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Tropical Cyclone Modeling With the Inclusion of Wave-Coupled Processes: Sea Spray and Wave Turbulence

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Key Points:

- Full-year regional hindcast of Tropical Cyclones (TCs) at the North West Australia
- Inclusion of wave-coupled processes improves TCs modeling, by reducing forecast errors and enhancing rapid intensification simulations
- Sea spray increases TC development while nonbreaking wave turbulence has the opposite effect with the first process dominating

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Waves critically modulate the air-sea fluxes, and upper-ocean thermodynamics in a Tropical Cyclone (TC) system. This study improves the modeling of TC intensification by incorporating non-breaking wave-induced turbulence and sea spray from breaking waves into an atmosphere-ocean-wave coupled model. Notably, wind forecast error decreased by around 10% prior to TCs' peak intensity. The positive feedback of sea spray along with compensatory negative feedback from non-breaking waves, overall enhanced TCs' intensity. These breaking and non-breaking wave-coupled processes consistently cool sea surface temperature, resulting in improvement of the modeled SST. Observed improvements in full-year TC cases ranging from Categories I to IV in this study suggest that an accurate characterization of ocean wave-coupled processes is crucial for improving TCs' intensity forecasts and advancing our understanding of severe weather events in both, the atmosphere and ocean.

Plain Language Summary

Tropical Cyclones (TCs), such as hurricanes and typhoons, are destructive natural disasters that can cause extensive damage. Our study focused on understanding the role of ocean waves and related processes in TCs. Through numerical modeling, we found that ocean waves, specifically breaking and non-breaking waves, have a substantial influence on TCs' intensity. Breaking waves contribute positively through the production of sea spray droplets, while non-breaking wave-induced turbulence has a compensatory negative effect, resulting in an enhancement in TCs' intensity. Incorporating both wave mechanisms into the models improved the accuracy of TCs' intensity and their underlying sea surface temperature. By highlighting the importance of ocean wave-coupled physics, we aim to enhance our understanding of TCs and improve disaster preparedness to mitigate their impacts on coastal communities.

1. Introduction

Historically, the focus of TC modeling improvements was primarily centered on meteorological dynamics, overlooking the intricate relationship between TCs and the underlying ocean waves (Janssen & Bidlot, 2021; Magnusson et al., 2021). However, recent advances in observational technologies, coupled with advanced numerical models, have revealed the important role of ocean waves in shaping the behavior, evolution, and modeling of TCs (Rizza et al., 2021; Wu, 2021; Xu et al., 2022).

The complex interaction between ocean waves and the overlying atmosphere introduces a range of feedback mechanisms that may alter the dynamics of TCs (A. V. Babanin, 2023; J.-W. Bao et al., 2011; Xie et al., 2010). Perhaps the first and most obvious impact is the alteration of sea surface drag by ocean waves. By incorporating a wave-dependent air-sea momentum scheme, significant improvements have been made in current forecasts (Bidlot et al., 2020; Magnusson et al., 2021; Wu, 2021). Typically it is parameterized in terms of sea state properties that impact the effective roughness of the sea surface, including wave age or wave steepness (Holthuijsen et al., 2012; Powell et al., 2003; A. Soloviev et al., 2012; A. V. Soloviev et al., 2014; Taylor & Yelland, 2001).

Waves can further modulate fluxes between atmosphere and ocean through a series of secondary processes, such as the production of sea spray (Veron, 2015). Under extreme weather conditions, waves experience rapid growth where they become steep and unstable, up to the point of wave breaking (A. Babanin, 2011). Once ocean waves break, parts of their energy are transferred to the generation of water droplets that are sprouted into the air above the ocean surface through their interactions with the winds, commonly referred to as sea spray. Sea spray droplets can impact the momentum flux, represented by the air-sea drag coefficient parameter, that is suggested to plateau under extreme wind velocity (Powell et al., 2003). In addition to dynamical impacts, the collective of droplets generated can significantly impact the heat turbulent fluxes between the atmosphere and ocean by enlarging the air-sea interface. Sea spray therefore has the capacity to alter the overall thermodynamic structure of TCs (Andreas, 1992, 1998; Andreas & Emanuel, 2001; Perrie et al., 2005; Sroka & Emanuel, 2021). Particularly, the inclusion of sea spray in TC modeling has shown to improve TC intensities through the modulation of their size and structure, and accuracy of sea surface temperature (SST) within the TC system (Perrie et al., 2004; Liu et al., 2011; L. Zhang et al., 2017, 2021). This demonstrates the intricate impacts wave processes can have on the atmosphere and underlying ocean. However, despite the importance of sea spray in TC dynamics, sea spray remains under-represented in TC modeling (J. Bao et al., 2000; Kudryavtsev & Makin, 2011; Liu et al., 2012; Magnusson et al., 2021; Makin, 2005; Wu, 2021; Xu et al., 2022).

The influence of ocean waves extends down to the upper ocean through wave-induced turbulence by non-breaking waves (wave turbulence, hereafter) (A. Babanin, 2006; Qiao et al., 2004). Wave turbulence influences upper-ocean dynamics at depths of the typical wavelength and may thus impact the ocean mixed layer depth (MLD) in energetic sea states and, importantly, the redistribution of heat within the upper ocean and cooling the ocean surface. Notably, improvements in the SST modeling within a TC system were observed when wave turbulence was considered (Aijaz et al., 2017; W. Zhang et al., 2022). However, due to the scarcity of direct observations of wave turbulence in the field, the exact importance of wave turbulence on upper-ocean dynamics remains uncertain. Nevertheless, noticeable enhancements in regional and global modeling performance, such as for the MLD, were observed when wave turbulence scheme was implemented into the boundary-layer parameterization (Huang et al., 2012; Zhao et al., 2017).

Intuitively, the sea spray and wave turbulence have counteractive roles in the processes leading up to TC intensification where sea spray tends to enhance the heat flux from the ocean to atmosphere, and wave turbulence tends to cool the ocean surface through mixing. Considering the complex feedback mechanisms within a TC system, the exact consequences of these processes on a TC system are far from straightforward. For example, using a coupled model (FIO-AOW), Zhao et al. (2017) first demonstrated that both sea spray and surface wave-induced mixing (Qiao et al., 2004) play crucial roles in improving forecast intensity of weak and strong TCs (Zhao et al., 2022). This emphasizes not only that sea spray and wave turbulence need to be included in models, but also, as they are wave coupled processes, that they need to be parametrized in terms of wave field properties to fully study the coupled effects. In this study, we explore the impacts of the sea spray and wave turbulence on TC dynamics. Particularly, we focus on the development and intensification period of all TCs that occurred in northwest Australia in 2013. This broader analysis should provide further confidence in the universality of the model implementation of the wave-related processes, their parameterizations and the simulation results. To do so, we incorporate the physics of ocean waves into the atmosphere-ocean-wave coupled system, through utilizing the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System version 3.3 (COAWST v3.3) (Warner et al., 2010). Within this framework, we parameterize the fluxes of kinetic energy by wave turbulence and heat fluxes by sea spray explicitly, whereas we consider the momentum exchange by sea spray only implicitly through a plateauing drag coefficient to reduce uncertainty associated with its implementation. By adopting the updated model, we simulate full-year TCs under four distinct conditions, enabling a comprehensive evaluation of the impacts of ocean wave-coupled physics on TC behavior and intensification. This allows us to gain valuable insights into the complex interactions between the atmosphere, ocean, and waves, leading to a more coherent understanding of the role of ocean waves in TC dynamics.

2. Methods

2.1. The Numerical Model System

The fully coupled atmosphere-ocean-wave model applied in this study is the COAWST version 3.3. This model comprises three independents but coupled components: the Weather Research and Forecast Model (WRF-ARW; https://www.mmm.ucar.edu/models/wrf), the Regional Ocean Modeling System (ROMS; http://www.myroms.org), and the Simulating Waves Nearshore model version 41.01 (SWAN; http://swanmodel.sourceforge.net/). To facilitate the exchange of met-ocean information among different components, the Model Coupling Toolkit (MCT) is utilized (Figure S1 in Supporting Information S1).

WRF-ARW v3.9, the atmospheric model, used in this study, solves the equations of motion for compressible fluids, taking into account the effects of pressure variations and density changes within the atmosphere with a variety of atmospheric physics (Skamarock et al., 2019). In this work, various physical packages were adopted to accurately capture sub-grid processes. That is, the Purdue Lin Scheme (Chen & Sun, 2002) for the micro physics process, the shortwave/longwave radiation scheme of RRTM (Mlawer et al., 1997) and Dudhia Scheme (Dudhia, 1989) for the shortwave-radiation/longwave-radiation process, respectively, the Mellor-Yamada-Nakanishi-Niino 2.5 level turbulent kinetic energy scheme (Nakanishi & Niino, 2006) and its surface layer scheme for the Planetary Boundary and Surface Layer process, and the 5-layer Thermal Diffusion Scheme for the land surface physical process. The 6-km model resolution and 10s dynamic time steps are applied within simulations (Figure S2 in Supporting Information S1). The model incorporates 61 vertical sigma levels spanning from the surface up to 20 hPa, providing a suitably high vertical resolution for simulating atmospheric vertical dynamic processes.

In the context of ocean dynamics, ROMS is defined as the ocean hydrodynamic component in the COAWST. It possesses the free surface capability and utilizes a vertical coordinate system based on the depth of the ocean, following the contours of the underlying bathymetry. This application focuses on a single domain with a horizontal resolution of 5 km, which effectively covers the northwestern Australia. The ROMS model incorporates 31 sigma levels.

To account for wave dynamics, a third-generation wave model, the SWAN model is employed. This model is capable of solving the wave action balance equation, considering crucial physical processes such as wind generation, wave propagation, wave transformation, wave-current interaction, wave-structure interaction, and wave dissipation. The SWAN model operates in a non-stationary mode, utilizing a time step of 60 s. It employs a spectral grid encompassing 36 wave directions, by specifying a directional resolution of 10°and 25 frequencies by defining the minimum frequency as 0.04 Hz. To conserve computational resources and spatial mapping/interpolation, the domain of the SWAN model aligns with that of ROMS. Facilitating the exchange of information between the coupled modeling system is the MCT.

2.2. Physical Processes of Ocean Waves

The COAWST model system is used to study the influence of ocean waves, specifically wave turbulence and sea spray, on the air-sea interaction under severe weather conditions. To consider the wave turbulence, we incorporate additional wave turbulence induced by the wave orbital motion into the generic length scale (GLS) turbulence closure schemes model in ROMS system:

$$\frac{D}{Dt}(k) - \frac{\partial}{\partial z}\left[\frac{K_M}{\sigma_k}\frac{\partial}{\partial z}(k)\right] = P + P_w + B - \varepsilon \tag{1}$$

and

$$\frac{D}{Dt}(\Psi) - \frac{\partial}{\partial z}\left[\frac{K_M}{\sigma_\Psi}\frac{\partial}{\partial z}(\Psi)\right] = \frac{\Psi}{k}(c_1 P + c_1 P_w + c_3 B - c_2 \varepsilon F_{wall}) \tag{2}$$

where k is the turbulent kinetic energy, K_M is the kinematic eddy viscosity, σ_k and σ_Ψ are the turbulence Schmidt number for k and Ψ, respectively. P, B, and ε are the shear production, buoyancy production, and modeled dissipation, respectively. F_{wall} is defined by a wall function, c_1, c_2, and c_3 are empirical coefficients defined to be consistent with von Karman's constant. $P_w = 5\left(\frac{H}{2}k\right)^2 \cdot k\omega^3 \frac{H^3}{8} e^{3kz}$ is the turbulence production due to the orbital motion of non-breaking waves, where H is wave height, k is the wave number, ω is the wave radian frequency, and z is the local ocean depth.

Sea spray droplets contribute to the air-sea interaction mainly through increasing the air-sea heat exchange. This surface process can be considered and implemented into the air-sea surface layer model in WRF system through additional air-sea turbulent heat fluxes resulted from the sea spray, following Zhao et al. (2017) and Xu et al. (2023):

$$H_s = \rho c_p C_h U(\theta_l - \theta_b) + H_{(s,sp)} \tag{3}$$

$$H_L = \rho L_v C_e U(q_l - q_b) + H_{(L,sp)} \tag{4}$$

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where H_s and H_L are the air-sea interfacial sensible and latent heat fluxes. The ρ is the air density in the surface layer, c_p is the specific heat capacity of air at certain pressure, L_v is the latent heat of vapourization, C_h and C_e are the exchange coefficient for heat and moisture, respectively. U is the horizontal wind velocity, θ_l and θ_b are the potential temperature at the lowest model level and bottom surface, respectively, q_l and q_b are the potential temperature at the lowest model level and bottom surface, respectively. The sea spray-induced sensible heat fluxes $H_{(s,sp)}$ and latent heat fluxes $H_{(L,sp)}$ can be iteratively computed by

$$H_{(s,sp)} = \alpha \rho_w c_{pw} T' V \tag{5}$$

$$H_{(L,sp)} = \beta \rho_w L_v Q' V - \gamma \rho_w c_{pw} T' V \tag{6}$$

$$V = \frac{4}{3} \pi \rho_w \int_{r_1}^{r_2} r^3 \frac{dF}{dr} dr \tag{7}$$

where $\alpha = 3.3$, $\beta = 5.7$, and $\gamma = 2.8$ (Andreas, 2003; L. Zhang et al., 2017) are the exchange coefficients that represent the interaction of individual sea spray droplet with ambient environment, ρ_w is the water density, c_{pw} is the water specific heat capacity, T' is defined by the temperature difference between generated spray droplet and ambient air temperature, Q' depicts the contribution of individual spray droplet to air-sea latent heat exchange due to phase changes (Andreas & Emanuel, 2001; Perrie et al., 2005; Xu, Voermans, Liu, et al., 2021; Xu et al., 2022), V is the volumetric concentration of in-time spray droplets, r_1 and r_2 are the smallest and largest sea spray droplets, r is the initial radius of generated sea spray droplets, and $\frac{dF}{dr}$ is the sea spray generation function which denotes the number of generated sea spray droplets per second per square meter of ocean surface per micrometer increment in r. In this study, V is computed based on one novel non-dimensional wave-steepness-dependent sea spray model (Xu, Voermans, Ma, et al., 2021). Detailed impacts of sea spray on the momentum exchanges are outside the scope of this study, although part of this exchange may be implicitly included in the air-sea surface scheme of WRF through parameterizing the drag coefficient scheme with a plateau (Davis et al., 2008).

2.3. Experiment Designs

The TCs considered in present work were TC Narelle (Category IV), TC Rusty (Category IV), TC Victoria (Category III), TC Alessia (Category I), and TC Christine (Category IV) (Figure S3 in Supporting Information S1). To ensure the consistency across all TC simulations, the initial and boundary conditions in the WRF model were provided using outputs from the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) data with a horizontal resolution of 0.25° × 0.25° and a 6-hr interval initialized at the same time. The outputs of HYbrid Coordinate Ocean Model and WaveWatchIII are used to obtain boundary conditions for ROMS and SWAN, respectively (Please see the Open Research for data sources). It is important to note that all physical schemes employed in the COAWST model were kept consistent for all cases.

Four numerical experiments are conducted for all TCs (Table S2 in Supporting Information S1). The control experiments, denoted as CNTRL experiments, where WRF, ROMS and SWAN were active. The wave turbulence experiments, referred as WT experiments, which include additional wave turbulence induced by the wave orbital motion based on Equations 1 and 2. The sea spray experiments, defined as SP experiments, which introduce sea spray generated additional turbulent heat fluxes based on Equations 3 and 4, and the experiments with both wave turbulence and sea spray (WT + SP experiments). Further information on model validation can be found in Text S5 in Supporting Information S1.

3. Results

Figure 1 illustrates the lifespans of all simulated tropical cyclones (TCs). As the TC tracks align closely with the Best-Track data of the Australian Bureau of Meteorology (BoM), and the differences between the models are minimal (Figure S4 in Supporting Information S1), this study primarily focuses on comparing TC intensity. A comparison with the CNTRL experiments reveals that the SP experiments deepen the minimum sea level pressure (SLP), while the WT experiments lead to an increased minimum SLP. However, when both the breaking and non-breaking wave mechanisms are included in the WT + SP experiments, a noticeable decrease in the minimum SLP is observed. This suggests that the TCs are intensified when both wave mechanisms are incorporated. Since SLP is closely related to local winds within the TC system, consistent results are observed in the simulated

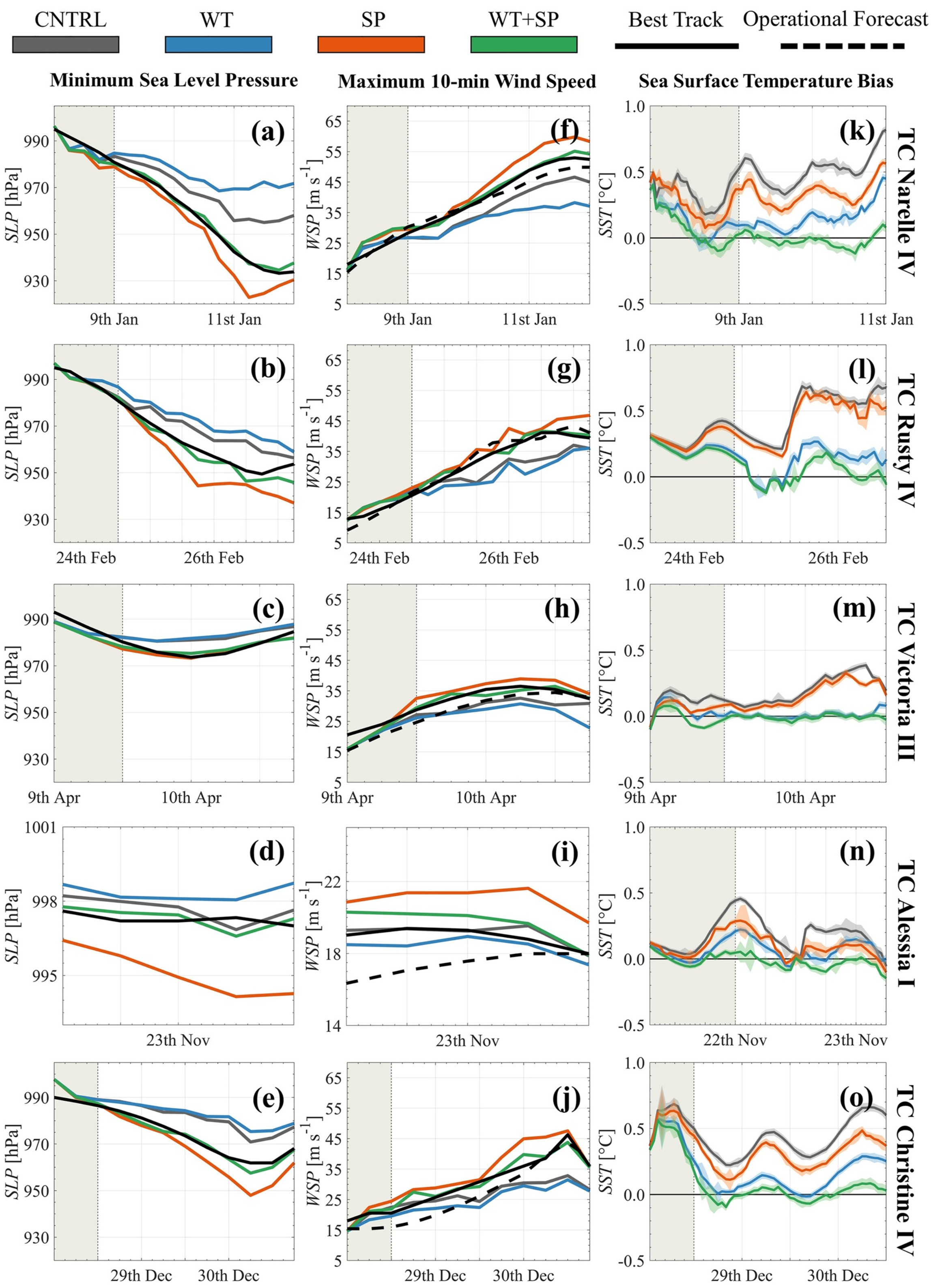
CNTRL
WT
SP
WT+SP
Best Track
Operational Forecast
Minimum Sea Level Pressure
Maximum 10-min Wind Speed
Sea Surface Temperature Bias
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
SLP [hPa]
WSP [m s-1]
SST [°C]
9th Jan
11st Jan
24th Feb
26th Feb
9th Apr
10th Apr
22th Nov
23th Nov
29th Dec
30th Dec
TC Narelle IV
TC Rusty IV
TC Victoria III
TC Alessia I
TC Christine IV

Figure 1.

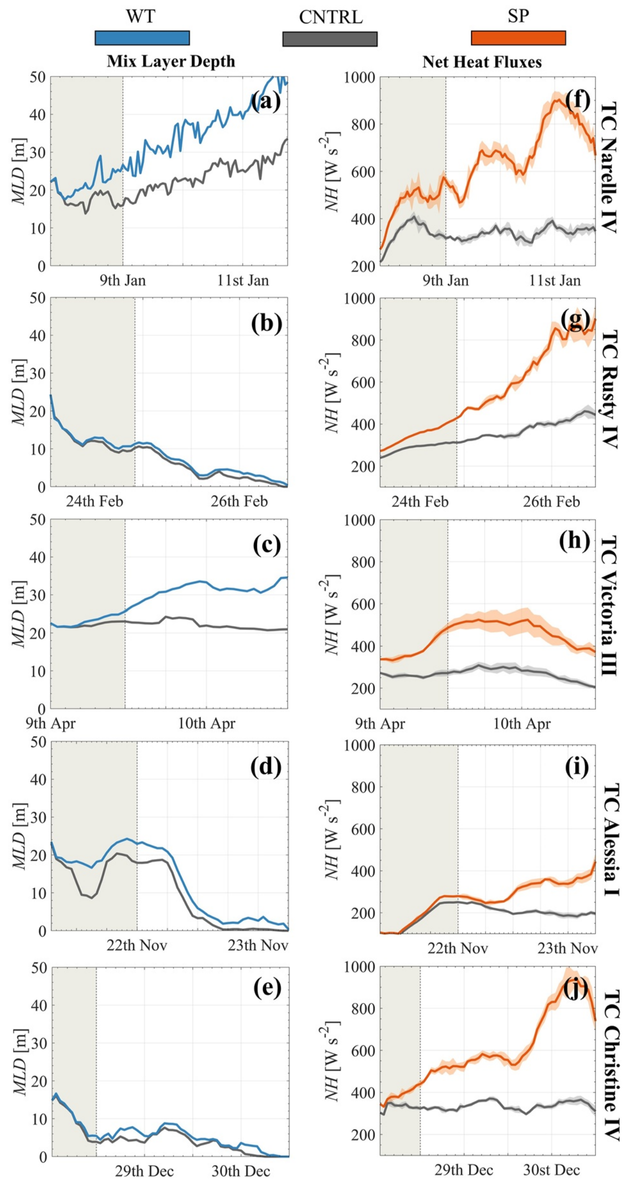

Figure 2. Time series of the 1-hr averaged (a–e) MLD and (f–j) net air-sea heat fluxes within three times of the radius of maximum winds from the TC center. The experiments of CNTRL, WT, and SP are depicted by gray, blue, and red solid line, respectively. The gray shadows depict the model spin-up period. The color bands in (f–j) state one standard deviation of their estimations.

wind patterns. That is, while the winds were neutrally compensated through including breaking and non-breaking waves in SP and WT experiments, respectively, (i.e., a decrease in the WT experiments, whereas an increase in the SP experiments), we observed that winds are stronger in WT + SP experiments. It is here where the modeling skill is improved in comparison to the CNTRL experiments and operational runs (Figures 1f–1j). This reduction in forecast error is also evident in the simulation of rapid intensification process of TCs. For example, TC Christine experienced rapid intensification with maximum sustained winds increased by 16 m s^{-1} within just 24 hr (i.e., from 12:00 on the 29th to 12:00 on the 30th). The WT + SP experiments greatly enhance the modeling skill in simulating the rapid intensification process in the TC Christine.

Figures 1k–1o presents the average simulated sea surface temperature (SST) bias within one radius of maximum winds (RMW) for all TCs in the study. In comparison to observations, the CNTRL experiment tends to overestimate SST. However, the inclusion of wave turbulence in the WT experiment leads to a cooling of SST. Similarly, the SP experiments exhibit an enhancement of SST cooling when compared to the CNTRL experiments. When including both wave-coupled processes, the WT + SP experiments, we observe the most pronounced cooling of SST, suggesting that their combined impacts consistently lead to SST cooling (e.g., the S6 in Supporting Information S1). The inclusion of ocean waves in the modeling framework substantially reduces the uncertainty associated with SST modeling under extreme weather conditions, as illustrated in Figures 1k–1o.

The wave-coupled processes impact TC dynamics through ocean surface mixing and air-sea heat fluxes. Enhanced ocean surface mixing, driven by wave turbulence, is represented by a notable deepening of the modeled MLD (i.e., the depth where water temperature 0.5°C cooler than that at the sea surface). A comparison between the WT experiment and the CNTRL experiment illustrates the increase in MLD (Figures 2a–2e and Figure S7 in Supporting Information S1). However, the extent of the MLD deepening is intricately related to local water depth conditions, with depth restrictions for those TCs situated closer to coastal zones, such as TC Rusty, TC Alessia, and TC Christine, in contrast to those farther offshore, as exemplified by TC Narelle and TC Victoria (see TC tracks in Figure S2, Supporting Information S1). In contrast, the inclusion of sea spray generated by breaking waves enlarges the air-sea interacting surface, resulting in a substantial increase in net air-sea heat fluxes (i.e., the combination of air-sea latent heat fluxes and sensible heat fluxes) (Figures 2f–2j). When comparing the SP experiment with the CNTRL experiment, it is observed that the net heat are significantly enhanced. This reconfirms that the primary impact of sea spray and wave turbulence on the air-sea coupled system is on the air-sea heat exchange and upper ocean mixing, respectively.

The impact of including non-breaking wave induced turbulence and sea spray from breaking waves on forecast error reduction can be summarized through the simulated results of minimum sea level pressure (SLP) and maximum 10-min sustained wind speed, as illustrated in Figure 3. A noticeable decrease in forecast error of TCs' intensities, approximately 15 hPa (corresponding to about 2% in Figure S8 in Supporting Information S1),

Figure 1. Time series of (a–e) the 6-hr averaged minimum sea level pressure (SLP), (f–j) the 6-hr averaged maximum 10-min sustained wind speed (WSP), and (k–o) the 1-hr averaged sea surface temperature (SST) bias with respect to the Group for High Resolution Sea Surface Temperature (GHRSST) within five times of the radius of maximum winds from the TC center for all TCs. CNTRL is the control experiments, WT is the wave turbulence experiments (blue solid lines), SP is the sea spray experiments (red solid lines), WT + SP demonstrates the experiments with both wave turbulence and breaking waves (green solid lines). The black solid and dashed lines are best tracks and operational forecast tracks, respectively (Please see the Open Research for data sources). Color bands denote one standard error of the estimations. The gray shadows depict the model spin-up period.

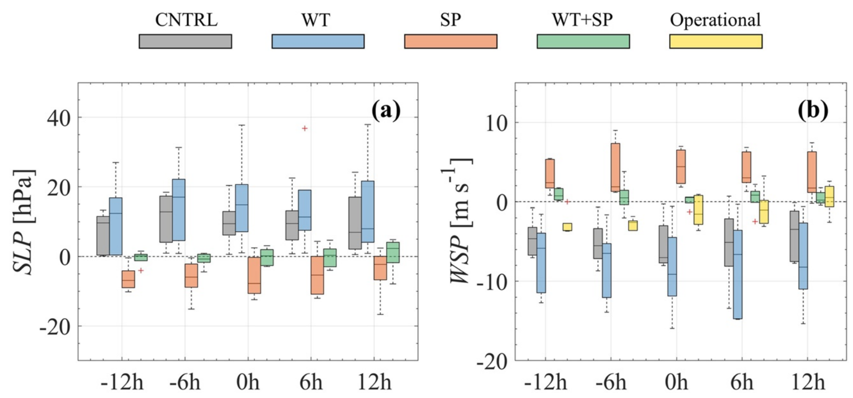

Figure 3. The 6-hr averaged TCs intensity relative to the best track. Panels (a) and (b) are the minimum sea level pressure (SLP) and maximum 10-m sustained wind speed of all TCs 12hr before and after the peak intensity, respectively. For each time, the central mark indicates the median, the bottom and top error bar state the minimum and maximum, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively.

is evident in the WT + SP experiments compared to the CNTRL experiments. Specifically, in the WT and SP experiments, the TC intensities are underestimated by approximately 17 hPa and overestimated by approximately 5 hPa, respectively. The improvement in TC intensities in the WT + SP experiments is further demonstrated by the simulated wind patterns. These experiments exhibit a significant reduction in forecast error of approximately 5 m s^{-1} (15%) compared to the CNTRL experiments. Notably, when compared to the current operational runs, the WT + SP experiments show a considerable reduction in forecast uncertainties. Specifically, the forecast error is decreased by approximately 10% around 12 hr prior to the approaching peak intensity for all TCs. We note that the inclusion of sea spray and wave turbulence importantly improves the TCs modeling. Importantly, this improvement is consistent for all tropical cyclones modeled in the full year hind cast.

4. Discussion

In the present work, we investigated the impacts of breaking waves and non-breaking waves on TCs through using a coupled air-sea-wave model. By incorporating wave-induced turbulence by non-breaking waves and the sea spray due to the wave breaking into the COAWST model system, we conducted numerical experiments of multiple TCs to provide general insights into their behaviors. We observed that the CNTRL underestimated the intensity of TCs when compared to observations. This discrepancy is highly recognized in current operational TC modeling, such as ECMWF's operational forecast (Magnusson et al., 2021; Wu, 2021). Here, we observe a notable reduction in forecast error in the WT + SP experiments. This is because the significant effects of sea spray facilitate TC intensification in the WT + SP experiments despite the wave turbulence potentially playing a counteractive role. For instance, in the case of TC Narelle, the inclusion of non-breaking wave-induced turbulence (WT) surprisingly led to a further reduction in TC intensity by an increase of approximately 20 hPa, conversely, the introduction of breaking waves through the inclusion of sea spray positively contributed to TC intensification (SP), resulting in a minimum sea level pressure of 922 hPa. This, in turn, leads to a reduction in forecast error in the comparison with CNTRL experiments. These findings indicate that the inclusion of wave-coupled processes improve the modeling skills of TCs, and this improvement seems consistent across the different TC categories.

Aligned with the overall improvement in TCs' modeling, a noticeable improvement in SST modeling within the TCs' system is seen through including sea spray and wave turbulence mechanisms, while uncertainties may remain in the SST satellite estimates due to the cloud coverage. In the comparison of SP experiments with CNTRL experiments, an enhancement of SST cooling is observed. This is attributed to the inclusion of additional air-sea turbulent heat fluxes induced by the sea spray, which contributes to the intensification of TCs. The intensified TC system generates stronger wind stress, imparting more momentum to the upper ocean and accelerating the currents within it. This leads to enhanced underlying oceanic mixing and cools the SST. In contrast, in WT experiments, the inclusion of additional turbulence induced by non-breaking waves results in the even stirring of the water column horizontally and vertically within the upper ocean. The upper warmer water is thoroughly mixed with the lower cooler water, which, under the local vertical temperature profiles (see Figure S9 in Supporting

Information S1), intensifies the cooling effect on the SST. As such, in contrast to the opposing influences of sea spray and wave turbulence on the intensity of TCs, their impacts on the SST cooling are consistent. It is through the combined and consistent effects between sea spray and wave turbulence, the most pronounced SST cooling is observed in the WT + SP experiments. Therefore, the inclusion of wave-coupled processes significantly reduces the uncertainty of SST modeling under extreme weather conditions, as depicted in Figure 1.

As the indicator of heat content in the upper ocean, SST can implicitly characterize the potential energy that supports the TC system. When the SST cooling is enhanced by the introduction of wave turbulence, the available potential energy is significantly decreased. This suppression, in turn, largely affects the development and intensity of the TCs, as shown in the WT experiments in Figure 1. As the local waves underlying TC system are forced by winds and substantially influenced by the local fetch, a decrease in wave growth is expected. As such, we expect negative feedback for the TCs when including non-breaking wave turbulence. In contrast, the contribution of sea spray to the TCs' intensification and development is positive, as shown in the SP experiments in Figure 2. This is because the inclusion of sea spray introduces additional turbulent heat fluxes, which assists in the development and intensification of TCs. The significantly intensified TCs are associated with stronger winds and larger fetch, resulting in more occurrences of breaking waves accompanied by an increased number of sea spray droplets. Nevertheless, severe TCs are associated with stronger oceanic mixing, the larger breaking wave and its induced sub-class intensified oceanic mixing (Figure S10 in Supporting Information S1), which cause cooling of the SST. This cooling, in turn, leads to a decrease in additional turbulent heat fluxes induced by the sea spray, due to the reduction in heat content provided by sea spray droplets to the atmosphere. This establishes negative feedback between sea spray and wave turbulence in the coupled atmosphere-ocean-wave system (Figure S9 in Supporting Information S1). Despite this negative feedback caused by wave turbulence, we see intensification of the TCs when considering both sea spray and wave turbulence, suggesting that the positive feedback caused by sea spray outweighs the negative feedback caused by wave turbulence. That is, all four TCs' modeling can be improved when the sea spray and the wave turbulence mechanisms are combined, while the wave-turbulence alone is sufficient to improve the SST bias in all four TCs relative to the control.

While TCs modeling can be sensitive to the coupling between dynamics and physical processes that are coupled with dynamical ocean models, this study primarily focuses on wave-coupled processes. The wave-coupled physical processes are considered through the inclusion of sea spray (Andreas & Emanuel, 2001; Perrie et al., 2005; Xu et al., 2022; Zhao et al., 2017) and wave turbulence (A. Babanin, 2006; A. V. Babanin & Haus, 2009; Ghantous & Babanin, 2014). While these wave-related algorithms have been widely applied (Aijaz et al., 2017; Xu et al., 2022; W. Zhang et al., 2022), uncertainties regarding sea spray and wave turbulence coefficients may arise due to the limited availability of robust observational data (D'Asaro, 2014; Veron, 2015; Peng & Richter, 2019; Zhao et al., 2022). To address these uncertainties, future experiments should prioritize comprehensive field observations that can provide accurate and detailed information on these physical processes (Xu, Voermans, Ma, et al., 2021). Despite the uncertainties, our model results consistently show improved TC modeling performance across different TC intensities by incorporating identical parameterizations of the wave-coupled processes. This is consistent with Zhao et al. (2022), which suggest that the intensity bias for TCs in a whole year in northwest Pacific region were reduced by 40% by considering wave effects. While future work should consider TCs occurring in global regions through using fully coupled models and additional physical processes in the air-sea interface such as rainfall and impacts of sea spray on air-sea momentum exchange, the resulting improvements in the TC performance highlights in this study the efficacy of our approach and demonstrates its potential to advance TC modeling despite the inherent challenges.

5. Conclusions

The incorporation of non-breaking wave-induced turbulence and breaking wave-induced sea spray droplets improves TC modeling. The results reveal a complex interplay between the wave coupled processes and the TC system, with negative feedback observed from wave turbulence and strong positive feedback observed from the inclusion of breaking wave-induced sea spray. While there is a clear positive influence from sea spray, a sub-class negative feedback between the sea spray and wave turbulence is expected. However, due to the dominance of the positive feedback caused by sea spray over the primary and subsequent negative feedback resulting from wave turbulence and enhanced ocean mixing, the introduction of ocean wave-coupled processes ultimately intensifies the TCs. These enhancements significantly improve the TCs modeling skills, leading to approximately 15 hPa improvement in minimum sea level pressure and a 5 m s^{-1} reduction (corresponding to about 15%) in forecast errors for maximum sustained winds. Notably, when compared to current operational runs, a noteworthy reduction of approximately 10% in forecast errors is observed around 12 hr prior to the TCs reaching their peak intensity. This reduction in forecast error highlights the importance of accurately representing the physical processes associated with ocean waves in TC simulations. Importantly, these results hold generalizability as the TC cases simulated encompass a wide range of intensities, from Categories I to IV, in our regional full year hind cast. This demonstrates that the influence of ocean waves-coupled processes on TC modeling is not limited to specific TC intensities but extends to a broader spectrum of TCs. Therefore, our results have significant implications for improving TC forecasting.

Data Availability Statement

The Best-Track Data of TCs are available in the past TCs' reports of Bureau of Meteorology (Australian Bureau of Meteorology, 2013). That is, TC Narelle (Severe Tropical Cyclone Narelle, 2013), TC Rusty (Severe Tropical Cyclone Rusty, 2013), TC Victoria (Tropical Cyclone Victoria, 2013), TC Alessia (Tropical Cyclone Alessia, 2013), and TC Christine (Tropical Cyclone Christine, 2013). Initial and boundary field data for the coupled model are available online from NCEP Global Forecast System (National Centers for Environmental Prediction, National Weather Service, NOAA, U.S. Department of Commerce, 2015), HYCOM + NCODA Global Analysis (HYCOM consortium, 2013), and WaveWatch III outputs (NOAA NWS National Centers for Environmental Prediction, Environmental Modeling Center, NOAA, U.S. Department of Commerce, 2013). The last access on above data is on 30 November 2023.

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