An atmosphere-wave coupled regional climate model

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Abstract

A coupled regional atmosphere-wave model system is developed with the purpose of investigating the impact of climate changes on the wave field as well as feed-back effects of waves on the atmospheric parameters. This study focuses on the effects of introducing a two-way atmosphere-wave coupling on the atmosphere and on wave parameters. The model components used are the regional climate model RCA and the third generation wave model WAM. Introducing a two-way coupling results in an altered frequency distribution of wind speed and wave heights. When also the impact of swell is included there is a shift towards higher wind speeds as well as higher significant wave heights in the four investigated grid-points.

Keywords: wave-climate, coupled wave-atmosphere model, swell, atmospheric forcing

Nomenclature

τ	=	total surface stress
τ_w	=	wave induced stress
ρ_a	=	air density
κ	=	von Karman constant
u_*	=	friction velocity
C_D	=	drag coefficient
U_{10}	=	wind speed at 10 meters
z	=	height above the sea surface
$U(z)$	=	wind speed at height z
z_0	=	roughness length
g	=	gravitational acceleration
α	=	Charnock coefficient
β	=	constant
c_p	=	peak phase speed
T_p	=	peak wave period
ψ_m	=	non-dimensional wind gradient
t	=	time
F	=	wave variance spectrum
f	=	frequency
θ	=	wave propagation direction
c_g	=	group velocity of waves
S	=	source term
S_{in}	=	wind input
S_{ds}	=	dissipation due to whitecapping
S_{bot}	=	bottom friction
S_{nl}	=	nonlinear wave-wave interaction
H_s	=	significant wave height
N	=	number of 30-min data points

1 Introduction

Surface waves are mainly generated by the wind, thus the wave field is dependent on the wind field. The high wind speed situations connected with atmospheric synoptic scale intense weather systems are the major wave generators. Waves propagate over quite long distances before they are dissipated. In order to describe the wave field it is not enough to know the local wind, also waves propagated from other areas need to be known. There is a feed-back from the waves to the atmosphere, since the state of the waves influences the friction at the surface and thus also the turbulence in the atmosphere and wind gradients. Surface waves can be divided into growing sea (young sea) and decaying sea (swell) with very different impact on the atmosphere. To be able to describe the wave field in a changing climate, a reliable description of the atmospheric conditions and the impact of waves is needed. To take the atmospheric forcing of the waves into account as well as to include the feed-back effects of the waves on the atmosphere an atmosphere-wave coupled modelling system is developed. Most previous studies using coupled models are developed for wave prediction and weather predictions purposes and it has been shown that the impact of the coupled system depends in a sensitive manner on the resolution of the atmospheric model [1]. In [1] it was shown using a two-way coupled weather-wave prediction model that the scores of the atmospheric parameters were slightly improved when introducing the coupling, a significantly larger improvement was seen in significant wave height. In [2] the impact on a developing storm was rather weak when introducing a coupled system, there were however larger effects on surface variables and sea surface fluxes. A general feature when introducing a two-way coupled system is a reduction of surface winds [2-3]. In these previous studies the strong reduction of surface friction in the presence of swell [4] has not been included. In the present study we develop a coupled regional climate-wave model. The coupled system is based on the regional climate model RCA (Rossby Centre atmospheric regional climate model) and the state-of-the-art third generation wave model WAM. We force the model system with re-analysis data representing the present climate to evaluate the method of coupling and the impact on atmospheric as well as on wave parameters of introducing a two-way coupled system. The system can then be used to investigate the wave fields in a changing climate if it is forced by climate simulations at the boundaries. There are few investigations using coupled wave-atmosphere models for climate purposes, and very few try to include the impact of swell on the atmosphere in a realistic way.

2 Theory

The communication between the atmosphere and the underlying surface is usually expressed by the friction of the surface or the surface drag – this represents the transport of energy from the atmosphere to the waves. In the atmosphere one usually assumes a constant flux layer and that the Monin-Obukhov similarity theory (MOST) is valid. This means that the wind stress can be expressed as:

$$\tau = \rho_a u_*^2 = C_D U_{10}^2 \qquad (1)$$

Assuming that MOST is valid the wind speed profile is related to the friction velocity according to:

$$U(z) = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_0} - \Psi_m\right] \qquad (2)$$

and the neutral drag coefficient can be related to the roughness length as:

$$C_{DN} = \kappa^2\left(\ln\frac{z}{z_0}\right)^{-2}. \qquad (3)$$

For the ocean surface the roughness length is often expressed by the Charnock equation [5]:

$$z_0 = \alpha\frac{u_*^2}{g}. \qquad (4)$$

Some studies show a Charnock coefficient depending on the state of the waves e.g. [6]. The state of the waves can be described by wave age, c_p/U_{10}. According to [7] the wave age at which waves are fully developed is $c_p/U_{10} = 1.2$. The wave age can also be described by c_p/u_*, where waves are considered fully developed for $c_p/u_* > 30$. We differentiate between three wave states:

growing sea: $\frac{c_p}{U_{10}} < 0.8$,

mixed sea: $0.8 < \frac{c_p}{U_{10}} < 1.2$,

swell: $1.2 < \frac{c_p}{U_{10}}$.

In a swell dominated wave field, the waves are not generated by the local wind. This is often the case during a decaying storm or when waves propagate from a distant storm. Since the swell waves travel long distances without fully dissipating it has been assumed that there is no transport of energy from the waves to the wind. Effects of swell on the turbulence structure in the overlying airflow are supported by both measurements, DNS (direct numerical simulation) and LES (large eddy simulation) [8-11]. One of the effects of swell is seen in the drag coefficient. When the swell direction follows the wind direction (following swell) the drag coefficient is reduced [12-13]. In [4] and [21] new expressions for the reduced drag coefficient and for the roughness length were developed (Figure 1).

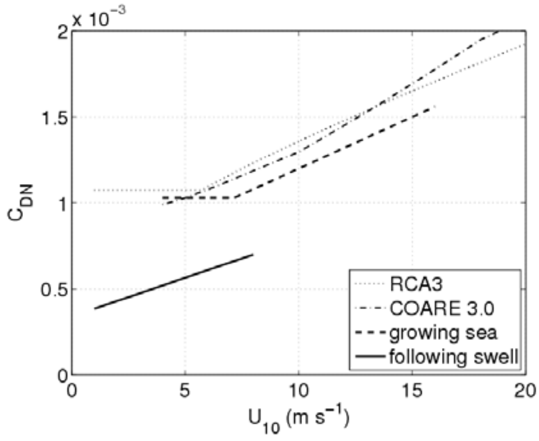

Figure 1. Drag coefficient for growing sea (dotted line show expression used in the original version of the RCA3 model, dashed-dotted line show the commonly used COARE algorithm [22] and dashed line the expression developed in [4]) and swell (solid line, expression developed in [4]).

Other deviations from MOST observed in the presence of swell include a low level wind maxima (e.g. [14]). The altered wind profiles with a low level wind maximum can also be reproduced by an analytical model, Figure 2 [15].

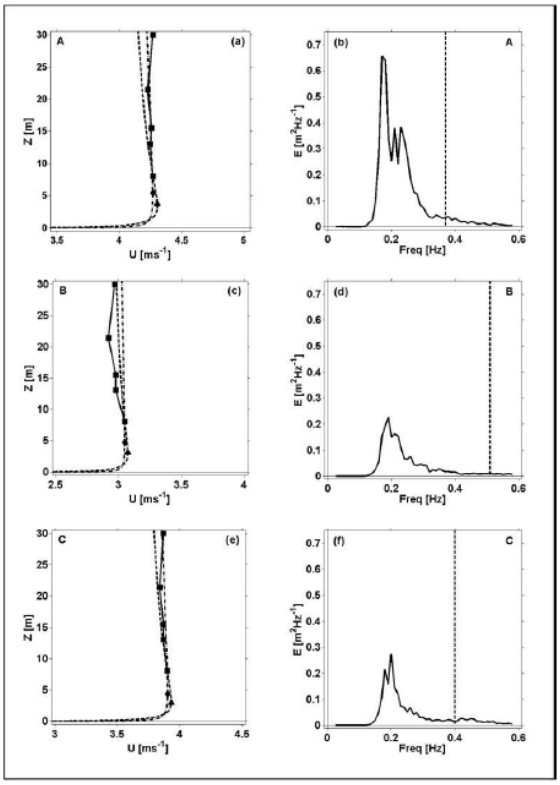

Figure 2. Measured (solid) and modeled (dashed and dashed-dotted using different relations for eddy-viscosity) wind profile for three situations with swell present (left). Measured wave spectra for the corresponding situations (right). The dotted vertical line represents the separation between the swell and young sea components of the wave spectra. Figure from [15].

3 Models

3.1 RCA

The atmosphere model RCA is developed at SMHI (Swedish Meteorological and Hydrological Institute) and its domain covers Europe (see Figure 3). It is a hydrostatic model, with terrain-following coordinates and the calculations are semi-Lagrangian, semi-implicit and with 30-min time step. The horizontal resolution is c. 50 km and resolved in the vertical by 24 levels between 90 m above the surface and 10 hPa. For the present study no present or future climate model is used for the boundary forcing to the RCA but reanalysis data from ERA40 [16]. The ECMWF (European Centre for Medium range Weather Forecasts) reanalysis uses all available observations integrated into a 3D model to give the best possible gridded data base on atmospheric parameters. The purpose of using reanalysis data is to evaluate the model system and investigate the impact on the atmosphere as well as on the wave field in using a coupled system. For more details on the model, see [17].

3.2 Wave model - WAM

The wave model WAM is a state-of-the-art third generation wave model designed for ocean wave modelling [18-19]. The WAM model is based on the spectral energy balance equation, which describes the evolution of the wave spectrum as the sum of the local wind input, wave dissipation, nonlinear wave-wave interaction and the propagation of waves from non-local sources. The wave transport equation is explicitly solved without prior imposed restrictions on the shape of the wave spectrum:

$$\frac{\partial}{\partial t}F(f,\theta)+\nabla\cdot\left(c_g F(f,\theta)\right)=S\,, \qquad (5)$$

where the source term is given by

$$S = S_{in} + S_{ds} + S_{bot} + S_{nl}\,. \qquad (6)$$

Wind speed at 10 meters from the atmospheric model is used as input to the model. When having a limited domain as in the present study, information of propagating waves should also be introduced at the boundaries. This is, however, not included in this study.

For the semi-enclosed basins (Baltic Sea and Mediterranean) this has minimal direct impact on the wave field. Also for the North Sea the direct impact of swell propagating across the boundaries is very limited since the majority of swell is expected to be transported from the western boundary of the domain. For the Atlantic basin the impact can, however, be substantial. The expected impact on the results is an underestimation of the swell part of the wave spectra, especially in the outer part of the modeling domain.

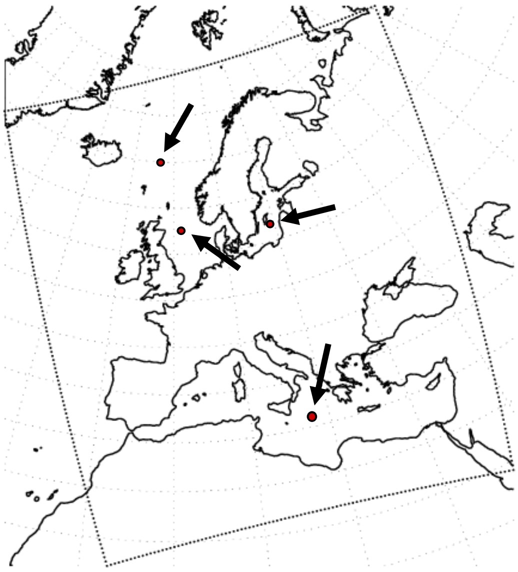

Figure 3. Dotted line shows the model domain for RCA and WAM used in the present study. Circles (with arrows) represent the four selected grid points investigated in detail.

3.3 Coupling

The models are coupled each time-step, using three different methods (C1, C2 and C3).

C1. One way coupling, the wave model is forced by the wind speed at 10 m and the information about the waves are not returned to the atmosphere.

C2. Two-way coupling, the wave model is forced by the wind speed at 10 m. A wave-dependent roughness length is calculated in the WAM-model and the value returned to the atmosphere. The roughness length is calculated using a sea state dependent Charnock coefficient following [20]:

$$\alpha = \beta \left(1 - \frac{\tau_w}{\tau} \right)^{-1/2} \qquad (7)$$

where $\tau_w = 0$ in the absence of surface waves. The constant β is chosen in such a way that the mean roughness for the one-way coupling (C1) and two-way coupling (C2) are approximately the same and that differences between the simulations should be due to the impact of the coupling and not by introducing a different roughness length.

C3. Two-way coupling, the wave model is forced by the wind speed at 10 m. The dominant phase speed of the waves and mean wave direction calculated in the wave model are returned to the atmosphere. The wave age is calculated in the atmospheric model using the wave parameter c_p/u_*. A wave-age dependent roughness length is calculated in the RCA using the following expression for the Charnock coefficient during wind-following swell:

$$\alpha = 0.0047 \left(\frac{c_p}{u_*} \right)^{-0.4} \qquad (8)$$

and when there is no swell present:

$$\alpha = 0.07 \left(\frac{c_p}{u_*} \right)^{-0.4} \qquad (9)$$

following the formulations in [21]. The constants in eq 8 and 9 (0.0047 and 0.07 respectively) are changed compared to [21] to have an average roughness length for wind sea agreeing with previous cases (C1 and C2).

It should here be noted that the reduction of surface roughness in the presence of swell is only taken into account in the third coupling method (C3).

4 Results

In a climate model (when there is no data assimilation) specific simulation periods always differ also for very minor differences in the model simulations (due to the chaotic nature of the atmospheric system). If the simulations are long enough for statistical significance it is more accurate to compare average differences or distributions of wave and atmospheric parameters than to compare actual time series. The coupled RCA-WAM system is run for a period of one year (December 1999 to November 2000) and the frequency distribution of wind speed and significant wave height is compared for four selected grid-points (Figures 4 and 5). Mean significant wave height, peak wave period and wind speed for the same grid-points and period are given in Table 1. When introducing the two-way coupling (C2) there are only small changes in the wave parameters or mean wind speed (Table 1). There is a reduction of mean significant wave height and a reduction in wave period. These results are in qualitative agreement with previous results [2-3] where a slight reduction in wind speed and significant wave height were seen in a two-way coupled wave-weather modelling system. There is also a redistribution in the frequency distribution (black and grey bars in Figures 4 and 5) with a decrease in the number of cases with very low wind speeds (except for in the Baltic Sea) as well as decreased number of very high wind speeds. There is mainly an increase in the number of very low significant wave heights and a decrease of situations with very high significant wave heights. The impact of introducing the reduction of surface friction due to swell in the two-way coupled system (C3) is significantly larger. For all the investigated grid points there is a redistribution towards more cases with higher wind speeds and thus also correspondingly higher waves (comparing black and white bars in Figures 4 and 5). This can also be seen as an increase in mean wind speed, mean significant wave height and mean wave period in Table 1. The increase of significant wave height and peak wave period is very large in the Mediterranean, which is in agreement with the swell dominance seen there in [21]. It can appear contradictory that when introducing the reduction of surface roughness in the presence of swell (mainly occurring for wind speeds below 8 ms^{-1}) the number of situations with high winds/high waves increases. One should, however, realise that the reduction of friction in one area leads to less energy transport from the atmosphere to the waves and to the possibility of higher winds (and corresponding more wave growth) at a later stage in the modelling simulation.

	C1	C2	C3
	H_s [m]		
Baltic Sea	0.99	0.98	1.03
Mediterranean	0.90	0.90	0.97
Atlantic	2.26	2.21	2.38
North Sea	1.77	1.73	1.85
	T_p [s]		
Baltic Sea	4.94	4.92	4.99
Mediterranean	5.35	5.34	5.44
Atlantic	8.79	8.68	8.94
North Sea	7.24	7.17	7.34
	U[ms^{-1}]		
Baltic Sea	7.1	7.1	7.3
Mediterranean	5.9	5.9	6.1
Atlantic	7.9	7.9	8.1
North Sea	8.1	8.1	8.3

Table 1: One year mean significant wave height (top 4 lines), peak wave period (middle 4 lines) and one year mean wind speed (bottom 4 lines) for the three coupling methods and four data points.

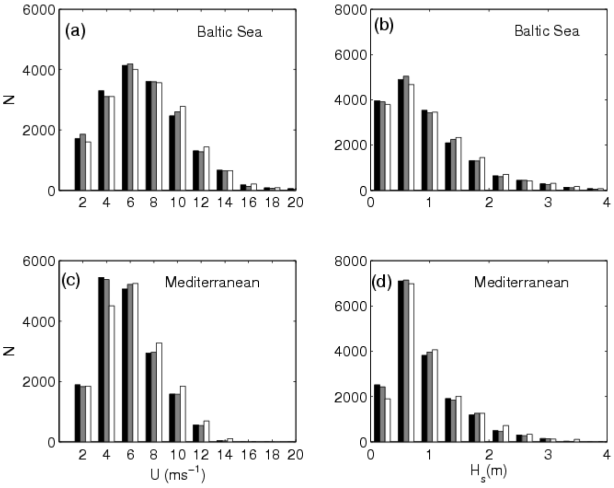

Figure 4. Frequency distribution of wind speed (a and c) and significant wave height (b and d) for two selected points (in Baltic Sea, 56º8.4'N 18º42'E, in a and b, in Mediterranean, 35º1.2'N 18º28'E in c and d). Black bars C1, grey bars C2 and white bars C3.

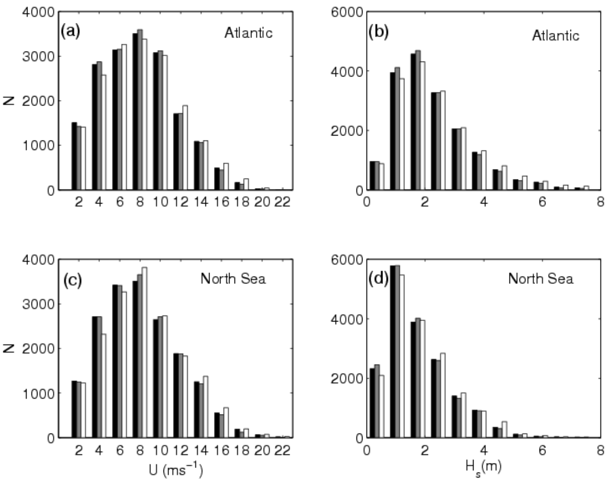

Figure 5. Frequency distribution of wind speed (a and c) and significant wave height (b and d) for two selected points (in the Atlantic, 65º34.2'N -1º54'E, in a and b, in the North Sea, 56º9.6'N 2º52'E, in c and d). Black bars are C1, grey bars C2 and white bars C3.

5 Conclusions

When using the coupled regional climate-wave model (RCA-WAM) forced by ERA-40 data on the boundaries, differences were shown in wind speed and significant wave height depending on the method of coupling. Using a two-way coupled system altered the frequency distribution for the four investigated grid-points, with slightly lower mean significant wave height. Introducing the reduced surface friction in the presence of swell in a two-way coupled system enhanced the mean wind speed, significant wave height as well as peak wave period for all of the investigated grid points. Changed surface roughness will also change the surface heat fluxes and potentially secondary parameters such as mixing, cloudiness and precipitation, circulation patterns in the atmosphere and depth of the mixed layer in an ocean model. Altered frequency distribution as well as average values of significant wave height and peak wave period for different regions may also have an impact on wave energy and wave resource assessment in different regions for present climate but also for potentially predictions in a changing climate.

Acknowledgements

Colin Jones, Ralf Döscher, Anders Ullerstig and others at SMHI for the use of the RCA model.

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