Response to Referee #1

Manuscript ID: egusphere-2026-2024

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

Dear Reviewer,

We sincerely thank you for the careful and technically insightful assessment of the manuscript. Our detailed responses are provided below.

General comment

Reviewer comment:
The manuscript describes the UK Met Office regional coupled modelling suite configured for the Singapore region and highlights the performance for the first half of 2019. Two-way coupling improved precipitation and the diurnal cycle over the oceans compared to an atmosphere-only simulation. The focus lies in understanding air–sea interactions and their impact on regional weather, particularly on momentum transfer and large-scale precipitation. The structure of the manuscript could see a few improvements, mainly for readability, clarity, and focus. One major concern is the role of both tuning and evaluation of ocean-only and wave-only components, specifically the wave part for Betamax with a value of 1.75 (Appendix A). It contradicts the primary objective, "the development of a fully coupled system enabling two-way interaction" (line 15–16). The parameter is significantly higher than the Met Office value of 1.39 and is equivalent to that from an ERA5-driven wave hindcast. The Miles–Janssen-type wind input is known to significantly increase wave feedback to the atmosphere through the Charnock coefficient in two-way coupled simulations and reduce surface wind speed. In addition, the manuscript could benefit from a clearer description of the coupled system and its components, to support the results of fully coupled and atmosphere-only simulations presented in Sect. 4. If the coupled system is valid, then surface variables and diagnostics will improve and agree well with observations. On the ocean side, similar concerns as for the waves. "Sensitivity experiments were conducted to optimise configuration choices, including light penetration schemes and bulk forcing formulations, resulting in improved SST representation […]" on lines 156–157 sideline any form of coupling feedback entirely. The total water-side stress is equivalent to the air-side stress only if the wave field is in equilibrium, i.e. the sum of wind input, dissipation and nonlinear interaction is zero. Most of the time, the wave field is not in equilibrium, which means that the air-side stress differs from the water-side stress. Atmosphere–wave–ocean coupler should take care of the flux exchange in the wave boundary layer, i.e. similar to Fig. 8 in Breivik et al. (2015).

Response

We agree that the original manuscript did not distinguish sufficiently clearly among three aspects of the study:

1. the development and configuration of the individual regional model components;
2. the implementation of the coupled atmosphere–ocean–wave system; and
3. the initial evaluation of the fully coupled configuration.

The primary objective of this manuscript is to document the development of cSINGV v1.0 as a kilometre-scale regional atmosphere–ocean–wave modelling system for the Western Maritime Continent and to provide an initial assessment of its performance. The manuscript is not intended to present a comprehensive optimisation or sensitivity analysis of all coupling parameters and feedback processes. We will revise the Introduction and the opening of the model-description section to define this scope more explicitly.

We also agree that the original description of the momentum-transfer pathway was insufficiently precise. In particular, the direct atmosphere-to-ocean stress and the WW3-derived ocean surface stress are not applied simultaneously in the fully coupled atmosphere–ocean–wave configuration.

In the fully coupled configuration, the momentum-transfer pathway is as follows. The atmospheric component supplies the 10 m zonal and meridional wind components to WW3. WW3 then provides NEMO with the zonal and meridional components of the stress transmitted to the ocean after accounting for the evolving wave field.

The direct atmospheric stress fields are passed from the atmosphere to NEMO only in the atmosphere–ocean configuration without an interactive wave component. Therefore, NEMO receives only one source of surface momentum forcing in each configuration and is not forced simultaneously by both direct atmospheric stress and WW3-derived ocean surface stress. This coupling strategy is consistent with the atmosphere–wave–ocean coupling framework presented by Breivik et al. (2015, their Fig. 8).

We agree that the existing coupling schematic (Fig. 2) does not illustrate these momentum-transfer pathways clearly. We will therefore revise the schematic to distinguish the pathways used in the atmosphere–ocean and atmosphere–ocean–wave configurations. We will also add a table listing the exchanged variables, and their directions of transfer in the fully coupled configuration.

Response concerning (betamax=1.75)

We thank the reviewer for this important observation. We agree that the ST4 wind-input parameter *betamax* influences the wave growth rate and, through the wave-dependent Charnock parameter, may modify the aerodynamic roughness and consequently near-surface wind speed in a coupled atmosphere–wave system.

The value *betamax*=1.75 was selected during the standalone development of the limited-area regional WW3 configuration, before the fully coupled experiments were conducted. The parameter was subsequently held fixed in all coupled simulations and was not adjusted to improve the performance of the coupled model. A value calibrated in a forced regional wave simulation is therefore not necessarily optimal for a two-way coupled configuration.

To address the reviewer's concern, we show below the January mean difference in 10 m wind speed between cSINGV and cSINGV_A. The differences are generally within ±0.5 ms^{-1} over most of the model domain and do not indicate a systematic domain-wide reduction in wind speed in the coupled configuration (Fig. R1). Similar behaviour is found in the other analysed months (not shown).

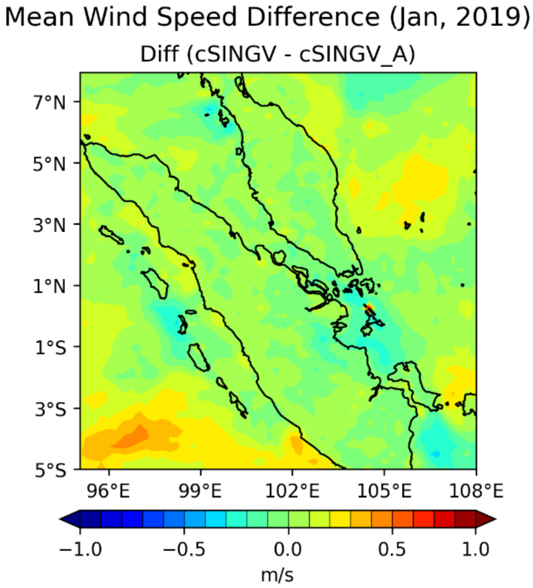


Figure R1. January-mean 10 m wind-speed difference between cSINGV and cSINGV_A (cSINGV minus cSINGV_A), in m s^{-1}.

Furthermore, the comparison against in-situ observations presented in Fig. 9 shows that the 10 m wind-speed RMSE is comparable in the coupled and atmosphere-only simulations during January–June 2019, with no systematic degradation indicative of an excessive reduction in surface winds associated with the selected *betamax* value.

Nevertheless, we agree that these diagnostics do not isolate the influence of *betamax*. The differences between cSINGV and cSINGV_A also reflect interactive SST, modified surface heat and moisture fluxes, and the subsequent atmospheric adjustment. Thus, although the present results do not show an obvious adverse effect of *betamax* = 1.7 on the simulated surface wind field, they do not demonstrate that this value is optimal for coupled simulations. A dedicated sensitivity experiment in which only *betamax* is varied would be required to isolate its influence. We will clarify this limitation in the revised manuscript.

Response concerning the ocean sensitivity experiments

Reviewer comment: *On the ocean side, similar concerns as for the waves. "Sensitivity experiments were conducted to optimise configuration choices, including light penetration schemes and bulk forcing formulations, resulting in improved SST representation […]" on lines 156–157 sideline any form of coupling feedback entirely.*

We thank the reviewer for highlighting this ambiguity. We agree that the original statement focused on the sensitivity experiments used to configure the ocean component and sideline any form of coupling feedbacks.

The standalone ocean sensitivity experiments were conducted before coupling, to establish a stable and physically credible regional NEMO baseline. The selected ocean configuration was then held fixed in the coupled experiments. We will revise the manuscript to clarify that these preliminary sensitivity experiments were intended to establish suitable behaviour of the standalone ocean component and were not used to tune the magnitude of the coupled response.

Specific comment 1

Reviewer comment:
Line 174: "wind field and current interpolation". Interpolation is performed within OASIS-MCT using remap weights. This setting will break the wave model because it does not know the future time step to establish linear regression.

Response

We thank the reviewer for identifying this imprecise wording. Here, "interpolation" referred to spatial remapping between component grids, not to temporal linear interpolation.

OASIS3-MCT uses precomputed remapping weights to transfer wind and current fields among the atmosphere, ocean and wave grids. No temporal linear interpolation requiring a future source field is applied.

Each component evolves with its own numerical timestep between coupling exchanges. We will replace "wind field and current interpolation" with:

"spatial remapping of the atmospheric wind and ocean-current fields between the component grids using precomputed OASIS3-MCT remapping weights."

Specific comment 2

Reviewer comment:
Line 185: "The atmosphere, ocean, and wave components […] exchange variables at an hourly coupling frequency". What is the reason for hourly intervals? Convective-scale processes could benefit from a higher coupling frequency.

Response

We agree that convective-scale atmospheric and upper-ocean processes may benefit from coupling intervals shorter than one hour.

The one-hour coupling interval in cSINGV v1.0 was selected as a practical compromise between computational cost, coupling overhead, and the need to represent evolving regional air–sea interactions. This choice was also informed by Zhao and Nasuno (2020), who examined the sensitivity of convection and associated oceanic responses to air–sea coupling frequency over the Maritime Continent. They found that experiments using hourly or more frequent coupling generally performed better, because they reproduced sea-surface temperature variability more realistically, whereas less frequent coupling tended to suppress convection.

However, we have not demonstrated that an hourly interval is optimal for cSINGV. We will therefore revise the manuscript to clarify that this interval represents a design choice for the initial system configuration rather than a physically optimal coupling frequency.

We will also acknowledge that sensitivity experiments using different coupling intervals would be valuable, particularly for rapidly evolving convective systems and high-frequency air–sea interaction processes (Makrygianni et al., 2026). Investigating the effects of high-frequency coupling on weather simulations over the Western Maritime Continent will therefore form part of future work.

Specific comment 3

Reviewer comment:
Line 191: “the coupling architecture and exchange variables” appears to double up on stresses received by the ocean. NEMO is subject to stress from both the atmosphere and the waves. It is unclear what wave fields are supposed to mean.

Response

We thank the reviewer for identifying this ambiguity. The ocean does not receive two simultaneous stress forcings in the fully coupled atmosphere–ocean–wave configuration.

In the atmosphere–ocean configuration, atmospheric wind stress is transferred directly from the atmosphere to NEMO. In the fully coupled atmosphere–ocean–wave configuration, the direct atmosphere-to-ocean stress fields are disabled and are replaced by the stress transmitted from WW3 to NEMO.

We will revise the schematic diagram and will also add a table describing the parameters exchanged between the component models to clarify this issue.

Specific comment 4

Reviewer comment:
Section 4.1. What is the purpose of an ocean-only evaluation? The title of the manuscript is about the development of a fully coupled modelling system.

Response

We appreciate this comment.

The ocean-only evaluation establishes whether the baseline regional NEMO component reproduces the observed SST adequately before its ocean fields are used interactively by the atmospheric component. Without a component-level assessment, biases originating in the ocean model could be incorrectly interpreted as coupling errors or as evidence of coupling benefits.

We will revise the introduction to Sect. 4 to explain that the ocean and wave assessments are included as baseline checks required for component models in the coupled system.

Specific comment 5

Reviewer comment:
Section 4.2. There appears to be a threshold in the Indian Ocean that the wave model cannot represent swell waves greater than 2 metres. It appears to be a feature coming from ERA5.

Response

We thank the reviewer for this observation. We examined the apparent reduction in the occurrence of significant wave heights (H_s) above approximately 2 m over the Indian Ocean in greater detail. This feature does not represent a numerical or physical threshold beyond which the regional wave model is unable to simulate higher waves.

The six-month time series of the maximum $H_s$over the Indian Ocean portion of the model domain (Fig. R2) shows numerous values exceeding 2 m, with maxima approaching 4 m during June. Values above 2 m also occur during several other months. This confirms that the regional model is capable of representing significant wave heights greater than 2 m. The feature near 2 m in the distribution is therefore more likely to reflect the frequency and spatial occurrence of higher-wave events during the evaluation period, and potentially the influence of the forcing and boundary conditions, rather than an intrinsic limitation of the wave model.

Nevertheless, the available output does not allow us to determine whether remotely generated swell from the southern Indian Ocean is represented accurately. Such an assessment would require partitioned wave parameters that distinguish the wind-sea and swell contributions to the total significant wave height. Unfortunately, only the combined significant wave height was archived for these simulations. We will clarify this limitation in the revised manuscript and identify the evaluation of partitioned swell and wind-sea components, including the influence of the ERA5-derived forcing and boundary conditions, as an area for future work.

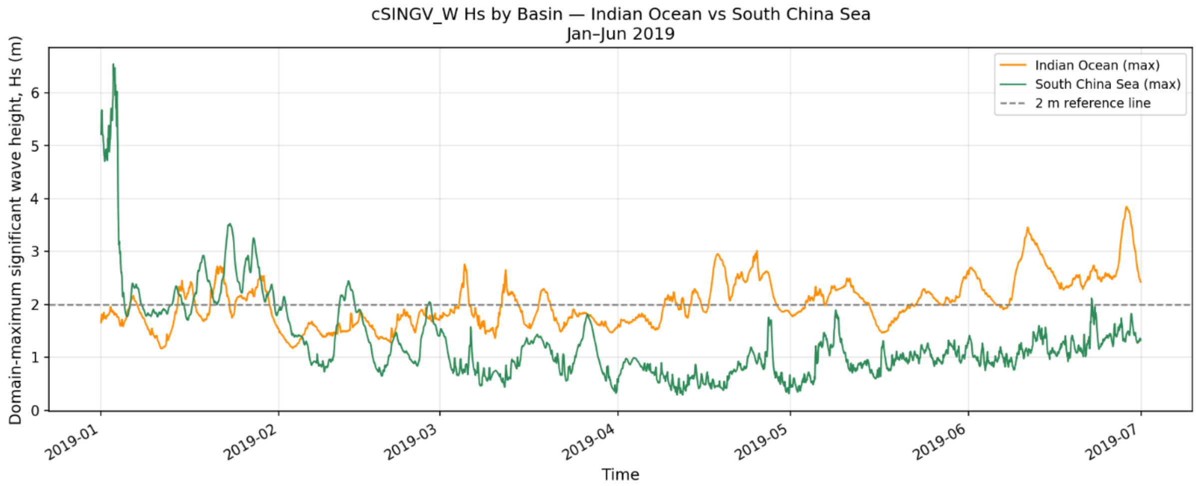


Figure R2. Time series of domain-maximum significant wave height (H_s) over the Indian Ocean and South China Sea regions from January to June 2019. The dashed line indicates the 2 m reference level.

Specific comment 6

Reviewer comment:

Lines 94–95: "Through evaluation against observational and reanalysis datasets, …". This sentence reads like a summary or highlight and does not belong in the objective statement.

Line 192: "The development of this fully coupled system represents the main technical contribution […]", in the wave model configuration, is the main objective of the paper and should appear at this point.

Response

We agree with the reviewer. We will remove the sentence "Through evaluation against observational and reanalysis datasets, …" from the objective statement. We will also move the statement "The development of this fully coupled system represents the main technical contribution […]" from the wave-model configuration section to the Introduction, where it will be incorporated into the statement of the main objective of the study.

Specific comment 7

Reviewer comment:

Lines 124–126 are riddled with acronyms. Why list all the applications for data assimilation, ensemble prediction, climate, and coupled configuration here? It is distracting for the reader and has no relevance to the manuscript's objective.

Response

We agree with the reviewer. We will simplify this paragraph by removing the non-essential acronyms and descriptions of applications that are not directly relevant to the present study.

Specific comment 8

Reviewer comment:
The paragraph on lines 315–321 appears better positioned in the Introduction and for the justification of the objective.

Response

We agree with the reviewer. The paragraph provides motivation and context rather than interpretation of the results. We will move the relevant material to the Introduction to justify the objective of this manuscript.

Specific comment 9

Reviewer comment:
Line 325–326: "Differences [in daily accumulated precipitation] between cSINGV and cSINGV_A are relatively small in this representation, and no clear systematic impact of coupling is evident at this scale." It is quite difficult to read the diagram and tell how different the simulations are from the observations. With a biased distribution, one could explain the drop in fractional skill score in Fig. 6.

Response

We agree that the present Hovmöller representation makes it difficult to quantify the differences between each simulation and the observations. We will therefore revise the discussion of Fig. 5 to clarify its intended purpose and will not use it as evidence of quantitative model skill. The figure is intended primarily to examine the large-scale temporal and longitudinal evolution of precipitation and to assess whether ocean and wave coupling produces a systematic shift in the precipitation distribution.

As suggested by the reviewer, we will add a bias diagnostic to the Supplement to quantify more clearly the differences between cSINGV, and cSINGV_A, and will revise the manuscript accordingly.

Specific comment 10

Reviewer comment:
The diurnal cycle of precipitation in Fig. 7 lacks units and has inconsistent scales. There appears to be significantly higher precipitation over land at noon, regardless of coupling, which is surprising, since about three-quarters of the domain is ocean and one-quarter land. Is this due to the land surface configuration RAL2-T?

Response

We thank the reviewer for this comment. We will revise Fig. 7 to include the precipitation units and use consistent scales across the panels.

Regarding the larger precipitation peak over land, a similar behaviour has been reported in previous SINGV simulations over the Western Maritime Continent. In particular, the long-term 2-km SINGV-RCM simulations of Prasanna et al. (2025) show a pronounced diurnal precipitation peak and an overestimation of precipitation intensity over land, together with an underestimation over the ocean (their Fig. 7). That study notes that this land-wet/ocean-dry bias is consistent with previous convection-permitting modelling studies over the Maritime Continent.

Therefore, the stronger land precipitation peak in both cSINGV and cSINGV_A appears to originate primarily from the atmospheric configuration. However, the present experiments do not allow us to attribute it specifically to RAL2-T or to its land-surface component; doing so would require dedicated atmospheric-physics or land-surface sensitivity experiments. We will clarify this point in the revised manuscript.

Specific comment 11

Reviewer comment:
Figure 12 shows the mean differences in latent heat flux and their decomposition into components: wind-speed contribution and moisture-gradient contribution. The coupled simulation indicates an increase in the upward flux of about 10–15 W/m^2. The decomposition into the two components highlights regional differences: wind speed confined to the Indian Ocean and moisture in the South China Sea. It would be interesting to the audience whether reduced fluxes arise mainly from weaker surface winds or weaker sea surface temperatures. For example, additional information showing differences in surface winds, Charnock coefficient, and sea surface temperature would help clarify. From a wave-field perspective, on the other hand, it looks like wind-sea contribution in the South China Sea versus swell contribution in the Indian Ocean. Clarification on this would greatly support the authors' claim for improved air–sea interaction in the region.

Response

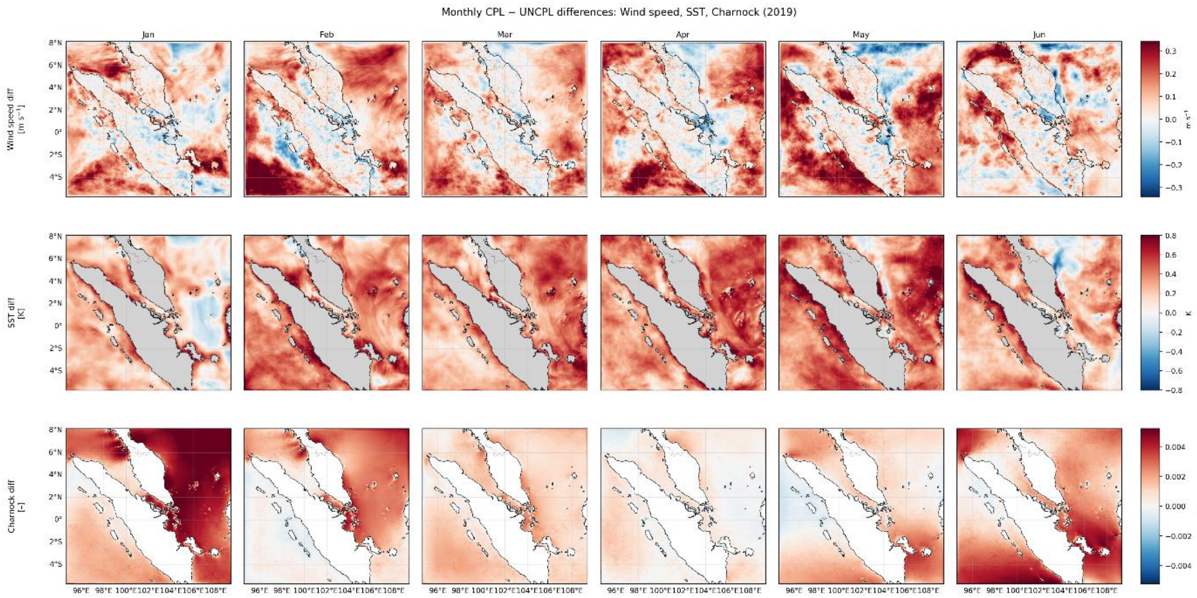
We thank the reviewer for this helpful suggestion. As suggested by the reviewer, to investigate the physical mechanisms underlying the latent heat flux differences in Fig. 12, we examined coupled-minus-atmosphere-only differences in 10 m wind speed, SST, and the Charnock coefficient (Fig. R4). The atmosphere-only configuration, cSINGV_A, uses a fixed Charnock coefficient of 0.011 over the open sea (Bush et al., 2023), whereas cSINGV uses the wave-dependent value supplied by WW3.

The additional diagnostics show that the coupled response is spatially heterogeneous. Differences in 10 m wind speed are generally modest (typically within approximately ±0.3 m s^{-1}) and do not show a uniform domain-wide reduction after atmosphere–ocean–wave coupling is introduced. Instead, regions of weaker and stronger winds coexist throughout January–June.

The SST differences are more spatially extensive, showing warming over much of the surrounding open ocean and localised cooling in several coastal and shelf regions. These SST changes modify near-surface saturation humidity and hence the air–sea humidity gradient, contributing to the latent heat flux response.

The wave-dependent Charnock coefficient also varies spatially and seasonally relative to the prescribed constant used in cSINGV_A, demonstrating that the coupled system modifies aerodynamic roughness in response to the evolving sea state. However, the wind-speed differences do not show a corresponding domain-wide reduction. This indicates that the atmospheric response reflects the combined effects of sea-state-dependent roughness, interactive SST, ocean-current feedback, and subsequent atmospheric adjustment.

We therefore agree that these additional diagnostics provide useful physical context for interpreting Fig. 12 and plan to include them in the revised manuscript.



We also agree that the spatial patterns may suggest contrasting wind-sea and swell regimes. However, significant wave height alone is insufficient to distinguish wind sea from swell. We will therefore avoid this attribution because the required diagnostics—such as partitioned wind wave and swell parameters—were not archived during the simulations.

We appreciate the reviewer's comments, which have helped us improve the manuscript.

On behalf of the authors,

Rajesh Kumar (Corresponding author)

References

Bush, M., Boutle, I., Edwards, J., Finnenkoetter, A., Franklin, C., Hanley, K., Jayakumar, A., Lewis, H., Lock, A., Mittermaier, M., Mohandas, S., North, R., Porson, A., Roux, B., Webster, S., and Weeks, M.: The second Met Office Unified Model–JULES Regional Atmosphere and Land configuration, RAL2, Geosci. Model Dev., 16, 1713–1734, https://doi.org/10.5194/gmd-16-1713-2023, 2023.

Makrygianni, N., Berthou, S., Flack, D. L. A., Lebeaupin Brossier, C., Beuvier, J., Castillo, J. M., Renzi, E., O'Neill, C., Peláez-Zapata, D., Dias, F., Lewis, H., and Bruciaferri, D.: Representation of meteotsunamis in km-scale regional simulations coupled at high frequency, Nat. Hazards Earth Syst. Sci., 26, 3185–3211, https://doi.org/10.5194/nhess-26-3185-2026, 2026.

Prasanna, V., Dipankar, A., Liu, J., Lim, G., Moise, A., Chua, X. R., Chen, C., Yu, J. J., Raavi, P. H., Luo, F., Hassim, M. E., Sahany, S., Sanchez, C., and Webster, S.: Evaluating SINGV-RCM for long-term high-resolution climate simulations over Southeast Asia, Int. J. Climatol., 45, e8932, https://doi.org/10.1002/joc.8932, 2025.

Zhao, N. and Nasuno, T.: How does the air–sea coupling frequency affect convection during the MJO passage?, J. Adv. Model. Earth Syst., 12, e2020MS002058, https://doi.org/10.1029/2020MS002058, 2020.