GCOAST: Skill assessments of coupling wave and circulation models (NEMO-WAM)

Joanna Staneva, Sebastian Grayek, Arno Behrens and Heinz Günther

Institute for Coastal Research, Helmholtz Zentrum Geesthacht (HZG,) Geesthacht, Max-Planck-str 1, 21502 Geesthacht, Germany

E-mail: joanna.staneva@hzg.de

Abstract. The coupling of models is a commonly used approach when addressing the complex interactions between different components of the Earth system. This study presents the development of a new, high-resolution, coupled ocean and wave model system for the North Sea and the Baltic Sea, which is part of the Geestacht COAstal model SysTem GCOAST. We focus on the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored, in particular in the coastal zone where its role seems to be dominant. The proposed coupling parameterisations account for the feedback between the upper ocean on the atmospheric circulation by accounting for the effects of the sea level, and ocean temperature and salinity. A focus is given on the newly implemented parameterisations that consider the effect of non-linear contribution and the component transfer of the momentum and energy fluxes from the atmosphere to the ocean through the waves interface. Sensitivity experiments are performed to estimate the role of different wave-ocean coupling components. The performance of the coupled modelling system is illustrated for the cases of several extreme events. For example, the inclusion of wave coupling changes sea surface temperature, the mixing and ocean circulation and the total sea level leading to better agreement with in-situ and satellite observations. The model comparisons with data from satellite altimeter and in-situ observations showed that the use of the fully coupled system reduces the errors, especially under severe storm conditions.

Accurate ocean predictions remain a challenging topic in coastal flooding research, not least along the European shelf, which is characterised by vast shallow tidal flats and a large coastal population. The increased demand for improved water level forecast requires further development and refinement of the physical processes represented by the hydrodynamical models to properly account for wave generated currents and the corresponding changes to the water level. The effect of coupling on model predictions becomes more important [1,2] with increasing the grid resolution, which therefore emphasises the need for coupling on the regional scales. Spatial and temporal changes in the wave and wave energy propagation are not yet sufficiently addressed in high-resolution regional models. The shallow water terms in the wave equations (depth and current refraction, bottom friction and wave breaking) play a dominant role near coastal areas, especially during storm events, where the wave breaking term prevents unrealistically high waves near the coast. Understanding the wave-current interaction processes is essential for the coupling between the ocean, atmosphere and waves in numerical models. Storm surges are meteorologically driven, typically by wind and atmospheric pressure. Waves combined with higher water levels may break dykes, cause flooding, destroy...
construction and erode coasts. The combined effects of wind waves can cause coastal flooding, high tides and storm surge in response to fluctuations in local and remote winds and atmospheric pressure[3]. The role of these processes can be assessed by high-resolution coupled wave and circulation models.

Using stand-alone ocean or atmosphere models, the wave interface that represents the boundary between them is not taken into account. This can cause bias in the upper ocean due to insufficient or, in some cases, strong mixing [4]; or because the momentum transfer is shifted in time and space compared to how the fluxes would behave in the presence of waves. Several parameterisations were recently proposed for momentum flux that is sea state dependent, e.g., [5,6], and for turbulence closure [7–11]. The skill of wave–ocean circulation coupled model simulations has been quantified at the coastal, regional and large scale [4,12,13]. Sea state dependent momentum stress impacts the ocean circulation, Lagrangian transport or biogeochemical models. Considerably enhanced momentum transfer from atmosphere to waves during young waves was shown in [14]. Later, wind stress formulation depending on the atmosphere wind stress and wind–wave stress released to the ocean was proposed in [15]. By an underdeveloped sea state and low wind, wave swell can even cause momentum transfer from the ocean to the atmosphere. The transfer of momentum and energy between the atmosphere and the ocean affects the atmosphere–wave–ocean boundary layer [16]. Parameterisations have been proposed based on observations or laboratory experiments to count for the sea state dependencies of wind stress [17–19]. The impact of wave-dependent surface stress on the ocean circulation was studied using surface stresses calculated from a numerical wave model in [20] to demonstrate the effects on the Ekman currents in the upper ocean and on storm surge predictions.

Wind stress dependencies on sea state conditions were implemented in numerical models in [14,21,22]. As shown in [23], the wave–current interaction significantly reduces momentum flux into currents in hurricane conditions, which consequently reduces the magnitude of subsurface currents. Surface waves can also affect model predictions of water levels and thus storm surges through changes in the stress and upper-ocean mixing and circulation (e.g. [24,25]). In growing sea states, waves extract momentum from the atmosphere so that the ocean receives less momentum from the atmosphere than if waves are not considered [26]. For our study area, the importance of wave forcing for ocean circulation and sea-level predictions was demonstrated by [3,12,27–30]. The impact of ocean–wave coupling in the near-coastal German Bight region of the southern North Sea was studied in [43,45], showing that the predictive skill of ocean circulation and sea level could be significantly enhanced by considering wave-induced processes. In extreme storm surge conditions over the North Sea, due to the strong non-linearity of wave–ocean–tidal interactions, wave–ocean coupling is considered to be significant for correct model predictions [12,32]. During storm events, ocean stress is significantly enhanced by the wind–wave interaction, leading to an intensification of zonal velocity and an increase in the estimated storm surge, demonstrating model predictions closer to observations[12].

In order to study the complex interdisciplinary processes, coastal system models accounting for non-linear interactions between ocean circulation, tides, waves and the atmosphere is of utmost importance. The Geesthacht coupled coastal model system (GCOAST) [33,34] was built upon a flexible and comprehensive coupled model system, integrating the most important key components of regional and coastal models. GCOAST encompasses: (i) atmosphere–ocean–wave interactions, (ii) dynamics and fluxes in the land–sea transition, and (iii) coupling of the marine hydrosphere and biosphere. In our study, we used the GCOAST circulation, wave and ocean model components to investigate the role of coupling on improving the simulation skills that is of crucial importance for both ocean forecasting and climate research. Those particles can be considered, for example, as simple representations of either oil fractions, fish larvae or search-and-rescue objects [35,36]. The wave-current interaction processes are momentum and energy sea state dependent fluxes, wave-induced mixing and Stokes-Coriolis forcing.
The paper is organised as follows: In Section 2, we describe the circulation and the wave models and the coupled wave–circulation processes, followed by a description of the results in Section 3 and conclusions in Section 4.

2. Methodology

2.1 Ocean and wave models

NEMO (Nucleus for European Modelling of the Ocean, [37]) is a framework of ocean related computing engines, from which we use the OPA package (for the ocean dynamics and thermodynamics) and the LIM3 sea-ice dynamics and thermodynamics package [37] Bouillon et al., 2009. In OPA, six primitive equations (momentum balance, the hydrostatic equilibrium, the incompressibility equation, the heat and salt conservation equations and an equation of state) are solved, where the Arakawa C grid is used in the horizontal. In the vertical, terrain-following coordinates, z coordinates, or hybrid z-s coordinates can be chosen. For a complete description of the model, see [37]. Previously, NEMO was applied to the Baltic Sea and the North Sea area in uncoupled mode [38], coupled to atmospheric models [39,40] and forced with a wave model [12,13,27]. For the north-western European shelf, NEMO is used as a forecasting model in the COPERNICUS Marine Services [30,41,42]. The wave model WAM [43,44] is a third-generation wave model, which solves the action balance equation without any a priori restriction on the evolution of spectrum. The system BS-waves is based on the state-of-the-art and well-established advanced third-generation spectral wave model WAM that runs successfully at many institutions worldwide. It is based on the spectral description of the wave conditions in frequency and directional space at each of the active model sea grid points of a certain model area. The version used in this study is the WAM Cycle 4.7, which is described in [45–47]. The source function integration scheme is made by [48], and the updated source terms of [49] are incorporated. The new version considers the wave-induced processes needed for coupling and decreed below. The wave and the circulation model are two-way coupled with OASIS Interface [35–37].

![Figure 1. Bathymetry of the GCOAST Model area (left panel); Wave induced processes into NEMO. This case simply justify the caption so that it is as the same width as the graphic.](image)

2.2 Wave effects in the ocean model

Ocean waves influence the circulation through a number of processes: turbulence due to breaking and non-breaking waves, momentum transfer from breaking waves to currents in deep and shallow water, wave interaction with planetary and local vorticity, Langmuir turbulence. The NEMO ocean model has been modified to take into account the following wave effects as described by [12] and [27]: (1) The Stokes-Coriolis forcing; (2) Sea state dependent momentum flux, set as a scalar dependence of the
flux from the atmosphere to waves and ocean or as a vector; and (3) Sea state dependent energy flux. A schematic overview of these processes is shown in figure 1.

However, the momentum flux the previous studies by [27], [30] and [12] has been treated as a scalar and not as a vector quantity. This results in not fully closing the balances of momentum and energy between the atmosphere and ocean. The normalised momentum flux that has been used was estimated as a scalar:

$$\tau = \frac{\tau_a - \tau_{in} - \tau_{diss}}{\tau_a}$$

In the wave model WAM the components of momentum and energy fluxes are separately estimated in vector form:

$$\overrightarrow{\tau_{vn}} = \rho_w g \int_0^{2\pi} d\omega \int_0^\infty d\omega d\theta \frac{k}{\omega} S_{vn}(\omega, \theta)$$

while the dissipation stress is given by

$$\overrightarrow{\tau_{diss}} = \rho_w g \int_0^{2\pi} d\omega \int_0^\infty d\omega d\theta \frac{k}{\omega} S_{diss}(\omega, \theta)$$

and the contribution of the non-linear term is:

$$\overrightarrow{\tau_{SNL}} = \rho_w g \int_0^{2\pi} d\omega \int_0^\infty d\omega d\theta \frac{k}{\omega} S_{SNL}(\omega, \theta)$$

Consequently, following the description in Section 2, we now introduce for all parts the components into $S_{DISS}$ and $S_{NL}$ (using $\sin(U)$ and $\cos(U)$),

$$\tau_{oc,x} = \frac{\tau_a \sin(U) - \tau_{in,x} - \tau_{diss,x}}{\tau_a}$$

$$\tau_{oc,y} = \frac{\tau_a \cos(U) - \tau_{in,y} - \tau_{diss,y}}{\tau_a}$$

In order to test these novel implementations, a one-dimensional model experiment with a constant wind speed of 15 m/s is performed, and four different experiments with the considering the non-linear term contributions ($snl$) and the components transfer are described in Appendix A.

We study the individual and combined role of newly introduced parameterisations by performing a series of process-oriented studies. Table 1 described the different experiments.

**Table 1. Model Experiments**

| Experiment | NEMO | Stokes-Coriolis Force | Ocean side Momentum Stress - components | Ocean side momentum Stress - scalar | Wave breaking |
|------------|------|-----------------------|----------------------------------------|----------------------------------|--------------|
| REFRUN     | √    |                       |                                        |                                  |              |
| STCOR      | √    |                       |                                        |                                  |              |
| TAUOC      | √    |                       |                                        |                                  |              |
| TKE        | √    |                       |                                        |                                  |              |
| TAUUST     | √    | √                     |                                        |                                  |              |
| TAUDIR     | √    |                       |                                        |                                  |              |
| TAUVEC     | √    |                       |                                        |                                  |              |
| TVCSTC     | √    | √                     |                                        |                                  |              |
| ALLWAVE    | √    | √                     |                                        |                                  |              |
3. Coupled wave-ocean model system for regional scales

3.1 Impact of coupling on the sea level simulations

2.2.1 Impact of wave induced forcing on sea level

In order to assess the relative impact of the three wave-induced processes, we will analyse here the time evolution and horizontal patterns of the difference between the coupled wave-ocean simulations (as in table 1) and the stand-alone ocean model (REFRUN -no explicit wave effects). It is important to mention here that the TVCSTC run is not a linear combination between the three runs considering the wave-induced processes separately (TKE, STCOR and the different TAU* runs), rather we aim to identify which of them are dominant for the changes in the water level over the extreme events.

Below we show test cases of simulated and observed surface elevations during interesting atmospheric conditions as depicted in January and February 2017 (as in figure 2). The left panels of figure 2 correspond to conditions of south-easterly wind and long swell event from 2-4 January 2016. This causes very low maximal sea level conditions over the entire German Bight coastal area as in Figure 3. Modelled sea surface heights are compared with observations from the EMOD-tide gauge database (available on http://www.emodnet.eu).

\[\text{Figure 2.:} 10 \text{ m wind (m/s) and mean sea level pressure (hPa) on on 2^{\text{nd}} \text{ January, 2016 (top), 30 of January, 2016 (middle) and 6^{\text{th}} \text{ of February, 2016 (bottom) patterns. during strong swell event (top panel) and local surge conditions (right panel).}}\]

The sea level amplitude was with about one meter below the normal over this area (see also figure 4 for the spatial variability of the sea level differences. During this event, the NEMO only simulations
(red line) overestimated the measurements for all tide gauges stations. It is clearly seen that through the newly introducing parameterisations of the wave induced forcing the simulated water level increased leading to better agreement with the observations. The left panels demonstrate the sea level variability during the storm on 30 January, 2016. In this case the north-westerly wind over the German Bight caused a higher water level that was underestimated by the NEMO stand-alone model. Again, a closer fit to the observations is simulated by the wave experiments that include the proposed parameterisation of transfer of momentum fluxes as vector components (TAIVEC). Therefore, the added value of the newly implemented wave-induced forcing during the storm events, but also in situations with lower water level is clearly noticeable.

![Figure 3](https://example.com/figure3.png)

**Figure 3** (top) Comparison of simulated and observed surface elevations at the near-coastal tide gauge data for the German Bight coastal area during strong swell event (left panel) and local surge conditions (right panel). The legend is given on the top of the figure.
Figure 4. Impact of coupling on sea level: differences between simulated surface elevations of the wave-ocean coupled model and the stand-alone NEMO model (REFRUN) on 2nd January 2016 (top), 30 of January 2016 (middle) and 6th of February, 2016 (bottom) patterns. During strong swell event (top panel) and local surge conditions (right panel). The different wave-induced experiments are shown on the bottom-left side of each pattern.

3.2 Impact of coupling between waves and ocean on simulated temperature and salinity

3.1 Sea Surface Temperature (SST)

Figure 5 presents Root Mean Square Errors (RMSE) of the sea surface temperature when compared with data from OSTIA [50] for the different NEMO stand-alone (REFRUN) and the wave-induced experiments, averaged over the whole 2015. The areas with best skills are also demonstrated on the bottom-right panel. While the RMSE is relatively low with values lower than 0.5, the panel showing the root mean squared error reveals areas, where the deviations in the temperature are in the order of 0.8 to more than 1 °C. These areas are concentrated in the Baltic Proper, the Gulf of Finland, the Danish Strait and near the Norwegian coast.
Figure 5. RMSE of the sea surface temperature when compared with data from OSTIA for the different NEMO-only and Wave-induced experiments, averaged over the whole 2015. The areas with best skills are also demonstrated on the bottom-right pane.

Figure 6 shows the bias of the experiments, including wave effects and the control simulation to determine regions, where the inclusion of wave effects leads to notable improvements or worsening during the storm on 01-10 January 2016. In general, both measures illustrate skill performance in the wave-experiments. The results point to several regions that appear noteworthy. First, it is noteworthy that the significant differences are due to the sea state momentum transfer and the Stokes-Coriolis forcing in the near coastal areas.
3.2 Comparisons with MARNET

Comparison of simulated temperature with measurements of FINO-1 station [50] shows that both the control run and the runs with wave effects describe very well the vertical evolution of temperature (left patterns) and salinity (right patterns) (Figure 7). The important features of both seasonal and vertical variability are very well present in all of the simulations. It is notably that salinity of the REFRUN runs deviates from the observational salinity. The time-evolution of salinity of the wave-induced experiments also much better captured, and the errors are significantly reduced. Compared to REFRUN the wave runs generally yields better results for temperature as well as and sudden down-bursts of salinity variations. This clearly demonstrates that the newly proposed method of introducing wave dependant sea side fluxes as vector led to an improvement of model skills and reducing of model errors also in the whole water column.

**Figure 6:** Differences of the rmse of SST (deg. C) between individual model runs (including wave-induced effects) and the control simulation.
that the coupling between ocean and wave models led to an improvement of model predictions. The

Figure 7: Temperature (left) and salinity (right) variability for 2015 at FINO-1 station at different
levels (depth is given on the right y-axis). The comparisons of MARNET data (black line), NEMO only
simulation (red line) and the wave-forced runs (see the legend on the top for the experiments) demonstrated
the improvements once the new wave-induced processes are included (RMSE between the MARNET observations and simulations are also shown on the bottom of each pattern).

4. Conclusion
We found improved skill in the predicted sea level and circulation during storm conditions when using
a coupled wave-circulation model. In the periods of storm events, the ocean stress was significantly
enhanced by the wind-wave interaction leading to an increase in the estimated storm surge (compared
to the ocean-only integration) to values closer to the observed water level. The numerical experiments
with the wave-forced NEMO model yielded an increase of and surge level in the south-eastern shallow
North Sea and along the North-Frisian Wadden Sea coast for the extreme surge events. We showed
that the coupling between ocean and wave models led to an improvement of model predictions. The
model comparisons with data from satellite altimeter and in-situ observations showed that the use of
the fully coupled system, especially with the newly proposed momentum transfer reduces the errors,
most noticeable under severe storm conditions. This justifies the further developments and
implementation of the coupled model systems and its synergy with the newly available satellite
observations, for both, operational and climate research and development activities.

5. References
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Appendix A

A one-dimensional model is run with a constant wind speed of 15 m/s. We performed four different experiments with the considering the non-linear term contributions ($s_{nl}$) and the vector new implementation of vector are described in Appendix. The experiment with transferring of momentum and energy flux as scalar component and without consideration of the non-linear term is named (NOSNL), $modulus_{SNL}$ is the old scalar version, but including $S_{NL}$. The experiment, in which the momentum and energy fluxes are transferred as vector components, but $SNL$ is not considered is named “Components”. Finally the new implementations in which both the vector components of the fluxes are considered together with the $S_{NL}$ term is named $Components_{SNL}$. In the second sensitivity one-dimensional runs, we repeated the runs with 15 m/s wind speed but turned the wind direction after 48 hours by 90°.

The results are shown in figures A1 and A2. The $modulus$ runs have the same behaviour and demonstrate an increase of about 20% of the momentum transfer to the ocean when the wind is turning. However, the Component runs show a decrease of the momentum transfer. The explanation is that in the case of a turning wind, the new developing sea uses a larger part of the momentum and the dissipation of the swell part of the spectrum is small.

**Figure A1**: Sea state-dependent momentum fluxes from the one-dimensional experiments with a constant with a wind speed of 15 m/s are performed. Four different runs are shown (see the legend): “$Modulus$” (blue line): is the old version with scalar components but without consideration of the non-linear term (NOSNL), $modulus_{SNL}$ (green line) is the old scalar version, but considering $SNL$, “$Components$” (red line) is the new implementation in which the two vector components of the fluxes are considered, but without $SNL$, in “$Components_{SNL}$” the contribution to the $SNL$ has been considered.
Figure A2: Sea state dependent momentum fluxes from the one-dimensional experiments with initially constant 15m/s wind speed but turned the wind direction after 48 hour by 90°. The legend is the same as for figure A1.