ECAS 2022

MDPI

Proceeding Paper

Influence of the Novaya Zemlya Bora on the Ocean-Atmosphere Heat Exchange: Results from the Coupled Model †

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† Presented at 5th International Electronic Conference on Atmospheric Sciences, 16–31 July 2022; Available online: https://ecas2022.sciforum.net/.

Abstract: The Novaya Zemlya bora is a strong downslope windstorm in the east of the Barents Sea. The impact of bora on the turbulent heat exchange between the atmosphere and the ocean and on processes in the ocean was investigated using the COAWST (Coupled-Ocean-Atmosphere-Wave-Sediment Transport) modeling system, which includes the atmospheric, oceanic and sea waves components. The sensitivity of turbulent fluxes during bora to different model coupling strategies was also studied.

Keywords: coupled modelling; turbulent heat fluxes; downslope windstorm; Barents Sea

Academic Editor(s): Anthony Lupo

Published: 14 July 2022

1. Introduction

Coupled modeling of the atmosphere and the ocean is common in climatological studies and studies devoted to tropical cyclones. However, other mesoscale phenomena such as strong and long-lasting orographic winds could also be a subject for coupled simulations since enhanced air-sea interaction is expected under such winds. For instance, the difference between turbulent heat fluxes in coupled and uncoupled simulations of the Adriatic bora is significant and attains 20% [1,2]. In addition, bora winds affect the water circulation, convection and mechanical mixing in the Adriatic Sea, as well as sediment transport and biological characteristics [3].

This study aims to evaluate the effect of coupling on simulation of the Novaya Zemlya bora. The Novaya Zemlya bora is the strongest and very frequent downslope windstorm in the Barents Sea region [4,5]. According to the Malye Karmakuly weather station, bora on the western coast of Novaya Zemlya (hereafter, "NZ") is observed on average 138 days a year, with 25% of the wind speed exceeding 20 m/s [5]. For this study, one winter episode of bora observed in December 2006 with the wind speed up to 34 m/s was chosen for simulations.

Three problems were studied in this paper: (1) The impact of coupling on turbulent fluxes under bora conditions; (2) The impact of bora itself on turbulent heat fluxes; (3) The impact of bora on ocean mixing and circulation. For this aim, numerical experiments were carried out with the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system [6] with different coupling strategies and parametrizations of wind input in the sea waves model and sea-surface roughness.

2. Materials and Methods

The COAWST modelling system links the models of the atmosphere (Weather Research and Forecasting model, hereinafter WRF), the ocean (Regional Ocean Modeling System, ROMS) and sea waves (Simulating Waves Nearshore, SWAN) and using the

Model Coupling Toolkit [7] models communicate with each other online. Also, an ice model of Budgell [8] was adapted for COAWST and added as a part of the ocean model.

The model domains for the NZ region are shown in Figure 1. The horizontal grid spacing for all models is 3 km. The WRF model grid has 50 vertical levels. ROMS grid has 26 vertical levels with grid spacing increasing with depth. SWAN model spectral resolution is 10°.

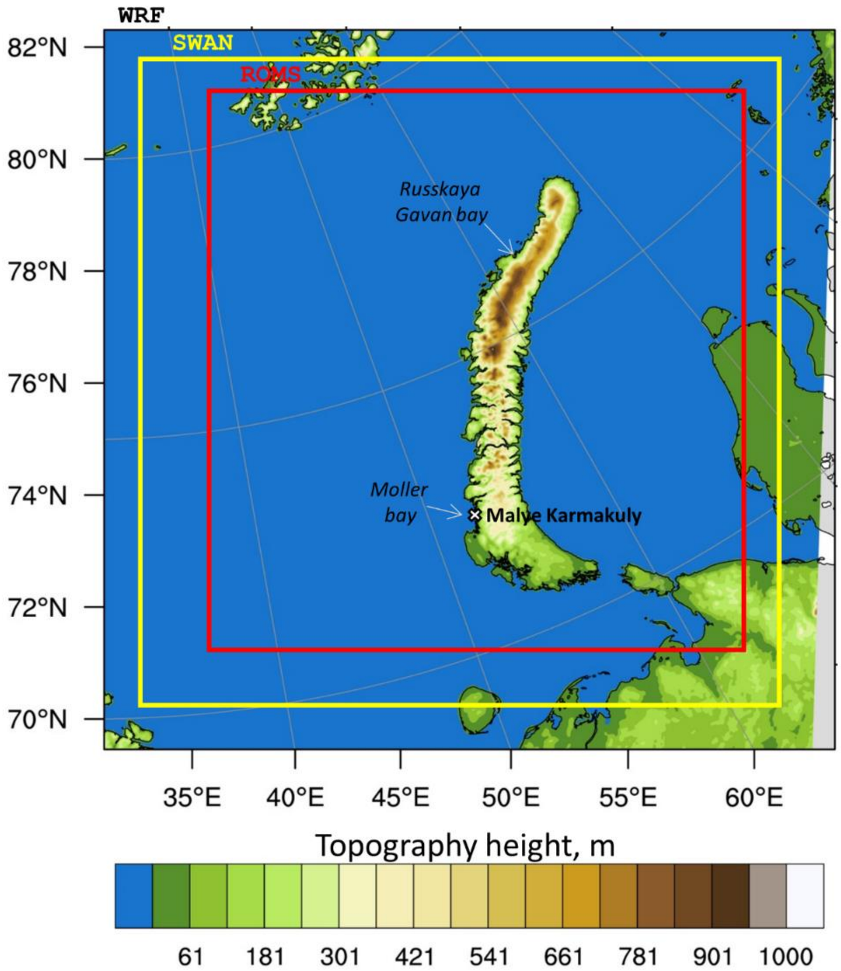

Figure 1. Model domains: WRF (coincides with the boundaries of the map), SWAN (yellow rectangle) and ROMS (red rectangle). Color shows topography height (m). X-mark shows the location of the weather station.

Totally, eight numerical experiments were carried out. The control experiment "A" represents a stand-alone WRF model run. Two experiments ("AO" and "AW") represent two-way coupling of atmospheric model with the ocean and sea waves models, respectively. "AWO" is a fully three-way coupled simulation. Additional series of calculations was run to assess the sensitivity of the results to some parameters in a fully coupled mode. The "AWO Janssen" experiment used wave growth due to wind according to Janssen [9,10] (hereinafter referred to as "Janssen") instead of parametrization [11] (hereinafter—"Komen"). Another series of experiments test the sensitivity of simulated results to the roughness length parametrization based on sea wave parameters. While standard Charnock formula [12] was used in WRF when uncoupled with SWAN ("A" and "AO" experiments) and parametrization [13] (hereinafter—"Drennan") was used in most of coupled calculations, two other schemes, named here "Taylor_Yelland" [14] and "Oost" [15], were also tested. Finally, the "AWO flat" experiment with flat topography simulated conditions of a simple cold-air outbreak under eastern winds (i.e., without the impact of bora).

The ERA5 atmospheric reanalysis, Simple Ocean Data Assimilation (SODA) ocean reanalysis version 3.3.2 and AMSR-E/Aqua satellite sea ice data were used as initial and boundary conditions in these simulations. The tides were set in ROMS model from the Oregon State University TPXO database [16]. Initial sea wave field was prepared with the coupled WRF and SWAN models: a four-day run on nested grids with the outer one including the North Atlantic was performed to account for the swell. ETOPO2 data was used to set bathymetry in ROMS and SWAN models.

WRF model was run with the Quasi–normal Scale Elimination boundary layer parametrization. Vertical mixing in ROMS was set using the Mellor-Yamada level 2.5 parameterization. The SWAN model ran in third-generation mode, taking into account wave breaking in the open sea and in shallow water and quadriplet interactions by default.

3. Results and Discussion

The following results were obtained from numerical experiments with the COAWST coupled model for one winter episode of strong Novaya Zemlya bora (10–12 December 2006).

In experiments with the on-line interaction between the atmosphere and sea waves (all experiments except "A" and "AO"), turbulent heat exchange increased (on average by 3% in "AWO" experiment) (Table 1, Figure 2) compared to the control experiment due to an increase in the roughness coefficient near the coast (up to 100–150 km from the coast) caused by young steep waves. In experiments with the on-line interaction of the atmosphere and the ocean, the turbulent heat exchange averaged over the region did not change compared to the control experiment (Table 1). When both ocean and wave models were coupled with the atmospheric model, there were three zones with different coupling effect on heat fluxes: (1) a narrow strip near the coast, where the fluxes decreased due to ocean cooling, (2) a zone where fluxes increased due to rough waves at a distance from 5 km to 100 km from the shore, (3) the open sea, where the effect of coupling on fluxes was generally small (Figure 2).

Table 1. Average differences in sensible (H), latent (LE) and total (H+LE) heat fluxes (W m^{-2}) between experiments in the NZ region. The relative differences are indicated in brackets, rounded to integers (in %).

	H	LE	H+LE
"AO"—"A"	1(0%)	1(1%)	1(0%)
"AW"—"A"	2(2%)	4(4%)	6(2%)
"AWO"—"A"	3(2%)	4(4%)	7(3%)
"Janssen"—"A"	3(2%)	5(4%)	8(3%)
"Taylor_Yelland"—"A"	5(3%)	4(4%)	9(3%)
"Oost"—"A"	8(5%)	8(8%)	16(6%)
"AWO"—"AWO_flat"	−27(−28%)	0(0%)	−28(−18%)

The influence of wind input parameterization in SWAN ("Komen" and "Janssen") on the average heat fluxes was small (Table 1). On the contrary, the choice of roughness parameterization had a significant impact. The "Taylor_Yelland" parameterization gave higher drag coefficient values near the coast and in the open sea compared to the "Drennan" parameterization, although on average the differences in heat fluxes between these parameterizations were small (Table 1). The "Oost" parameterization gave higher values of both the drag coefficient and the heat fluxes near the coast and in the open sea; the difference between the "Oost" and "A" experiments was on average 6–7% (Table 1). Verification of simulated wind speed and significant wave height against altimeter observations in the open sea showed that the "Oost" experiment performed worse than other experiments, while experiments with "Drennan" parametrization were better than others.

Moreover, coupling with the wave model with the "Drenan" parameterization reduced the wind speed bias by a factor of two compared to an uncoupled simulation.

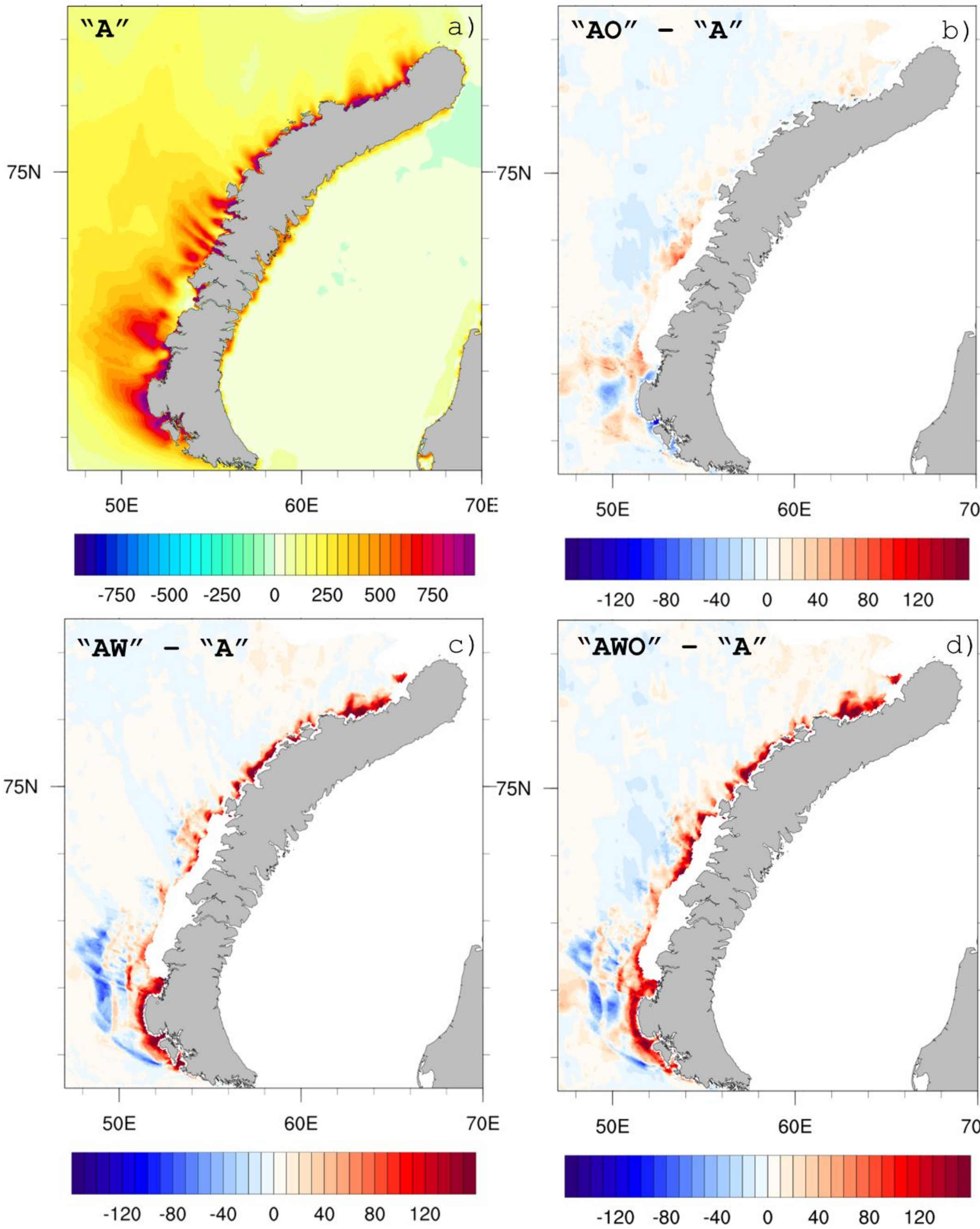

Figure 2. Total turbulent heat flux (W m^{-2}) in experiment "A" (**a**) and difference in heat fluxes (W m^{-2}) between coupled experiments "AO" (**b**), "AW" (**c**), "AWO" (**d**) and uncoupled experiment "A" averaged over the bora period (10–12 December). Areas with sea ice from experiment "A" in (**b**–**d**) are shaded in white.

Comparison of the "AWO" and "AWO flat experiments showed that topography of NZ and orographic winds reduces the turbulent heat exchange between the ocean and the atmosphere by 18% on average over the region (Table 1). The average ocean heat content in the NZ region decreased by 2.7% during bora episode, but it decreased even more in the flat experiment. At the same time, in the coastal region, heat transfer locally increased by 50–150% under the bora conditions compared to flat experiment. Ocean mixing away from the shore is significantly reduced in the bora conditions since wind wake (not present in the flat experiment) is formed downstream of the zone of high wind velocities near the shore. Also, bora intensified ocean current along the western coast of Novaya Zemlya by 0.1–0.25 m/s on average (Figure 3). Finally, bora clearly contributed to the formation of dense waters on the NZ shelf (Figure 3) due to salinization caused by increased evaporation and formation of new ice. In the flat experiment, this densification was weakened. This bora impact could be far-reaching since the dense water on the NZ shelf is a known source of the Arctic Intermediate and Bottom Water [17].

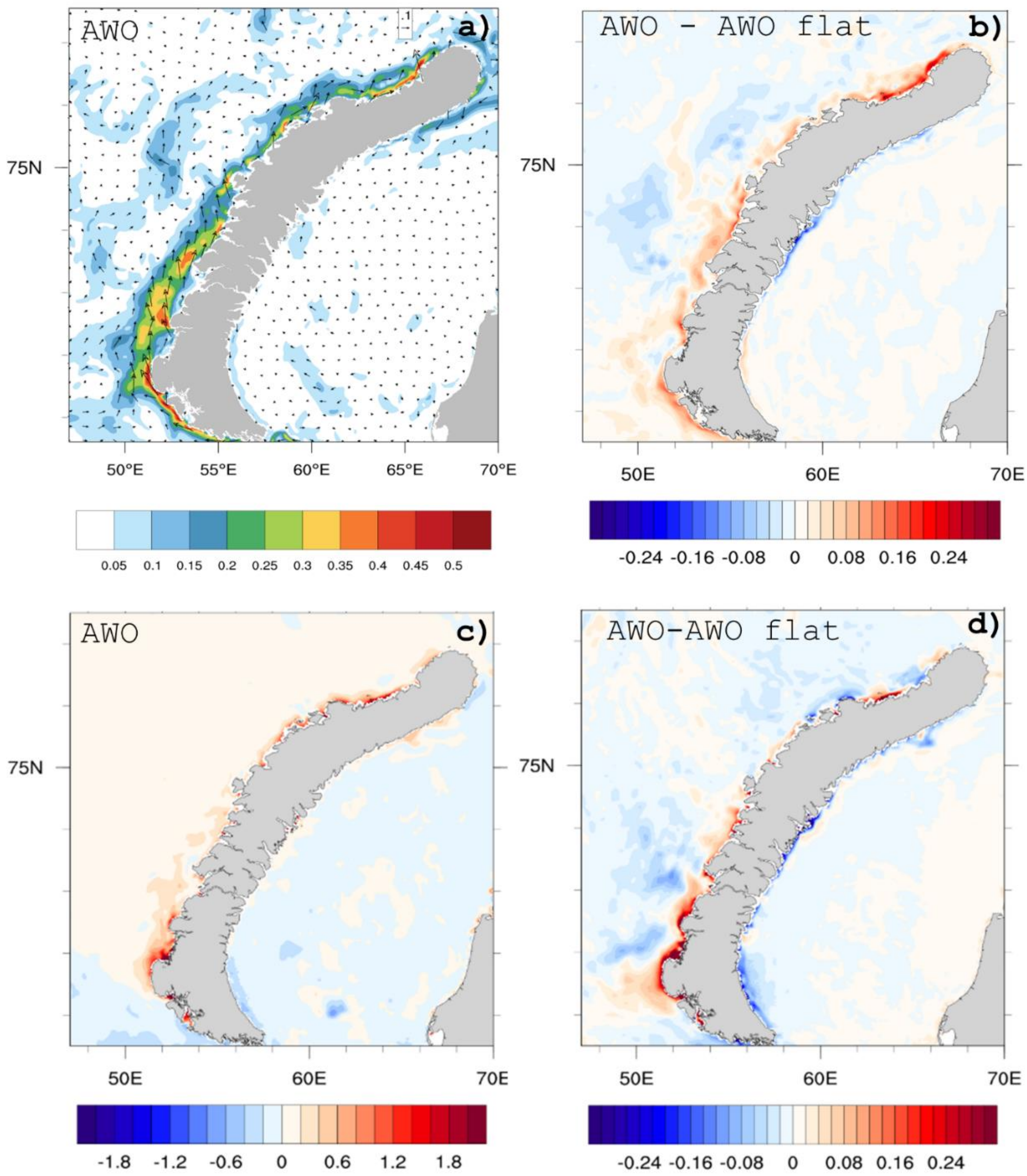

Figure 3. Depth-averaged current speed (m/s) (**a**), difference in current speed (m/s) between "AWO" and "AWO flat" experiment (**b**), change of water density (kg/m^3) during bora (**c**) and difference in water density (kg/m^3) between "AWO" and "AWO flat" experiment averaged over the bora period (10–12 December).

As expected, the greatest effect of bora is concentrated in the coastal region. There is no direct influence of bora wind in the open sea, since the horizontal scale of bora does not exceed 100 km. However, bora as a phenomenon as a whole—including the formation of a wind wake, as well as the adiabatic heating of the descending air, which spreads over a long distance (e.g., [5])—largely determines the atmosphere-ocean energy exchange and ocean mixing. Bora has a significant impact on the processes in the ocean directly near the coast: coastal currents and especially formation of dense waters.

Funding: This research received no external funding.

Institutional Review Board Statement:

Informed Consent Statement:

Data Availability Statement: The COAWST modeling system is distributed freely via github (https://github.com/jcwarner-usgs/COAWST). The ERA5 reanalysis was downloaded from NCAR Research Data Archive (https://rda.ucar.edu/datasets/ds633.0/). The SODA reanalysis is available at https://www.soda.umd.edu/. AMSR-E/Aqua daily sea ice concentration and snow depth with 12.5-km resolution is available at https://nsidc.org/data/AE_SI12/versions/3. TPXO tides data is available to registered users at https://www.tpxo.net/home. ETOPO2 database is available at https://www.ngdc.noaa.gov/mgg/global/etopo2.html.

Acknowledgments: The author is very grateful to Andrey Debolsky for technical assistance in connecting the sea ice model to the COAWST modelling system.

Conflicts of Interest: The authors declare no conflict of interest.

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