Regional Coupled Suite and OASIS3-MCT coupler. The primary contribution of this work lies in the development of a fully coupled system enabling two-way interactions between atmosphere, ocean, and waves at kilometre scale. The ocean and wave components are specifically configured and optimised for the WMC, a region characterised by complex coastlines, shallow seas, and strong air–sea interactions.

The model is evaluated using a six-month simulation (January–June 2019) against multiple observational and reanalysis datasets. The ocean and wave components show good agreement with reference datasets, with sea surface temperature errors generally below 0.5 °C and significant wave height errors around 0.2 m. The influence of coupling is assessed by comparing the coupled and uncoupled atmospheric configurations. Results show that coupling improves the spatial organisation of precipitation, the diurnal cycle over the ocean, and the offshore propagation of convection, while differences in near-surface atmospheric variables remain modest. Process-based analysis indicates that these improvements are primarily linked to enhanced latent heat flux driven by thermodynamic air–sea feedbacks associated with sea surface temperature variability. Case studies of Sumatra squall events further indicate that coupling can influence the organisation and persistence of eastward-propagating convection, with the magnitude of this impact depending on the dominant convective regime. Overall, cSINGV provides a physically consistent framework for representing coupled processes in the WMC and offers a useful platform for investigating air–sea–wave interactions at convection-permitting scales.

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1 Introduction

The Western Maritime Continent (WMC; Fig. 1) is characterised by complex topography, warm and predominantly shallow seas, and strong air–sea interactions (Neale and Slingo, 2003). Located between the Indian and Pacific Oceans, the region lies within the active propagation zones of the Madden–Julian Oscillation (MJO), the Intertropical Convergence Zone (ITCZ), and the boreal summer and winter monsoons, and consequently experiences some of the highest precipitation rates globally (Zhang, 2005; Yamanaka, 2016; Jiang and Li, 2018; Karlowska et al., 2024a). These rainfall patterns are driven by deep convection, sea-breeze convergence, and large-scale circulations such as the Walker and Hadley cells (Stone and Chervin, 1984; Kim et al., 2020). In addition, rainfall over the WMC is governed by interactions across multiple temporal and spatial scales, including interannual variability associated with ENSO, intraseasonal variability linked to the MJO, and synoptic-scale equatorial waves, together with local processes such as the diurnal cycle and topography (Peatman et al., 2014; Birch et al., 2016; Wei et al., 2020; Peatman et al., 2021; Senior et al., 2025). The diurnal cycle is a dominant feature of convection over the WMC, with thunderstorms typically developing over land in the afternoon and propagating offshore overnight (Mori et al., 2004; Yokoi et al., 2017; Peatman et al., 2025). Accurately representing these multiscale interactions remains a major challenge for numerical models, particularly given the strong coupling between the atmosphere and ocean in the region (Jiang et al., 2020, Xue et al., 2020 and references therein).

Air–sea interactions provide a key pathway linking these multiscale processes in the WMC, with sea surface temperature (SST) playing a central role in modulating atmospheric convection, surface fluxes, and boundary-layer processes (DeMott et al., 2015; Yoneyama and Zhang, 2020; Savarin and Chen, 2022; Karlowska et al., 2024a). Observations show that diurnal SST variability can significantly influence intraseasonal variability and surface turbulent fluxes, thereby affecting atmospheric dynamics (Ruppert and Johnson, 2015; Yan et al., 2021; Itterly et al., 2021). Despite this, atmosphere-only models typically prescribe SST as a fixed lower boundary, preventing realistic ocean–atmosphere feedbacks and often leading to biases in surface fluxes, SST variability, and convective organisation (e.g., Lau and Nath, 2003). Even small SST errors can substantially alter the timing and spatial distribution of precipitation (Dipankar et al., 2019), highlighting the importance of resolving SST variability for accurate prediction over the WMC. Similarly, ocean-only models rely on prescribed surface fluxes, limiting the ocean's dynamical response to atmospheric forcing (Bonino et al., 2022). Coupled atmosphere–ocean models overcome these constraints by enabling two-way interactions, improving SST and atmospheric simulations, particularly when high-frequency coupling is used (Wei et al., 2014; Seo et al., 2014; Zhao and Nasuno, 2020; Lan et al., 2024). Previous efforts have also demonstrated the feasibility and benefits of regional coupled atmosphere–ocean modelling over the Maritime Continent. For example, Thompson et al. (2021) describe the development of a kilometre-scale (~4.5 km) coupled prediction system based on the Met Office Unified Model and NEMO. Their results demonstrate that the coupled system provides realistic simulations of SST, sea surface height (SSH), and subsurface ocean structure when evaluated against observations. These studies highlight the capability of regional coupled systems to improve ocean state representation in the Maritime Continent.

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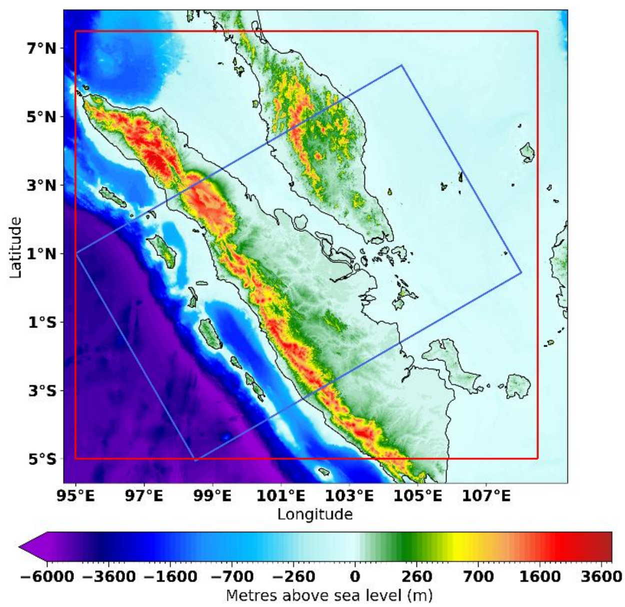

Figure 1: Ocean bathymetry and land orography over the Western Maritime Continent domain used in the cSINGV modelling system. The red box indicates the domain used for model evaluation in this study. The rotated blue box is used for the Sumatra Squall case study.

In addition to SST, ocean surface waves play an important role in air–sea interactions by influencing surface fluxes, upper-ocean mixing, and coastal dynamics (Cavaleri et al., 2012). Wave-induced effects on flux parameterisations can affect wind speeds and precipitation (Rutgersson et al., 2012; Wu et al., 2019). In the WMC, MJO-driven wind variability enhances wave activity and modulates air–sea exchanges (Hilmi et al., 2018). Wave-state-dependent fluxes have been shown to improve MJO representation by reducing biases in winds and latent heat fluxes (Ikuyajolu et al., 2024). Waves also influence upper-ocean mixing, circulation, and stratification (Babanin, 2006; Breivik et al., 2015), with demonstrated benefits for ocean and coastal forecasts (Bruciaferri et al., 2021; Wang et al., 2022; Jing et al., 2025). These findings highlight the importance of including wave processes in coupled systems.

Increasing horizontal resolution further improves convection representation, as finer grids allow explicit treatment of small-scale processes (Li et al., 2017). Convection-permitting resolutions (~1–3 km) substantially improve the simulation of the diurnal precipitation cycle over the Maritime Continent (Argüeso et al., 2020). Over the WMC, a 1.5 km configuration outperforms coarser (~4.5 km) models in representing rainfall (Heng et al., 2020). Coupled systems also benefit from higher resolution; for example, a 2.2 km atmosphere–ocean configuration improves diurnal variability and SST–precipitation relationships compared to coarser (~12 km) models (Howard et al., 2024). Together, these results emphasise the need for high-resolution coupled modelling to reduce persistent biases in WMC simulations.

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Despite these advances, significant challenges remain in representing air–sea interactions and associated precipitation processes over the WMC. Many existing studies either employ atmosphere-only convection-permitting models without interactive ocean feedbacks, or coupled systems at coarser resolutions that rely on parameterised convection. In addition, wave coupling is often neglected, further limiting the representation of air–sea momentum exchange and upper-ocean processes. Consequently, few studies have combined kilometre-scale, convection-permitting atmospheric models with fully coupled ocean–wave components in the WMC region.

To address these gaps, we develop and evaluate a 1.5 km convection-permitting coupled atmosphere–ocean–wave modelling system for the WMC. The primary objective of this study is to assess the performance of the newly developed fully coupled model relative to uncoupled configuration, with a particular focus on the representation of precipitation, diurnal variability, and air–sea interactions. Through evaluation against observational and reanalysis datasets, this study demonstrates the potential of kilometre-scale coupled systems for improving regional prediction and supporting future climate applications.

The remainder of this paper is organised as follows. Section 2 describes the model components and the coupled modelling framework. Section 3 outlines the experimental design, datasets, and evaluation methodology. Section 4 presents the model evaluation results, including the assessment of coupling effects. Finally, Section 5 summarises the main findings and conclusions, while Section 6 outlines future developments.

2 Model components and coupled system design

2.1 Overview of the cSINGV system

The cSINGV modelling system is a high-resolution (1.5 km) regional coupled atmosphere–ocean–wave framework developed for the WMC. It integrates a convection-permitting atmospheric model based on the Met Office Unified Model (UM), an ocean model based on the Nucleus for European Modelling of the Ocean (NEMO), and a spectral wave model based on WAVEWATCH III (WW3), within a unified coupling framework based on the UK Met Office Regional Coupled Suite (RCS) (Castillo et al., 2022).

In this study, the atmospheric component (hereafter referred to as cSINGV_A) is based on the numerical weather prediction system SINGV, used at the Meteorological Service Singapore (MSS). The ocean and wave components (hereafter referred to as cSINGV_O and cSINGV_W, respectively) have been newly developed and configured for the WMC. The primary development presented here is the integration of these components into a fully coupled system (cSINGV), enabling two-way interactions between the atmosphere, ocean, and waves.

The model domain spans 94.6°E–109.36°E and 5.7°S–8.13°N (Fig. 1), covering the complex coastal and shelf regions of the WMC. The system is designed to capture multiscale interactions, including diurnal variability, coastal processes, and air–sea–wave coupling, which are critical for accurately representing weather and climate in this region. The individual component models and the coupling framework are described in detail in the following sections.

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2.2 Atmospheric and land surface model (cSINGV_A)

The atmosphere and land surface components in cSINGV are based on a fixed-resolution latitude–longitude grid with a horizontal spacing of 1.5 km over the model domain. It is a fully non-hydrostatic model with a terrain-following vertical coordinate system, consisting of 80 vertical levels extending up to a model top of 38.5 km. The vertical resolution is approximately 5 m near the surface and 1.45 km at the model top, with a 60-second time step for model integration. The configuration is consistent with the MSS operational numerical weather prediction system, SINGV (Huang et al., 2019).

Several configurations of SINGV have been developed at MSS, reflecting its adaptability across a range of applications. These include SINGV-DA for data assimilation (Heng et al., 2019), SINGV-EPS for ensemble prediction (Porson et al., 2019), uSINGV for urban-scale modelling (Simón-Moral et al., 2020), SINGV-RCM for regional climate applications (Prasanna et al., 2024), and a regional coupled atmosphere–ocean configuration at 4.5 km resolution (Thompson et al., 2021).

Land surface processes are represented using the Joint UK Land Environment Simulator (JULES v7.5; Best et al., 2011), which includes nine surface fraction types. The atmosphere and land surface components are compiled as a single executable and coupled implicitly at each model time step following Best et al. (2004), ensuring consistent land–atmosphere interactions. Physical parameterisations include the Prognostic Cloud fraction and Prognostic Condensate (PC2) scheme (Wilson et al., 2008), as used in previous implementations (Huang et al., 2019). The boundary-layer parameterization follows a blending approach developed by Boutle et al. (2014), which combines the one-dimensional scheme of Lock et al. (2000) with the three-dimensional Smagorinsky-Lilly scheme (Lilly, 1962). The cloud microphysics scheme is based on Wilson and Ballard (1999), while radiation processes are modelled using the Edwards and Slingo (1996) scheme, which includes six shortwave bands and nine longwave bands (Manners et al., 2012).

The configuration used in this study (cSINGV_A) adopts the Regional Atmosphere and Land v2 in the Tropics (RAL2-T) configuration (Bush et al., 2023). This configuration is used as the baseline atmospheric system onto which the ocean and wave components are coupled. SST is prescribed and updated daily in cSINGV_A to provide a consistent reference for comparison with the coupled simulations. Ocean surface currents are set to zero, and the Charnock parameter is prescribed as a constant value of 0.011 over all ocean points. No additional tuning or modifications are applied beyond this configuration.

2.3 Ocean model development and configuration (cSINGV_O)

The ocean component was newly configured and developed for application over the WMC. The ocean component, cSINGV_O, is based on version 4.0.4 of the NEMO (NEMO development team, 2021), configured at 1.5 km horizontal resolution. NEMO is a primitive-equation, hydrostatic model extensively used in climate and operational forecast applications (Madec et al., 2017). The model employs an orthogonal curvilinear coordinate system with Arakawa C-grid staggering for its horizontal grid, and the bathymetry is derived from the General Bathymetric Chart of the Oceans (GEBCO) dataset (https://www.gebco.net/data-products/historical-data-sets#gebco_2020, last access: 26 February 2026).

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Featuring 51 vertical levels within a terrain-following coordinate system, the model incorporates the stretching function by Siddorn and Furner (2013). In our study, the ocean model configurations utilize baroclinic time steps set at 60 seconds. The Generic Length Scale (GLS) turbulence model (Umlauf and Burchard 2013) is employed to calculate turbulent viscosities and diffusivities. For the computation of the bottom drag coefficient, an implicit form of non-linear parameterization with a log-layer formulation is applied, setting the minimum and maximum drag coefficients at 0.0001 and 0.15, respectively. The Flather boundary condition (Flather 1976) is adopted for sea surface height (SSH) and barotropic velocities, while a flow relaxation scheme (FRS, Davies 1976) is implemented for tracers and baroclinic velocities at the lateral open ocean boundaries.
The configuration (cSINGV_O) is largely based on the regional NEMO setup of Thompson et al. (2021), with additional modifications introduced during the upgrade from version 3.6 to 4.0.4 (see Table S2). Sensitivity experiments were conducted to optimise configuration choices, including light penetration schemes and bulk forcing formulations, resulting in improved SST representation across both deep ocean and shallow shelf regions.

2.4 Wave model development and configuration (cSINGV_W)

The wave component, cSINGV_W, was newly configured and tuned for the WMC. It is based on version 7.12 of the third-generation spectral wave model WW3 (Tolman, 2014), developed by the U.S. National Centers for Environmental Prediction. To better represent the complex coastlines around Singapore, the model is configured with a two-tier spherical multiple-cell (SMC) grid (Li, 2012), using the same computational domain and bathymetry as the ocean component. The SMC approach enables multi-resolution meshes, allowing fine-scale representation of coastlines and small islands while maintaining coarser resolution in the open ocean. This feature provides more effective refinement of coastal areas compared to a regular WW3 grid (Li et al., 2019), which is particularly beneficial in the coastal environment of the WMC. The model grid has a resolution of approximately 1.5 km in coastal regions, expanding to 3 km in offshore areas.
The model employs the ST4 source term package (Ardhuin et al., 2010) to represent wave growth and dissipation processes. Nonlinear wave–wave interactions are parameterised using the discrete interaction approximation (NL1; Hasselmann et al., 1985), while shallow-water processes include depth-induced breaking (DB1; Battjes and Janssen, 1978) and bottom friction (BT1; Hasselmann et al., 1973). Wave propagation is computed using a second-order upstream non-oscillatory scheme (UNO; Li, 2008), and dispersion correction is applied through the PR2 option to mitigate the garden sprinkler effect (Booij and Holthuijsen, 1987). Wind input and stress calculations are handled internally within the source term formulation (FLX0), with additional options for wind and current interpolation (WNT1, WNX1, CRT1, CRX1). A summary of the model configuration and compilation switches is provided in Table S1.
Specific adjustments to key parameters, including the wave growth parameter *betamax* and shallow-water physics options, were performed for application in the WMC. The tuning strategy and sensitivity experiments are described in Appendix A.

2.5 Coupled modelling framework

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The coupled modelling system is implemented using the Regional Coupled Suite (RCS), which provides a flexible framework for integrating multiple model components using the cylc workflow engine (Oliver et al., 2019). Coupling between the atmosphere, ocean, and wave components is achieved through the OASIS3-MCT coupler (Valcke et al., 2015), enabling the exchange of fluxes and state variables between components.

The configuration used in this study is based on the RCS suite (suite ID: u-bf945), with a dedicated *cSINGV* branch developed for this application and available via the Met Office repository (https://code.metoffice.gov.uk/svn/roses-u/b/f/9/4/5/u-bf945_add_cSINGV_br). This branch provides the specific coupling setup and workflow required for the coupled system, ensuring reproducibility of the model configuration.

The atmosphere, ocean, and wave components operate on their native grids and exchange variables at an hourly coupling frequency. The framework supports two-way interactions between components, allowing for feedbacks such as the influence of SST on atmospheric fluxes, wave-dependent surface roughness effects, and the impact of ocean currents on wave evolution. This setup enables the representation of air–sea–wave interaction processes at convection-permitting scales, which is a key aspect of the cSINGV system. A schematic overview of the coupling architecture and exchanged variables is shown in Fig. 2.
The development of this fully coupled system represents the main technical contribution of this study and provides a framework for investigating multiscale interactions between the atmosphere, ocean, and waves in the WMC.

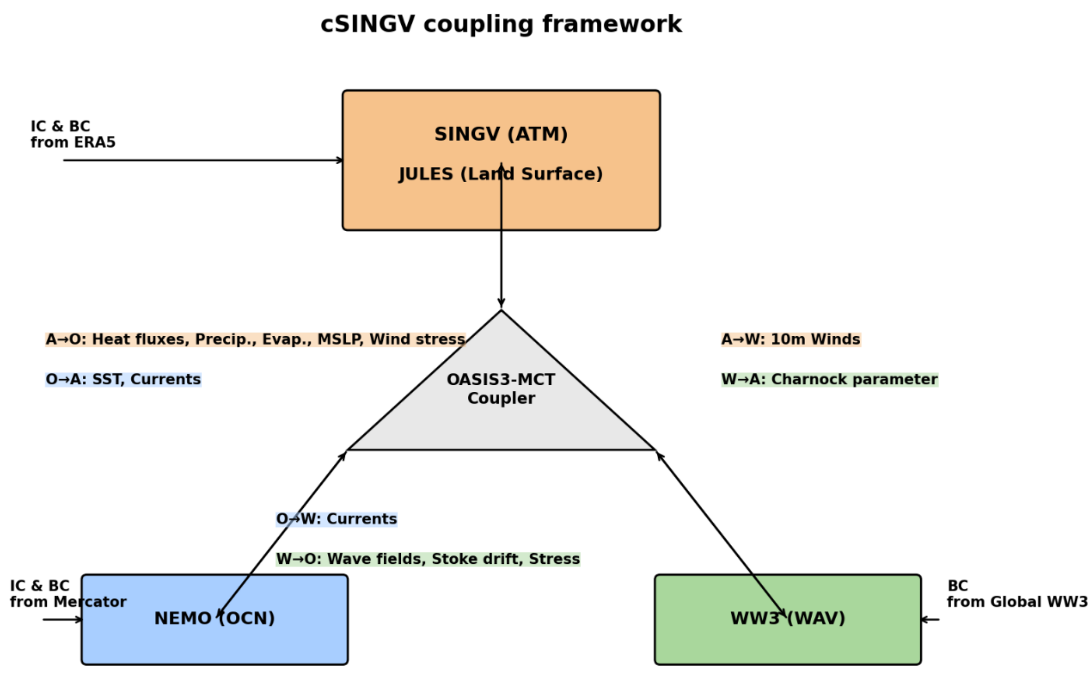

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Figure 2: Schematic representation of the cSINGV coupled atmosphere–ocean–wave modelling system. The atmospheric model (SINGV; Unified Model–based configuration) is coupled with the Joint UK Land Environment Simulator (JULES) for land surface processes, the Nucleus for European Modelling of the Ocean (NEMO) for ocean dynamics, and the WAVEWATCH III (WW3) for wave processes. Coupling between components is achieved through the OASIS3-MCT coupler, which exchanges fluxes and state variables between the atmosphere (A), ocean (O), and wave (W) components at hourly intervals. IC and BC denote initial conditions and lateral boundary conditions, respectively.

3 Experimental design, datasets, and evaluation methodology

3.1 Experimental design

Simulations are conducted for January–June 2019 using both standalone and coupled configurations:

- Atmospheric-only (cSINGV_A)
- Ocean-only (cSINGV_O)
- Wave-only (cSINGV_W)
- Fully coupled system (cSINGV)

Atmospheric lateral boundary conditions are provided by reanalysis data, while ocean initial and boundary conditions are obtained from ocean reanalysis products. Wave boundary conditions are derived from a high-resolution global WW3 simulation using an SMC grid.

3.2 Datasets

The atmospheric model lateral boundary conditions are provided by the 3-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, ERA5 (Hersbach et al., 2020). Ocean model initial and lateral boundary conditions are obtained from the daily Mercator Ocean reanalysis (Lellouche et al., 2021). Wave boundary conditions are derived from a high-resolution global WW3 simulation using a four-tier spherical multiple-cell (SMC61250) grid, with resolutions of 50, 25, 12, and 6 km from the open ocean to coastal regions (Li, 2019; Kumar et al., 2025), forced by ERA5 winds. Tidal forcing at the ocean lateral boundaries is prescribed using tidal elevations and currents from the Finite Element Solution dataset (FES2014b; Carrère et al., 2016; https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html). River runoff is represented using monthly climatological fields from Dai and Trenberth (2002). In addition, monthly chlorophyll concentrations from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; O'Reilly et al., 2000) are used in the ocean model to parameterise light absorption and its influence on the upper-ocean heat budget.

For model evaluation, multiple observational and reanalysis datasets are used. Precipitation is evaluated against the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM IMERG V06B; Huffman et al., 2019: doi.org/10.5067/GPM/IMERG/3B-HH/06), hereafter referred to as GPM, which provides reliable estimates over Southeast Asia (e.g. Da Silva et al., 2021). Three-hourly 10 m wind speed and 2 m air temperature observations are obtained from the World Meteorological Organization (WMO) MetDB database (Met Office, 2008). SST is evaluated using the Operational Sea

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Surface Temperature and Sea Ice Analysis (OSTIA: https://doi.org/10.48670/moi-00168) dataset and the GLORYS12V1 product from the Copernicus Marine Environment Monitoring Service (CMEMS; Lellouche et al., 2021: https://doi.org/10.48670/moi-00021). Significant wave height (Hs) is validated using multi-mission satellite altimeter observations (Piollé et al., 2022) obtained from CMEMS.

3.3 Evaluation methodology

Model performance is evaluated using a range of statistical metrics. The root mean square error (RMSE) is used to assess 10 m wind speed, 2 m air temperature, sea surface temperature (SST), and significant wave height (Hs), and is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}$$

where M_i and O_i denote the modelled and observed values, respectively, and N is the number of samples.

For wave evaluation, additional metrics are applied. The bias is defined as:

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)$$

The Pearson correlation coefficient (r) is given by:

$$r = \frac{\sum_{i=1}^{N}(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(M_i - \bar{M})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}}$$

The scatter index (SI), representing the normalised RMSE, is defined as:

$$\text{SI} = \frac{\text{RMSE}}{\bar{O}}$$

Distributional agreement between modelled and observed significant wave height is assessed using the Kolmogorov–Smirnov (KS) statistic (Massey, 1951), defined as:

$$\text{KS} = \max | F_m(x) - F_o(x) |$$

where $F_m(x)$ and $F_o(x)$ are the cumulative distribution functions of modelled and observed values, respectively.

Probability distribution functions (PDFs) were estimated using kernel density estimation (KDE; Parzen, 1962), implemented via KDEpy (Odland, 2018).

For precipitation, the Fraction Skill Score (FSS; Roberts and Lean, 2008) is used to evaluate the spatial representation of rainfall. It is computed for selected precipitation thresholds and neighbourhood sizes and is defined as:

$$\text{FSS} = 1 - \frac{\sum(P_f - P_o)^2}{\sum(P_f^2 + P_o^2)}$$

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where P_f and P_o represent the fractional coverage of forecast and observed precipitation exceeding a specified threshold within a given neighbourhood.

The evaluation of atmospheric variables was performed using the MetPlus framework, which provides a standardized environment for model verification and ensures reproducibility of the analysis (https://metplus.readthedocs.io/en/latest/).

4 Model evaluation and coupling impacts

This section presents the evaluation of the cSINGV system with a focus on the newly developed ocean and wave components, followed by an assessment of the impact of atmosphere–ocean–wave coupling. The atmospheric component used in this study corresponds to the SINGV configuration, which has been extensively evaluated in previous studies. Therefore, only its role as a reference configuration is considered here.

We first evaluate the standalone ocean (cSINGV_O) and wave (cSINGV_W) components to establish their ability to represent key marine processes in the WMC. We then assess the fully coupled system (cSINGV) relative to the uncoupled atmospheric configuration (cSINGV_A) to examine the influence of coupling.

4.1 Ocean model evaluation (cSINGV_O)

The ocean component is evaluated through comparisons of SST with OSTIA and CMEMS reanalysis datasets for the period January–June 2019. Given that SST is the key variable linking the ocean to the atmosphere in the coupled system, the evaluation focuses on its representation.

The WMC region is characterised by two distinct ocean regimes: the shallow Sunda Shelf in the South China Sea (SCS) and the deeper Indian Ocean basin west of Sumatra (Fig. 1). To assess model performance across these contrasting environments, the analysis is conducted separately for these regions (Fig. S1). Figure 3 shows the time series of domain-averaged RMSE of daily SST relative to OSTIA for (i) the full domain, (ii) the Indian Ocean, and (iii) the South China Sea over the six-month simulation period.

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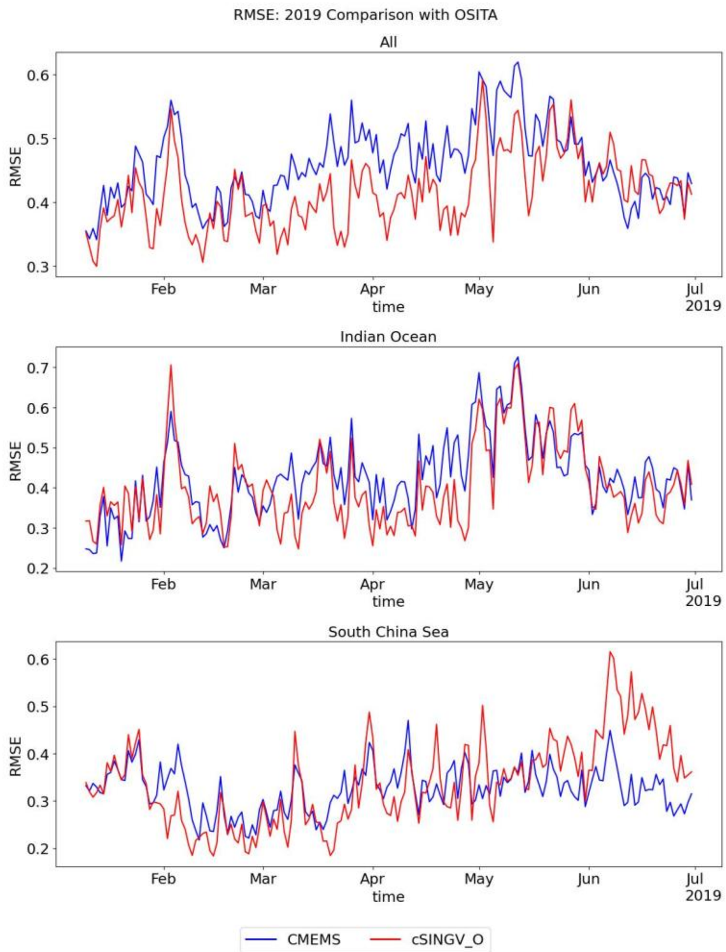

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Figure 3: Time series of daily domain-averaged RMSE of SST relative to OSTIA for the cSINGV_O simulation (red) and CMEMS reanalysis (blue) for January–June 2019, shown for (a) the full domain, (b) the Indian Ocean region, and (c) the South China Sea (Sunda Shelf).

The model reproduces SST variability well across both regions, with domain-averaged RMSE values generally below 0.5 °C throughout the simulation period. Some deviations are evident in the Indian Ocean during February and May, but the model captures the overall temporal variability and maintains errors comparable to CMEMS. In the SCS, SST variability is also well represented, with consistent agreement across the simulation period. Additional comparison with the regional NEMO configuration of Thompson et al. (2021) shows that the large-scale SST patterns are well reproduced (Fig. S2), and domain-averaged RMSE values are comparable (Fig. S3), providing further confidence in the ocean configuration.

4.2 Wave model evaluation (cSINGV_W)

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Following the model tuning described in Appendix A, the cSINGV_W configuration is evaluated against multi-mission satellite altimeter observations for January 2019 over the full domain and two subregions: the Indian Ocean and the South China Sea, representing distinct wave regimes. January 2019 was selected as it includes Tropical Storm Pabuk, providing a strong-wind case suitable for assessing wave growth.

The model reproduces the variability of Hs well across the domain (Fig. 4). Scatter comparisons show strong agreement with observations, with most values distributed close to the 1:1 line. For the full domain, the RMSE is approximately 0.2 m, with a correlation coefficient exceeding 0.926.

Performance is slightly reduced in the Indian Ocean (RMSE = 0.21 m), likely reflecting swell-dominated conditions, while improved agreement is observed in the South China Sea (RMSE = 0.185 m), consistent with wind-sea-dominated dynamics.

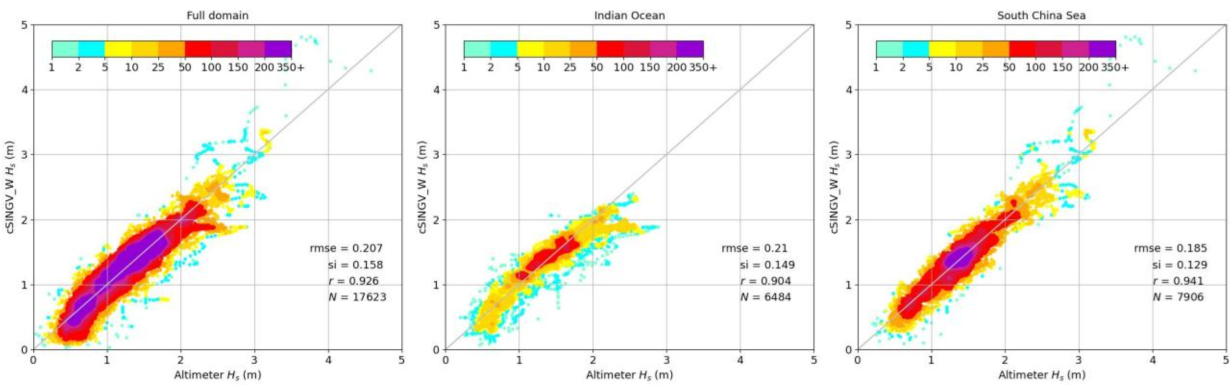

Figure 4: Validation of stand-alone cSINGV_W model against altimeter significant wave height (Hs) for January 2019 for the (a) whole domain, (b) Indian Ocean and (c) South China Sea region.

The statistical distribution of Hs was further evaluated using probability density functions (Fig. S4). The model captures the overall shape of the observed distribution, with good agreement in the bulk of the distribution (KS = 0.051). Regional differences are consistent with the scatter analysis, with reduced variability in the Indian Ocean (KS = 0.086) and close agreement in the South China Sea (KS = 0.025).

Overall, the standalone ocean and wave evaluations demonstrate that the individual components provide a credible representation of key marine processes, forming a robust foundation for the development of the fully coupled cSINGV system.

4.3 Evaluation of the coupled system (cSINGV)

Building on the evaluation of the standalone ocean and wave components, we now examine the performance of the fully coupled system (cSINGV) and the influence of atmosphere–ocean–wave coupling by comparing the coupled (cSINGV) and uncoupled (cSINGV_A) configurations.

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It should be noted that the uncoupled simulation is forced with observed SST (OSTIA), while the coupled simulation uses dynamically evolving SST from the ocean model. As such, this comparison does not represent a fully controlled experiment, but rather provides insight into the role of interactive coupling processes in modulating the simulated fields.

The uncoupled configuration (cSINGV_A) serves as a reference simulation, providing a baseline against which the impact of coupling is assessed. Therefore, differences between the two configurations should be interpreted in terms of coupling-induced process changes rather than a strict measure of model improvement.

We first assess precipitation, a key component of the WMC climate system, characterised by a pronounced diurnal cycle, offshore propagation of convection, and strong sensitivity to air–sea interactions. It also has significant societal impacts, including flooding and landslides across the region. Previous studies have reported mixed impacts of atmosphere–ocean coupling on precipitation, depending on model configuration and region (Aldrian et al., 2005; Wei et al., 2014; Xue et al., 2020). Here, we assess how the coupled (cSINGV) and uncoupled (cSINGV_A) configurations represent key rainfall characteristics.

To provide a qualitative overview, Hovmöller diagrams of daily accumulated precipitation were constructed using GPM satellite observations, together with cSINGV and cSINGV_A simulations, across longitudes 95.5°E–108°E for January–June 2019 (Fig. 5). Both model configurations reproduce the broad temporal and spatial variability of rainfall seen in GPM, although they tend to produce more moderate and intense rainfall compared to the observations. Differences between cSINGV and cSINGV_A are relatively small in this representation, and no clear systematic impact of coupling is evident at this scale. However, the similarity between the two model configurations indicates that the inclusion of coupling does not introduce spurious or unrealistic rainfall features.

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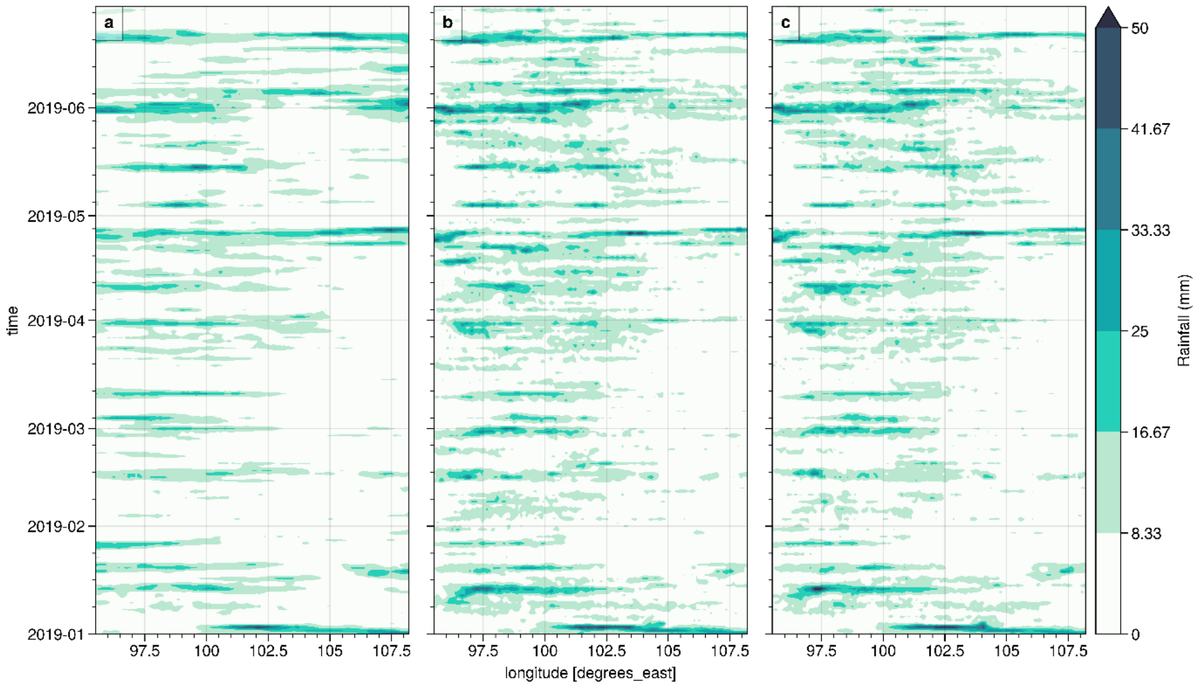

Figure 5: Hovmöller diagrams of daily rainfall (mm/day) averaged over latitude from January to June 2019 for (a) GPM observations, (b) the coupled model simulation (cSINGV), and (c) the uncoupled simulation (cSINGV_A).

To quantify spatial performance, we evaluate the FSS, which measures the agreement between simulated and observed rainfall patterns, with GPM serving as the reference dataset. FSS is particularly well-suited for evaluating precipitation, as it is less sensitive to exact grid-point matches compared to traditional metrics. Figure 6 presents FSS as a function of neighbourhood width for March and June 2019, selected as representative months. Two precipitation thresholds are considered: ≥0.1 mm and ≥10 mm. For March, across a range of neighbourhood sizes and precipitation thresholds, the coupled configuration generally exhibits higher FSS values than the uncoupled configuration, indicating improved spatial organisation of precipitation. At higher thresholds, both configurations exhibit lower skill, although cSINGV maintains a modest advantage. Similar behaviour is observed in June and across the remaining months, although differences are generally smaller for other months (January, February, April, and May; Fig. S5).

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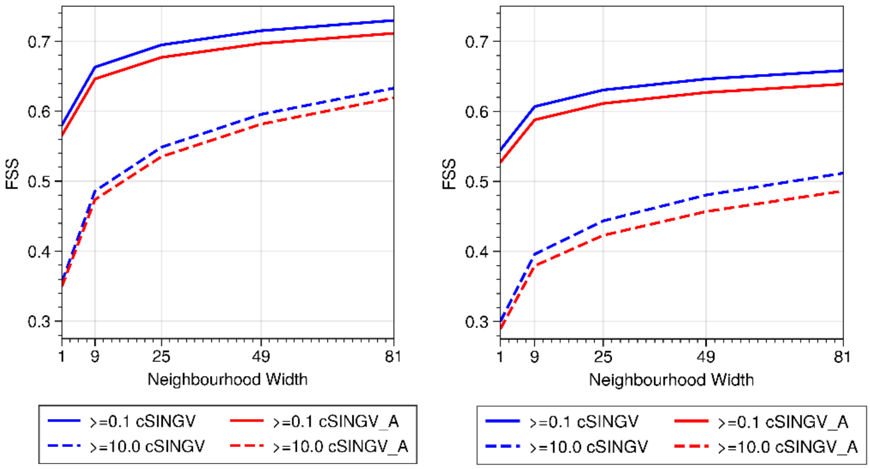

Figure 6: FSS as a function of neighbourhood width for March (left) and June (right) 2019, evaluated at two precipitation thresholds: ≥0.1 mm (solid lines) and ≥10.0 mm (dashed lines). Blue lines represent the coupled model (cSINGV) simulations, while red lines represent the uncoupled model (cSINGV_A) simulations. The neighbourhood width is expressed in terms of grid cells; for example, a width of 81 corresponds to a 9 × 9 grid box, equivalent to approximately 13.5 km × 13.5 km at the model resolution of 1.5 km.

We next examine the diurnal cycle of precipitation, a defining feature of rainfall over the WMC linked closely to land–sea breezes, convection, and ocean–atmosphere interactions. Evaluating the model's ability to reproduce these cycles therefore provides an important test of its representation of regional processes. Figure 7 shows the mean diurnal cycle averaged over January–June 2019 for land and sea regions. Over land, both cSINGV and cSINGV_A reproduce the general shape of the diurnal cycle but exhibit a phase lead of approximately 2–3 hours relative to GPM observations, along with an overestimation of peak intensity. Differences between the two configurations are small, indicating limited impact of coupling over land. In contrast, over the ocean, the cSINGV configuration more closely reproduces the observed timing and amplitude of nocturnal rainfall, while the cSINGV_A simulation underestimates rainfall and deviates more from observations. This indicates that coupling improves the representation of oceanic convection, which is closely linked to SST variability and surface flux feedbacks. Although both configurations underestimate precipitation overall, cSINGV shows improved agreement with the observed cycle across most hours.

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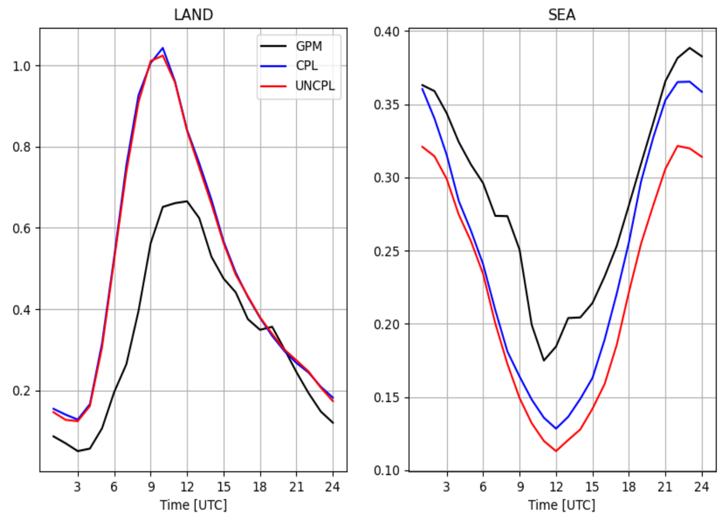

Figure 7: Diurnal cycle of precipitation over land (a) and sea (b) for the six months (Jan-Jun, 2019) simulation period.

Another key feature of the WMC precipitation system is the offshore propagation of convection. Convection typically initiates over land during the afternoon, peaks in the evening, and subsequently propagates offshore during the night and early morning hours (Peatman et al., 2025). This behaviour strongly influences coastal rainfall and provides a useful benchmark for model evaluation. Figure 8 shows the diurnal evolution of precipitation along a coastal transect across western Sumatra (location shown in Fig. S6) for June 2019. The x-axis represents distance relative to the coastline (negative values indicating the offshore direction), while the y-axis denotes local time (LT).

In GPM observations, rainfall develops over land in the afternoon and propagates offshore during the evening or night with maxima extending progressively away from the coastline. The cSINGV configuration captures the observed propagation of rainfall from Sumatra toward the adjacent ocean more coherently than the cSINGV_A simulation. While some biases in intensity remain, the cSINGV better represents both the timing and spatial extent of offshore propagation, whereas the cSINGV_A configuration exhibits weaker and less organised structures. These differences suggest that coupling improves the representation of coastal rainfall variability.

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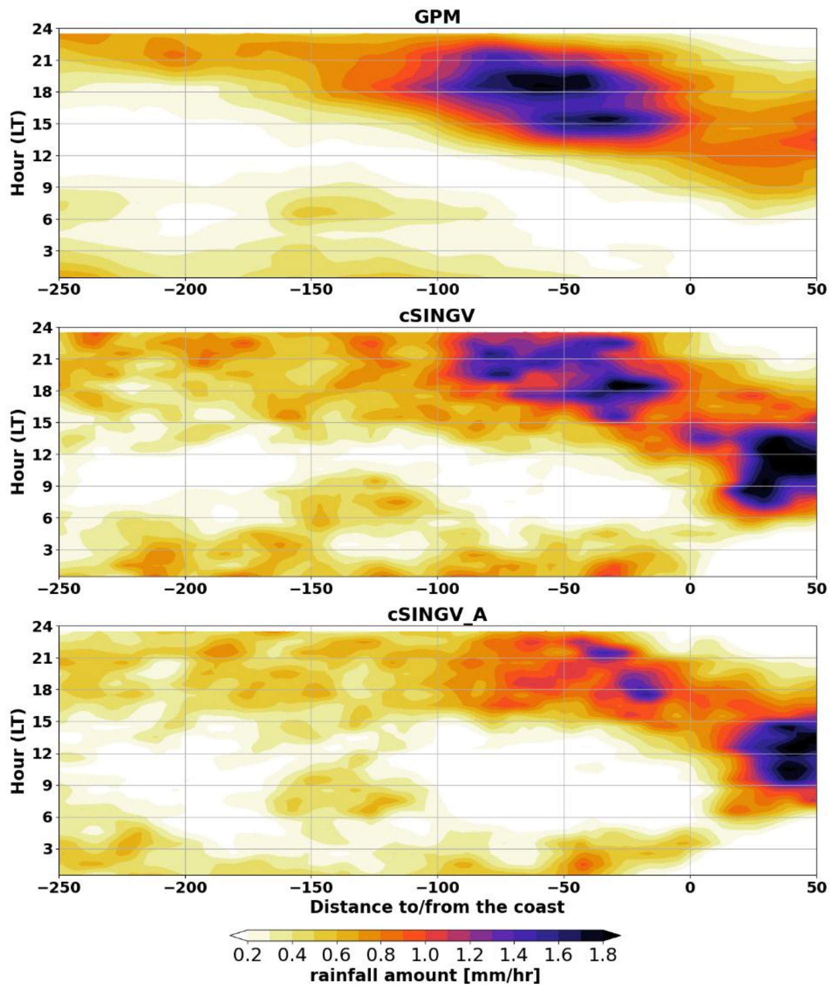

Figure 8: Diurnal rainfall Hovmöller diagram across the Sumatra transect for June 2019 derived from GPM observations (top), coupled simulation (cSINGV; middle), and uncoupled simulation (cSINGV_A; bottom). The y-axis shows local time (LT), and the x-axis represents distance relative to the western Sumatra coastline, with negative values indicating offshore (Indian Ocean) and positive values indicating inland regions. Shading denotes rainfall intensity (mm hr^{-1}).

Overall, the coupled configuration shows improved performance in representing key characteristics of precipitation over the WMC, including spatial organisation, the diurnal cycle over the sea, and offshore propagation, while differences over land remain limited.

We next assess near-surface atmospheric variables using observations from WMO MetDB stations (Fig. S7). For 10 m wind speed (Fig. 9), both configurations show similar performance, with comparable agreement against observations and only minor differences between the coupled and uncoupled simulations. Similarly, 2 m air temperature (Fig. 10) is well represented in

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both configurations, with small biases and limited sensitivity to coupling. These results suggest that near-surface atmospheric variables are less strongly influenced by coupling at the timescales considered in this study.

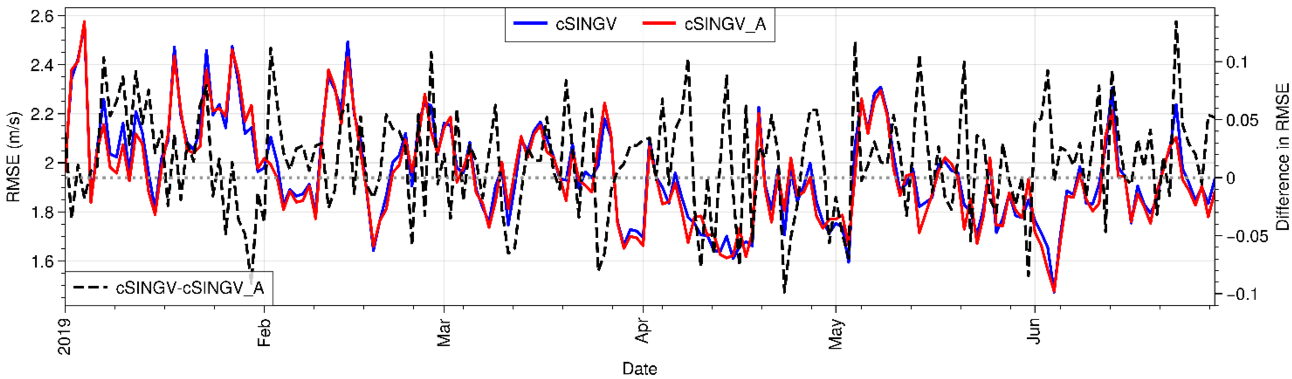

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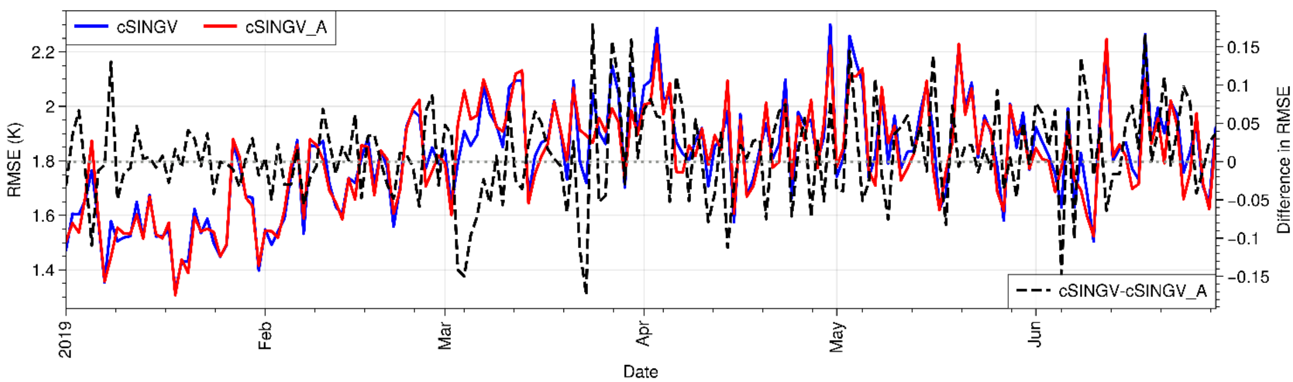
Figure 9: Daily mean wind speed rmse (m/s) for January-June 2019 against in-situ observations, for the coupled model (blue), uncoupled model (red), and the difference in rmse between the coupled and uncoupled model (black).



395 **Figure 10: Daily mean 2 m air temperature rmse (K) for January-June 2019 against in-situ observations, for the coupled model (blue), uncoupled model (red), and the difference in rmse between the coupled and uncoupled model (black).**

4.4 Impact of atmosphere–ocean–wave coupling (cSINGV vs cSINGV_A)

To further assess the impact of coupling at the event scale, we examine a set of Sumatra squall events. Sumatra squall lines are among the most frequent and impactful convective systems over the WMC, often producing intense rainfall, strong winds, and localized flooding (Lo and Orton, 2016). These systems typically initiate along the western coast of Sumatra and propagate eastward across the Straits of Malacca toward Peninsular Malaysia and Singapore. Their evolution is influenced by both land-based processes, such as orographic lifting and diurnal heating, and air–sea interactions, making them a useful benchmark for assessing the role of coupling in regional simulations.

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In this section, we analyse a set of representative Sumatra squall events, focusing on the April 2019 case and supported by additional events identified from the MSS squall database based on a threshold of maximum 1 h accumulated precipitation exceeding 50 mm. The analysis is based on rotated Hovmöller diagrams constructed along a transect aligned with the typical propagation pathway from Sumatra to Singapore (Fig. 1), allowing a consistent assessment of the spatiotemporal evolution of convection.

4.4.1 Sumatra squall event: 25–27 April 2019

In late April 2019, two successive squall events developed under similar large-scale conditions (Fig. 11). The first system formed on 26 April along the western coast of Sumatra and propagated eastward across the Straits of Malacca, bringing heavy rainfall to Singapore. MSS reported 118.7 mm at Changi Airport, the highest daily total for April 2019 (maximum 1 h accumulation of 83.4 mm). A second squall formed on 27 April and affected parts of southern Sumatra and adjacent regions, where rainfall exceeding 200 mm triggered flooding and landslides (Paski et al., 2021).

We focus on the event impacting Singapore in the early hours of 27 April. GPM observations show a coherent convective system forming over Sumatra, propagating eastward, and reaching Singapore at approximately 00 UTC. The coupled simulation (cSINGV) captures this eastward propagation and maintains a relatively organised convective structure as the system traverses the Straits of Malacca. In contrast, the uncoupled configuration (cSINGV_A) produces weaker and more fragmented convection, with reduced organisation during its propagation and a diminished signal over Singapore (Fig. 11). These differences indicate that coupling contributes to sustaining organised convection during its eastward propagation.

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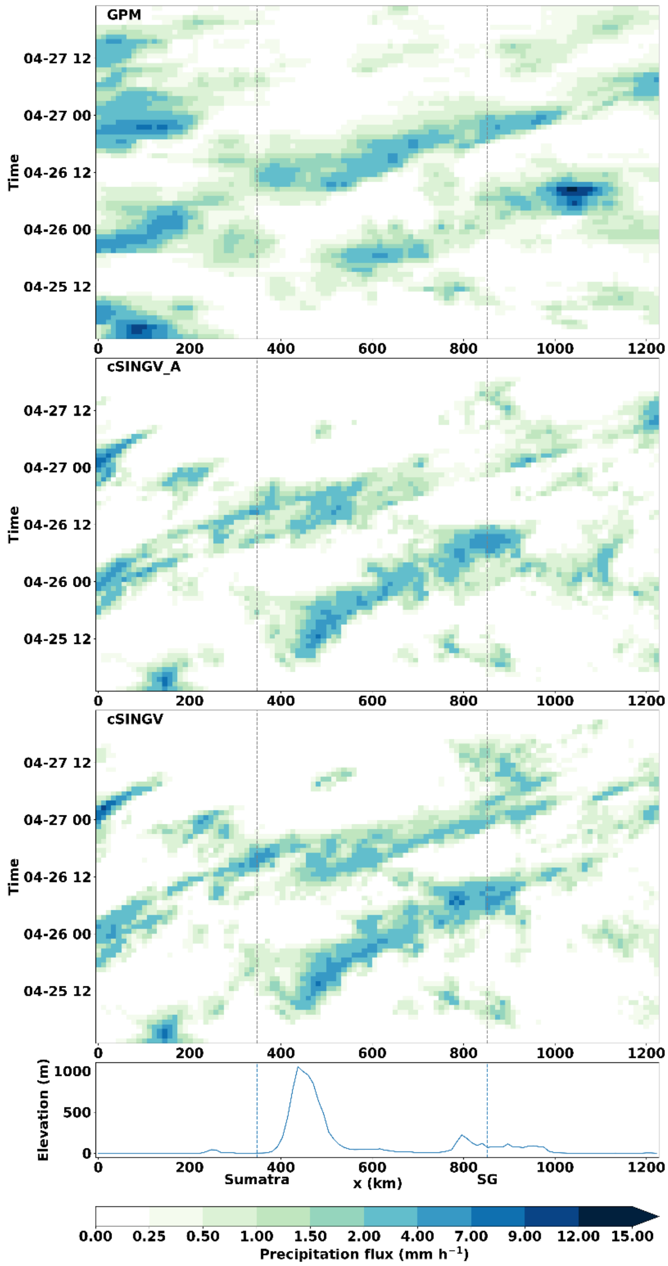

Figure 11: Rotated Hovmöller diagrams of precipitation for the Sumatra squall event (25–27 April 2019) along a transect from Sumatra to Singapore. Top: GPM observations, middle: uncoupled model (cSINGV_A), bottom: coupled model (cSINGV).

425 To place the April 2019 event in a broader context, additional squall cases identified from the MSS database were examined (figures in the Supplement: Fig. S8-10).

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The 2–4 April 2019 event (maximum 1 h accumulation of 54 mm) represents a predominantly land-driven case (Fig. S8). Convection initiates over or near the Sumatra mountain region and propagates eastward, with GPM showing relatively coherent structure during the early stages. Both coupled and uncoupled simulations reproduce this evolution with only minor differences, indicating that convection is primarily controlled by land-based processes.

A similar behaviour is observed in the 3–4 September 2019 event (maximum 1 h accumulation of 84 mm), where convection remains broad and fragmented during propagation (Fig. S9). Both model configurations show comparable skill, with only slight improvements in organisation in the coupled simulation. Notably, while significant rainfall over Singapore is recorded in the MSS database, the GPM observations do not clearly capture this signal, whereas both simulations indicate convection reaching the region.

In contrast, the 2–4 November 2020 event (maximum 1 h accumulation of 75.8 mm) exhibits a more organised and continuous convective structure during its eastward propagation, closely resembling the April 2019 case. While both simulations capture the eastward movement, the coupled configuration maintains a more coherent and intense convective band as the system approaches Singapore, whereas the uncoupled simulation becomes more fragmented (Fig. S10). This behaviour is consistent with enhanced air–sea interactions in the coupled system, which support the persistence and intensity of convection over the ocean.

Taken together, these cases demonstrate that the impact of coupling depends on the dominant convective regime. When convection is initiated and primarily governed by land-based processes, both coupled and uncoupled configurations perform similarly. In contrast, for more organised systems that originate offshore (west coast of Sumatra), coupling plays a more important role by enhancing surface fluxes and supporting the maintenance of convective structure. This regime-dependent behaviour provides a consistent physical interpretation of the coupling effects identified in this study and links directly to the surface flux analysis presented in the next section.

4.5 Impact of Coupling on Air–Sea Fluxes

To further investigate the processes underlying the differences between the cSINGV and cSINGV_A simulations, we examine the influence of coupling on surface fluxes, with a focus on latent heat flux (LHF). As discussed in Section 4.4, the largest differences between the two configurations occur during the propagation of organised convection, suggesting an important role for air–sea interactions.

Figure 12 shows the mean difference in LHF between the coupled and uncoupled simulations for January–June 2019. The coupled configuration exhibits enhanced upward fluxes across much of the domain, with localised anomalies exceeding 15 W m^{-2} along the Sumatra–Java coastal regions. These enhancements indicate increased transfer of moisture and energy from the ocean to the atmosphere, supporting convective development and maintenance.

To better understand the underlying mechanisms, the LHF differences are decomposed into two components: (i) a wind-speed contribution (ΔU), and (ii) a moisture-gradient contribution ($\Delta(q_s - q_a)$), where q_s is the saturation specific humidity at the sea

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surface and q_a is the near-surface atmospheric humidity. The wind-related contribution is relatively modest (approximately ±5 W m⁻²), whereas the moisture-gradient term exhibits larger amplitudes (up to ±12 W m⁻²) and spatial patterns closely aligned with SST differences (Fig. S11). This suggests that thermodynamic feedbacks associated with SST variability are the primary driver of enhanced LHF in the coupled simulation.

From a process perspective, the increased LHF in cSINGV supplies additional moisture and energy to the lower atmosphere, supporting the organisation and persistence of convection during its propagation. This mechanism is consistent with the case studies presented in Section 4.4. In particular, for the 25–27 April 2019 and 2–4 November 2020 events, the coupled configuration maintains a more coherent and intense convective structure over the ocean, whereas the uncoupled simulation exhibits more rapid weakening. The enhanced moisture supply associated with stronger air–sea humidity gradients provides a physically consistent explanation for this behaviour.

In contrast, for land-driven cases such as 2–4 April 2019 and 3–4 September 2019, where convection is primarily initiated over the Sumatra landmass, differences in LHF between the two configurations play a smaller role in shaping the system evolution. This is consistent with the relatively similar behaviour of cSINGV and cSINGV_A in these cases, indicating that the influence of coupling on convection is secondary when land-based forcing dominates.

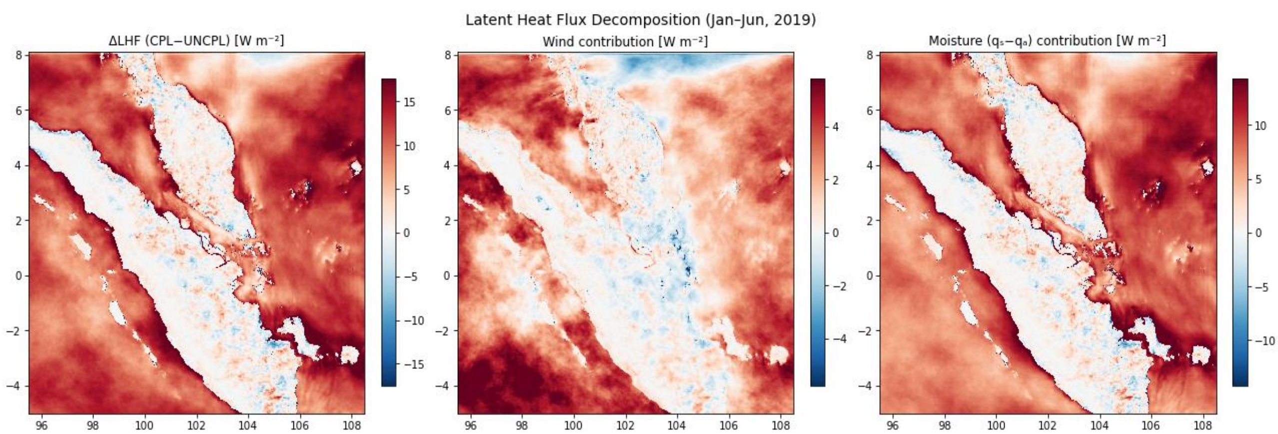

Figure 12: Mean latent heat flux difference (ΔLHF; CPL–UNCPL) over January–June 2019 (left), with decomposition into contributions from surface wind speed (middle) and near-surface humidity gradient (right). Positive values indicate enhanced upward flux in the coupled simulation.

Overall, the coupled configuration provides a more physically consistent representation of key processes in the WMC, including oceanic precipitation, offshore propagation, and air–sea flux interactions. While improvements in near-surface atmospheric variables remain limited and some biases persist for precipitation, particularly over land, the results indicate that atmosphere–ocean–wave coupling contributes to improved simulation of precipitation characteristics and associated processes in this region.

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5 Summary and conclusions

The WMC is characterised by complex interactions between atmospheric convection, ocean variability, and surface wave processes across multiple temporal and spatial scales. Accurately representing these coupled processes remains a major challenge for numerical models, particularly at convection-permitting resolutions.

In this study, a high-resolution (1.5 km) regional coupled atmosphere–ocean–wave modelling system, cSINGV, has been developed by integrating the SINGV atmospheric model with newly configured ocean (cSINGV_O) and wave (cSINGV_W) components within the Regional Coupled Suite framework. The system enables two-way interactions between the atmosphere, ocean, and waves, providing a unified platform to investigate air–sea–wave coupling processes in the WMC.

The standalone evaluation of the ocean and wave components demonstrates that both models provide a credible representation of key marine processes. The ocean model shows good agreement with SST observations and reanalysis datasets, while the wave model reproduces the observed variability and distribution of significant wave height. These results provide confidence in the individual components and establish a robust foundation for the development of the fully coupled system.

The coupled system (cSINGV) is evaluated against an uncoupled atmospheric configuration (cSINGV_A). It should be noted that the uncoupled configuration is forced with observed SST from OSTIA, whereas the coupled system uses dynamically evolving SST from the ocean model. The use of observed SST in the uncoupled simulation provides a realistic surface boundary condition, allowing it to serve as a reference configuration. This facilitates a clearer assessment of the performance of the coupled model relative to the uncoupled baseline.

The results indicate that coupling influences several key characteristics of precipitation over the WMC. In particular, differences are observed in the spatial organisation of rainfall, the diurnal cycle over the ocean, and the offshore propagation of convection. These effects are most pronounced in oceanic regions, while near-surface atmospheric variables such as wind speed and air temperature show comparatively limited sensitivity to coupling.

Process-based analysis suggests that these differences are primarily associated with thermodynamic air–sea feedbacks. Analysis of latent heat flux reveals that the coupled system produces enhanced upward fluxes, primarily driven by increased air–sea humidity gradients associated with SST variability. This enhanced moisture supply supports the organisation and persistence of convection over the ocean. Case studies of Sumatra squall events further demonstrate that the influence of coupling is regime dependent. For land-driven convection, both coupled and uncoupled configurations show similar behaviour, whereas for convection originating over the ocean, the coupled system produces more organised convective structures and sustains their propagation more effectively than the uncoupled configuration.

Overall, this study demonstrates that high-resolution atmosphere–ocean–wave coupling provides a physically consistent framework for representing air–sea interactions in the WMC and offers a valuable tool for investigating coupled processes in this region.

6 Future developments

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The river runoff fluxes applied at ocean model coastal grid cells currently use a climatological dataset, rather than being dynamically couped river discharge from the SINGV–JULES land surface system. The inclusion of interactive freshwater fluxes between the land and ocean components represents an important priority for future development. Ongoing work is focused on improving the representation of river discharge within the coupled atmosphere–land system, with the aim of enabling fully consistent land–ocean coupling in future versions of cSINGV.

Further development will focus on advancing cSINGV towards an operational environment prediction system through the implementation of coupled data assimilation. This includes the integration of atmospheric, oceanic, and wave observations to provide dynamically consistent initial conditions across all components of the coupled system.

In addition, future studies will extend the evaluation of cSINGV across a wider range of meteorological regimes, including monsoon transitions, cold surges, and tropical cyclones. These developments will support the progression of cSINGV towards a more comprehensive and operational coupled prediction system for MSS.

7 Appendix A

The tuning and configuration of the wave model are based on a set of sensitivity experiments designed to assess the impact of key parameters on model performance. The wave component is evaluated against multi-mission satellite altimeter observations for January 2019, using simulations forced by atmospheric winds from cSINGV_A.

Sensitivity experiments were conducted to assess the influence of key parameters, focusing on the wave growth parameter (*betamax*) and shallow-water physics options (WW3DG, 2019). The parameter *betamax* controls the maximum wind input growth rate and strongly influences wave development, particularly in young seas. Typical values range from 1.2 to 1.8, depending on the parameterisation and regional conditions.

One-month simulations for January 2019 (forced with cSINGV_A winds) were used to evaluate model performance under different *betamax* values (Table S3). January 2019 was selected as it includes Tropical Storm Pabuk, providing a strong-wind case suitable for assessing wave growth. A value of 1.75 was found to provide the best agreement with altimeter observations based on correlation, bias, RMSE, and scatter index.

In addition to *betamax*, sensitivity experiments were performed to assess the impact of shallow-water physics options, including wave–bottom interactions, depth-induced breaking, and triad wave–wave interactions, which are particularly relevant in coastal and shelf regions (WW3DG, 2019). Simulations using different combinations of these parameterisations were evaluated using the tuned *betamax* value. The selected configuration (experiment 10; Table S4) was found to provide the best overall performance across the evaluated metrics.

The resulting tuned configuration is used in the wave model evaluation presented in Section 4.2.

Code availability

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The cSINGV modelling system is based on established community models, including the Met Office Unified Model (UM), the NEMO ocean model (v4.0.4), and WAVEWATCH III (WW3 v7.12), coupled using the OASIS3-MCT coupler within the Regional Coupled Suite (RCS) framework.

The coupled configuration used in this study is based on the RCS suite (suite ID: u-bf945), with a dedicated *cSINGV* branch developed for this application and accessible via the Met Office repository (https://code.metoffice.gov.uk/svn/roses-u/b/f/9/4/5/u-bf945_add_cSINGV_br). This branch provides the workflow and coupling configuration required to reproduce the coupled atmosphere–ocean–wave system presented in this study.

The configuration files, namelists, model grids, ancillary files, forcing datasets, and run scripts required to reproduce the cSINGV v1.0 simulations are archived in a Zenodo repository (DOI: 10.5281/zenodo.21449436). The repository is currently under restricted access because it contains materials associated with third-party software and datasets that are subject to licensing restrictions (Kumar, R. 2026). Access may be granted upon reasonable request to the corresponding author for the purpose of reproducing the results presented in this manuscript, subject to the applicable licence agreements.

The source code of the Unified Model (UM) used in this study is archived on the JASMIN data infrastructure. Instructions for obtaining access to the archived UM source code are provided in the accompanying UM_Source_code.docx file included in the Zenodo repository. Access to the Unified Model source code is subject to the Met Office licensing conditions.

The Joint UK Land Environment Simulator (JULES) is available free of charge under licence. Further information on obtaining access for research purposes is available at http://jules.jchmr.org (last access: 20 January 2025). The JULES vn7.5 trunk code is accessible to registered users via the Met Office JULES code repository (https://code.metoffice.gov.uk/trac/jules/wiki; last access: 20 January 2025).

The NEMO ocean model and WAVEWATCH III are open-source models and can be accessed through their respective repositories following registration (https://www.nemo-ocean.eu/; https://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.shtml).

OASIS3-MCT (version 4.0) is available as open-source software from https://oasis.cerfacs.fr/en/ (last access: 20 March 2026). Model evaluation of near-surface atmospheric variables was performed using the MetPlus framework (last access: 4 April 2026; https://metplus.readthedocs.io/en/latest/).

The configuration files, namelists, model grids, and post-processing scripts used in this study are available from the corresponding author upon reasonable request.

Data availability

The high-resolution six-month simulations of the atmosphere, ocean, wave, and coupled configurations generate large data volumes and are therefore not publicly archived. These data can be made available from the corresponding author upon reasonable request.

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Processed datasets used for the analysis and figure production in this study are publicly available via Zenodo at https://doi.org/10.5281/zenodo.18797904 (Kumar and Alvin, 2026).

The ERA5 reanalysis data used in this study are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://www.ecmwf.int/). Ocean reanalysis data are obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) (https://marine.copernicus.eu/).

Precipitation data from the GPM IMERG product are available from NASA (https://gpm.nasa.gov/), and satellite altimeter data are obtained from CMEMS (https://marine.copernicus.eu/). OSTIA sea surface temperature data are available from the UK Met Office (https://www.metoffice.gov.uk/).

Observational station data from the WMO MetDB database are subject to access restrictions and are not publicly available but can be obtained through appropriate data-sharing agreements.

Author contributions

R.K. and J.M.C. developed the coupled modelling system, with support from C.S. and B.T. Ocean model was developed by R.K. Wave model was developed by R.K. and J.L. C.S. and P.P. contributed to the evaluation methodology. R.K., and A.N performed the data analysis. A.N. and K.S contributed to the wave model evaluation. H.Y. and L.J provided system and software support. R.K. performed the simulations and led the manuscript writing, with contributions from K.F., C.S., B.T and H.Z. All authors contributed to the interpretation of results and to the review and editing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The author thanks Dr Dale Barker, Director of CCRS, for his support, encouragement, and constructive comments throughout this work. We are also grateful to Segolene Berthou (Met Office) for her support during the development of the coupled system and for valuable scientific and technical discussions on model coupling. We also thank Jeff Polton (National Oceanographic Centre, UK) for insightful suggestions on NEMO model tuning, and V. Prasanna (CCRS) for helpful discussions on model evaluation.

We acknowledge the Working Group on Regional Coupled Modelling (Met Office) for valuable technical discussions, and the MONSOON HPC facility for supporting the initial stages of model development and testing. The authors also acknowledge the use of computational resources provided by the HPC CCRS.

We thank ECMWF, CMEMS, and NASA for providing the datasets used in this study.

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