Royal Netherlands
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On the added value of coupled wind-wave-current modelling

A. Sterl

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Andreas Sterl

Koninklijk Nederlands Meteorologisch Instituut (KNMI)
P.O. Box 201, NL-3730 AE De Bilt, Netherlands
phone: +31-30-2206766; e-mail: sterl@knmi.nl

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Abstract

Tides, currents, wind, waves, and sea level (surge) influence each other in several ways. These interactions are often not accounted for. We here review some recent papers that report results from coupled modelling with the aim to get an impression of how large coupled effects might be, and in which regions and under which circumstances they might be significant. In general, the reviewed papers report an improved model performance if feedbacks between different models are accounted for. Based on this assessment a strategy for developing a coupled modelling system can be developed.

Revision: The original version (10 April 2018) contained an error in interpreting the results of Janssen et al. (2001). This error has been solved by slightly changing the wording in the first paragraph of Sect. 3.1.1, and by revising the conclusions (Sects. 3.1.5 and 5) and the Executive Summary accordingly.

Contents

Samenvatting

Atmosfeer (wind), hydrografie (waterstand en stromingen) en golven beïnvloeden elkaar. Onderzoek suggereert dat het meenemen van deze terugkoppeleffecten het resultaat van modelsimulaties verbetert.

Op de open zee blijkt de koppeling tussen atmosfeer en golven het grootste effect te hebben. Deze koppeling wordt veroorzaakt doordat de windschuifspanning (stress) afhangt van de toestand van het zeeoppervlak (sea state). Jonge en steile golven onttrekken bij dezelfde windsterkte meer impuls aan de atmosfeer dan oude en gladde golven. Het netto effect is een reductie van de windsnelheid en de golfhoogte in de orde van 10% onder storm condities. De effecten zijn grootschalig, maar het effect op de golven lijkt te verdwijnen in ondiep water. Helaas onderzoeken de gereviewde publicaties niet het effect van de veranderde windsterkte op de waterstanden, en ze vermelden ook niet hoe de *stress* verandert. De kennis van de stress is nodig om de invloed van de atmosfeer-golf interactie op de waterstanden te kunnen schatten.

De verticale impulsflux (stress) vanuit de atmosfeer gaat voornamelijk naar het golfveld, van waar het het grootste deel direct doorgegeven wordt naar de stroming. Een klein deel van de impuls wordt door de golven getransporteerd en langs de kust afgegeven. Het effect hiervan op de waterstanden dient nader onderzocht te worden.

In ondiep water, zoals de Waddenzee, bepaalt de actuele waterstand de wrijvingsverliezen van stromingen (bv het getij) en golven (breking), waardoor de interactie tussen stromingen, waterstand en golven belangrijk wordt. Het meenemen van deze effecten *verhoogt* de golven en de waterstanden en leidt tot een betere overeenstemming tussen modeluitvoer en waarnemingen. Omdat het water voor de kust ondiep is, hebben deze koppelingseffecten een directe impact op de beoordeling van de kustveiligheid.

In principe kunnen deze koppelingseffecten in een recalibratie van bijvoorbeeld de dragcoefficiënt in ondiep water verdisconteerd worden. Echter zou dit inconsistenties en nieuwe onzekerheden in de modelketen kunnen introduceren omdat de calibratie plaatsafhankelijk kan worden.

Voor zover onderzocht blijkt de (horizontale) resolutie een belangrijke factor te zijn om goede modelresultaten de verkrijgen. Dit geldt met name in de Waddenzee en de estuaria met hun nauwe zeegaten en een grote ruimtelijke variatie van waterdieptes. Echter, het belang van resolutie is niet beperkt tot de water- en golfmodellen. Ook de resolutie van het aandrijvende windveld is belangrijk. Een hogere resolutie betekent hier grotere lokale windsnelheden, een grotere ruimtelijke variabiliteit en een betere representatie van de kustlijn.

Uit deze samenvatting kunnen de volgende aanbevelingen afgeleid worden:

- Onderzoek de gevolgen van de atmosfeer-golf koppeling op de stress, en in het verlengde ervan op de waterstanden.
- Onderzoek het effect van impulstransport door de golven op de waterstand.
- Verhoog de resolutie van modellen langs de kust, en investeer in de koppeling van verschillende modellen (atmosfeer, golven, stromingen), rekening houdend met ondiep-water effecten.

De eerste aanbeveling kan relatief makkelijk geïmplementeerd worden door een bestaand model (bv IFS/WAM van het ECMWF) met en zonder koppeling te draaien. Voor het volgen van de tweede aanbeveling is een gekoppeld golf-oceaan model nodig. De implementatie van de derde aanbeveling vereist een langdurige inspanning, waarbij modelverbeteringen (parameterisaties), koppeling en resolutieverhoging en hun wederzijdse impact onderzocht moeten worden.

Executive Summary

Atmosphere (wind), hydrography (water level and currents) and waves influence each other. Published evidence indicates that taking these feedbacks into account by using coupled models improves model performance.

It appears that in the open sea the coupling between atmosphere and waves has the largest coupling effects. This coupling accounts for the fact that the stress is sea-state dependent, with younger and steeper waves extracting more momentum from the atmosphere than older and smoother waves. The net effect is a reduction of the wind speed and the wave height in the order of 10% under storm conditions. The effects are large-scale, but the impact on wave heights seems to vanish in shallow water. Unfortunately, none of the reviewed papers investigate the impact of the wind changes on water levels, nor do they report on changes in wind *stress*, which could be used to estimate the effects on water levels.

The vertical momentum flux (stress) from the atmosphere primarily goes into the wave field, from where the largest part is directly released to the currents. A small part of the momentum is transported by the waves and released near the coast. The effect of this release on the water levels needs to be investigated.

In shallow water like the Wadden Sea, the actual water level determines frictional losses of currents (e.g., tide) and waves (breaking), making the interaction between currents, water level and waves important. Taking these effects into account leads to an *increase* of wave and surge heights, which compare better with observations. As shallow waters naturally occur along the coast, these effects impact the assessment of coastal safety.

In principle, these shallow water effects can be taken into account indirectly, e.g., by recalibrating the drag coefficient in shallow water. However, this could introduce new inconsistencies and uncertainties in the modelling chain as the calibration may become location dependent.

Resolution is found to be an important factor in obtaining good model results. This is especially true for the Wadden Sea and the estuaries with their narrow tidal inlets and high spatial variability of water depth. However, the importance of resolution is not limited to the ocean and wave models. The spatial resolution of the forcing (wind) field is important, too. Higher resolution means higher instantaneous winds, higher spatial variability and better representation of the coastline.

This summary leads to the following recommendations:

- Investigate the impact of atmosphere-wave coupling on stress, and the ensuing effect on water levels.
- Investigate the effects of the momentum transport by waves on modelled water levels.
- Increase the model resolution along the coast and invest in the coupling of different models (atmosphere, waves, currents), taking shallow-water effects into account.

The first recommendation can be implemented relatively easily by running an existing model (e.g., IFS/WAM of ECMWF) with and without coupling. A coupled wave-ocean model is needed for the second recommendation. The implementation of the third recommendation asks for a long-term effort to investigate improved model parameterizations, coupling and increased resolution and their mutual impact.

1 Motivation

Tides, currents, wind, waves, and water level influence each other in several ways as schematically depicted in Fig. 1. The water movement (currents and waves) is caused by the winds in the atmosphere. They exert a stress on the water surface, which means that horizontal momentum is transferred form the atmosphere to the ocean, and the water is set into motion. The stress depends on the *relative* velocity between atmosphere and ocean, the surface roughness, the air density (i.e., temperature) and the atmospheric stability. The stability dependence is only important at low wind speeds and will not be considered further. Waves transfer most of their momentum to the ocean, inducing currents, and increase the water level at the coast due to wave set-up.

In most cases the interaction is in both directions, but not all interactions are equally important. All feedbacks from water level on other phenomena are only important in shallow water, where *relative* water level changes are large. Currents and water level are so intimately related that they cannot be modelled in isolation.

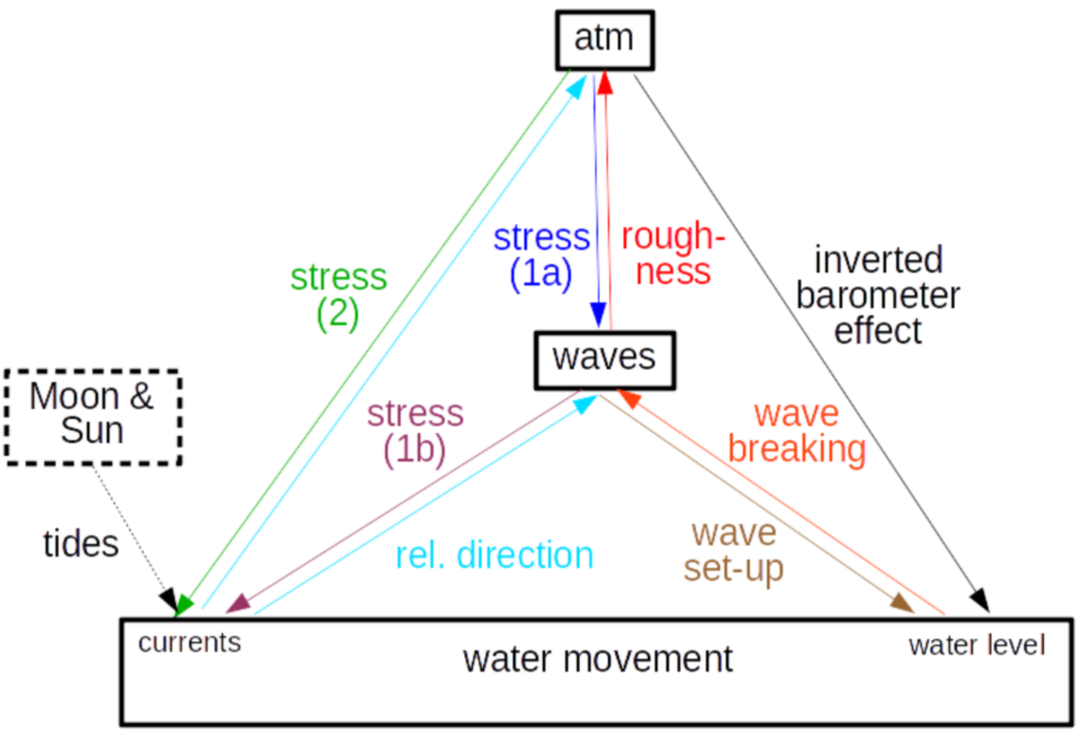

Figure 1: Mechanical interaction processes at the air-sea interface. The atmosphere (wind) exerts a stress (= vertical transport of horizontal momentum) on the water surface, which causes waves to grow (stress(1a)) and currents to flow (stress(2)). When breaking, the waves transfer their momentum to the currents (stress(1b)). Growing waves make the surface rougher, altering the stress exerted by the atmosphere on the ocean. Ocean currents change the relative velocity between water and waves, and water and wind. In the first case the wave steepness is impacted (Doppler effect), and in the second case the stress extracted from the atmosphere is changed. Currents influence the water level near the coast, and the water level influences the currents and the wave breaking. Currents and water level are so intimately related that they cannot be modelled in isolation. The water level is influenced by the atmospheric pressure through the inverted barometer effect, and wave set-up adds to the water level right at the coast. Finally, the currents are influenced by the externally imposed tidal forcing.

The transfer of momentum (stress) from the atmosphere to the waves and the currents requires some attention. It is common practise to calculate the momentum leaving the atmosphere, i.e., the stress exerted by the atmosphere on the ocean, and use that stress as input for both a wave and a circulation model. As momentum is conserved, this approach is fundamentally flawed. It can be justified by the fact that *most* of the momentum which is initially transferred to the waves is nearly immediately transferred to ocean currents by wave breaking. This implies that stress(1a) = stress(1b) = stress(2) in Fig. 1, essentially meaning that waves do not carry momentum. The impact of accounting for momentum carried by waves is discussed in Sect. 3.2.

Although wind, waves, and currents are intimately related and feed back on each other (Fig. 1), they are often modelled in isolation (uncoupled). An atmosphere model is run where the surface roughness only depends on wind speed, and the modelled wind is used to force a wave model or a circulation model. This approach is only valid if the feedback processes from the ocean to the atmosphere are small. This assumption is investigated in this report. Usually wind rather than stress is used to drive the ocean when running uncoupled models. In that case it is very important that the same stress parametrization is used in both models (Van Nieuwkoop et al., 2015). Often this requirement is not met.

From the discussion of the effects depicted in Fig. 1 a few important conclusions can be drawn:

- The effects depending on water depth are most pronounced in shallow water along the coast, where fractional changes in water depth due to tides and surges are large.
- The same is true for current-dependent effects. Currents in the open sea are usually small, but (tidal) currents can reach sizeable values in shallow water.
- As the wind stress depends on waves and currents, the drag coefficient is not a unique function of wind speed.
- The processes mentioned are not related in a simple cause-effect chain, but influence each other in various direct and indirect ways.

The last point suggests that in order to properly account for all the interactions, a modelling system has to be used in which all of them are represented simultaneously, i.e., a coupled atmosphere-ocean-wave system. However, before starting developing such a system, one must have an idea of the relative importance of the processes mentioned. To this end we here review some of the recent papers that report results from coupled models. Usually, they concentrate on one interaction at a time, e.g., waves & currents, or waves & water level.

2 Background

2.1 Atmospheric stress

The stress τ_{atm} exerted by the wind on the ocean is usually parameterized as

$$\tau_{\text{atm}} = \rho_a \, u_*^2 = \rho_a \, C_{D,z} \, U_z^2, \tag{1}$$

where ρ_a is the density of air, u_* the *friction velocity*, U_z the wind speed at a height z above the sea surface, and $C_{D,z}$ the corresponding *drag coefficient*. Usually, $z = 10$ m is used as the reference height, and this value is used here. For convenience, we will use the abbreviation C_D for $C_{D,10}$.

Over a flat surface the wind profile is logarithmic (see Tennekes, 1973),

$$U(z) = \frac{u_*}{\kappa} \ln(\frac{z}{z_0}), \tag{2}$$

where $\kappa = 0.41$ is the von Kármán constant and z_0 the *roughness length*. Together with (1) this gives

$$C_D = \left(\frac{u_*}{U_{10}}\right)^2 = \frac{\kappa^2}{\ln^2\left(\frac{10}{z_0}\right)}. \tag{3}$$

Over land, the surface does not change its shape, and the roughness length is constant in time, while varying in space. However, the roughness of the sea surface depends on the sea state. The varying roughness length is usually parameterized as

$$z_0 = 0.1\frac{\nu}{u_*} + \alpha\frac{u_*^2}{g}, \tag{4}$$

where ν is the kinematic viscosity of air, g the acceleration due to gravity, and α the *Charnock parameter*. The first term in (4) describes the effect of viscosity on the roughness and is only relevant at low wind speeds. The second term in (4) has been introduced by Charnock (1955) and is meant to describe the effect of the sea state. Usually, the Charnock parameter is treated as a constant, which implies a one-to-one relation between wind and roughness and, consequently, stress.

2.2 Wave stress

In wave modelling, waves are usually described by the *energy density spectrum* $E(\vec{x};\omega,\varphi)$. For each position $\vec{x}$ it specifies the amount of energy at (angular) frequency ω and travelling in direction φ. The development of the energy density spectrum is described by the energy balance equation

$$\frac{\partial E}{\partial t} + \vec{\nabla}\cdot(\vec{c}_g E) = S_{\text{in}} + S_{\text{nl}} + S_{\text{dis}} + S_{\text{bot}}. \tag{5}$$

The first term on the left describes the change of the energy density E with time, and the second the advection of energy with the group velocity c_g. The terms on the right are the source terms:

S_{in} energy input from the wind

S_{nl} redistribution of wave energy by non-linear four-wave interaction to higher and lower frequencies. High-frequency waves will break (dissipation, S_{dis}), while low-frequency waves gain energy and grow. Together, these two effects result in a shift of the peak frequency of the energy spectrum.

S_{dis} loss of wave energy through dissipation (whitecapping)

S_{bot} loss of wave energy interaction with the bottom: friction, depth-induced breaking and non-linear three-wave interactions.

The magnitude of the three source terms S_{in}, S_{nl}, S_{dis} and their sum is shown in Fig. 2 for young (3 hours after storm onset) and old (96 hours after onset) wind sea. For young sea the wind input is larger than for old sea. Young sea is steeper (rougher) than old sea. In both cases a large part of the wind input is directly lost to the ocean via whitecapping (dissipation). Despite the large loss young waves still gain energy ($S_{\text{tot}} > 0$ if integrated over frequency) and grow. For old waves the loss is nearly complete ($S_{\text{tot}} \approx 0$), and the waves do not grow any more.

The wind input source term leads to the wave-induced stress (Janssen, 1991)

$$\vec{\tau}_{\text{wav}} = \int_0^{2\pi}\int_0^{\infty}\frac{\vec{k}}{\omega}S_{\text{in}}\,d\omega\,d\varphi, \tag{6}$$

where $\vec{k}$ is the wave vector. Replacing S_{in} in this equation by S_{dis} or S_{bot} yields expressions for $\vec{\tau}_{\text{dis}}$ and $\vec{\tau}_{\text{bot}}$, which describe the momentum *lost* by the waves due to dissipation and bottom effects, respectively.

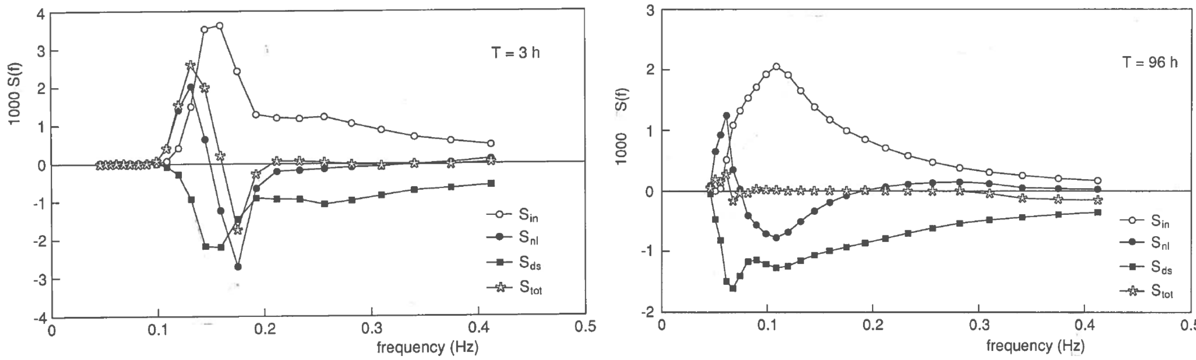

Figure 2: The energy balance for (*left*) young duration-limited sea (3 hours after storm onset) and (*right*) old wind sea (96 hours after onset) in deep water ($S_{\mathrm{bot}} = 0$). (These are Figs. 3.9 and 3.10 from Komen et al., 1994.)

2.3 Oceanic stress

Eq. 1 specifies the momentum $\vec{\tau}_{\mathrm{atm}}$ that leaves the atmosphere. On the ocean side, it is distributed between waves ($\vec{\tau}_{\mathrm{wav}}$) and currents ($\vec{\tau}_{\mathrm{oce}}$),

$$\vec{\tau}_{\mathrm{oce}} = \vec{\tau}_{\mathrm{atm}} - \vec{\tau}_{\mathrm{wav}}. \tag{7}$$

However, waves lose momentum to the ocean through dissipation, be it whitecapping on open sea or bottom-induced breaking closer to the coast. The accompanying stresses $\vec{\tau}_{\mathrm{dis}}$ and $\vec{\tau}_{\mathrm{bot}}$ are added to the ocean as well, so that (note that S_{dis}, $S_{\mathrm{bot}} < 0$ as waves *lose* energy)

$$\vec{\tau}_{\mathrm{oce}} = \vec{\tau}_{\mathrm{atm}} - \vec{\tau}_{\mathrm{wav}} - \vec{\tau}_{\mathrm{dis}} - \vec{\tau}_{\mathrm{bot}} \tag{8}$$

is the momentum received by the ocean. Besides friction the bottom term $\vec{\tau}_{\mathrm{bot}}$ also contains a part that is known as the *wave radiation stress.* It provides an extra force on the water movement in shallow water, leading to the *wave set-up*, an increase of the water level due to the presence of waves.

As momentum is transported by the waves, $\vec{\tau}_{\mathrm{dis}}$ and $\vec{\tau}_{\mathrm{bot}}$ can affect the ocean far away from the place where the waves were created by $\vec{\tau}_{\mathrm{wav}}$. However, as discussed in Sect. 2.2, most of the energy (and thus the associated stress) going into the waves is directly lost to the ocean. Only young waves absorb a small part of the input and carry it away.

Neither the partitioning (7) of the atmospheric stress into a part acting on the circulation and a part acting on the waves, nor the release of momentum from the waves to the ocean (8) is usually not taken into account when forcing an ocean circulation model. Instead, the total atmospheric stress (1) is applied to the ocean. The practical reason for this neglect is that using (8) requires running a wave model even if one is only interested in the circulation. The scientific justification is that most of the stress going into the waves is immediately lost to the ocean. Only young waves retain some of the stress and carry it away to finally release it near the coast ($\vec{\tau}_{\mathrm{bot}}$). An impact of using (8) rather than the total atmospheric stress $\vec{\tau}_{\mathrm{atm}}$ when forcing an ocean circulation model is therefore only expected near intensifying or moving storms (young sea) and along the coasts. However, such situations are particularly important for high water levels, and the consequences of momentum transport by waves on water levels need to be investigated.

2.4 Other effects

There are some other effects that affect the atmospheric stress.

- According to (1), the stress is proportional to the air density ρ_a, which is temperature and pressure dependent, but often treated as constant. Between 0 and 20°C, the density varies from 1.2922 kg/m^3 to 1.2041 kg/m^3, a difference of about 7%.

- The linear dependence of the density on pressure (Ideal Gas Law) accounts for a 5% variation over a 50 hPa range, which can be considered as typical for the North Sea.

- Furthermore, equations (2) and (3) are only valid for neutral atmospheric stratification. In stable (unstable) conditions the drag coefficient is smaller (larger) than the value given by (3) (see Komen et al., 1994, p 58 and p 270).

The impact of temperature and pressure on density (first two points) can be reduced by choosing a reference air density that is typical for winter storms on the North Sea, minimizing the actual deviations between reference and actual densities, respectively. The effects of stability (third point) are small at high wind speeds, which are most relevant for coastal safety considerations. Therefore, these effects are not considered further in this report, but they might become important in specific cases, for instance for a storm occurring during unusually warm conditions.

3 Literature review

In this section we review some recent papers using coupled models to investigate interactions and feedbacks between atmosphere, ocean and waves. As the papers usually concentrate on one interaction at a time, e.g., waves & currents, or waves & water level, we group papers accordingly. Where possible, each review is preceded by a short summary of the models used and the main findings.

3.1 Atmosphere-waves

3.1.1 ECMWF model

Usually, the Charnock parameter α in (4) is treated as a constant. Values cited in the literature vary between 0.014 and 0.034. This large spread partly results from the fact that the roughness depends on the sea state, but that the sea state has no one-to-one relation with the wind speed. When, at a given wind speed, the waves are still growing, they extract more momentum from the atmosphere than if they have reached an equilibrium. This is the reason why, since 1998, ECMWF's forecast system includes a wave model. Following Janssen (1989, 1991), they calculate α as

$$\alpha = \frac{\hat{\alpha}}{\sqrt{1 - \tau_{\text{wav}}/\tau_{\text{atm}}}}, \qquad \hat{\alpha} = 0.006, \tag{9}$$

where τ_{wav} and τ_{atm} are the moduli of the respective stresses. As the calculation of $\vec{\tau}_{\text{wav}}$ requires the wave spectrum to be known, ECMWF use a coupled atmosphere-wave model for their weather forecasts.

Janssen and Viterbo (1996) and Janssen et al. (2001) show that the coupling between atmosphere and wave models leads to decreasing wave heights in the mid-latitudes. At the same time the forecast skills both for both the atmosphere and the wave models increases. The improvement strongly increases with the resolution of the atmosphere model. At higher resolution the variability on small spatial scales is higher, and it is these scales that are important for wind-wave coupling.

3.1.2 Wahle et al. (2017)

atmosphere: COSMO-CLIM – 10 km

waves:	WAM (cy 4.5.4) – 5 km + 0.9 km in German Bight (nested)
ocean:	-
domain:	North Sea (60°N)
result:	2-way coupling reduces H_s and U_{10}, better agreement with obs; largest effect on open sea. Model resolution is very important.

A North Sea version of WAM is driven by winds from the regional climate model COSMO-CLIM, which covers the larger North Sea area (Fig. 3). In the one-way coupled version, WAM is driven by winds from COSMO-CLIM. In the two-way coupled version, surface roughness information from WAM (see (9)) is passed back to COSMO-CLIM, thus altering the winds.

The German Bight region is additionally covered by a high-resolution (0.9 km) WAM version which receives its boundary conditions from the larger model. It is forced by the COSMO-CLIM winds, but no roughness information from the high-resolution wave model is passed to the atmosphere. The two-way coupling is only done through the coarser resolution version. The German Bight version of WAM includes parameterizations of shallow-water effects (depth induced wave breaking and depth refraction), which lack in the North Sea version.

The coupled wave-atmosphere model system was used to simulate a 3-month period from October to December 2013. This period includes the time when storm Xaver (known as *Sinterklaasstorm* in the Netherlands) passed over the study area on 4 and 6 December 2013, and wind gusts exceeded 130 km/h (36 m/s). In the German Bight, the arrival of Xaver coincided in time with a high tide.

Averaged over the whole 3-month period, the two-way coupled model results are in better agreement with *in situ* and remotely sensed data of H_s and U_{10} than those from the one-way coupled model. The coupling results in lower values for H_s and U_{10} (see Fig. 4), and the effect is felt nearly everywhere. During storm Xaver, wave heights at the location of one buoy (Helgoland) decrease from more than 8 m to $\approx$ 7 m due to the coupling, matching the buoy measurements better. The corresponding 10 m wind speeds are lowered from $\approx$ 22 to $\approx$ 20 m/s. In addition to this extreme event, such large differences between one- and two-way coupled model results are only observed for young seas (wave age well below 20).

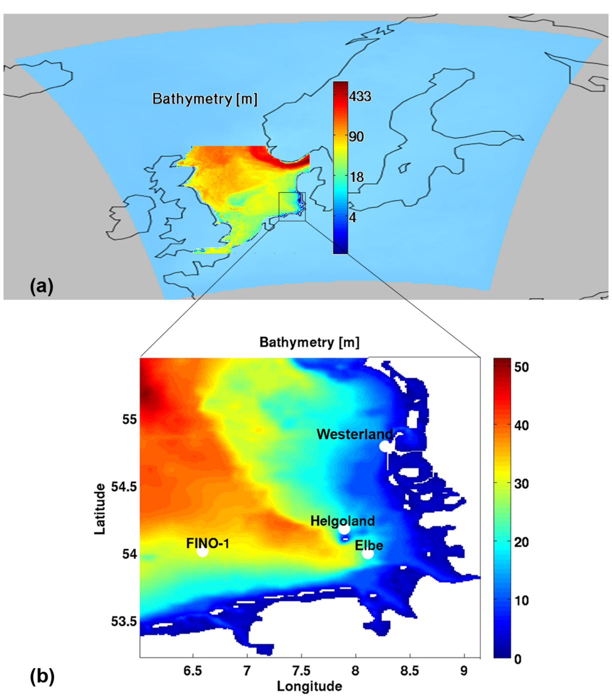

Figure 3: (a) Bathymetry (m; logarithmic scale) of the North Sea embedded in the COSMO model area (blue), and (b) bathymetry (m) of the German Bight as used in the WAM model. (This is Fig. 1 of Wahle et al., 2017).

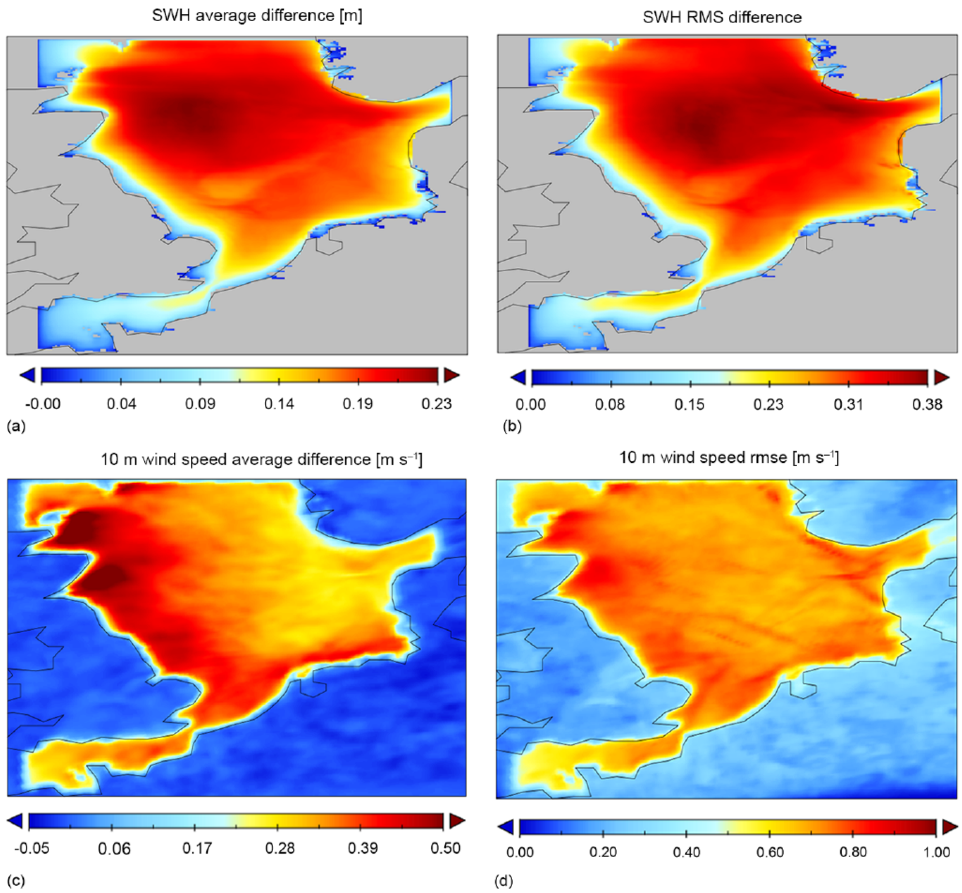

Figure 4: (a,c) Average difference and (b,d) rms difference of WAM modelled significant wave height (m, top panels) and COSMO modelled wind speed (m/s, bottom panels) when comparing one-way minus two-way coupled modelling results. The differences are calculated as averages over the whole 3-month period (Oct - Dec 2013) of the experiment. (This is Fig. 10 of Wahle et al., 2017).

Coupling increase the surface roughness in storm conditions. It is therefore easy to understand that the wind speed decreases. However, the impact on the stress and thus on wave height is less clear. One expects a compensating effect between reduced wind speed and increased roughness, and Janssen et al. (2001) even finds increasing wave heights.. It is unclear what the causes are for the reduced wave heights in Wahle et al. (2017).

It should be noted that wave height results from the 0.9 km German Bight domain are better than those from the 5 km North Sea domain, especially in shallow water, even in the one-way coupled case (i.e., the atmosphere model is run with a constant Charnock parameter). This demonstrates the importance of resolution, especially in shallow areas with strongly varying bathymetry, although the inclusion of shallow-water effects is also important. However, even for the high-resolution model results improve in the two-way coupled model, even though the wave information that is fed back to the atmosphere only stems from the coarse-resolution North Sea model.

3.1.3 Süld et al. (2015)

atmosphere: Harmonie/AROME (2.5 km)
waves: WAM (2.5 km)

ocean: -
domain: North Sea, Baltic, Scandinavia, part of Nordic Sea

This paper is a short conference proceeding and lacks detail. It only presents first results.

The Harmonie model is coupled to the WAM wave model following the approach explained in Sect. 3.1.1. The WAM grid is modified (rotated) so as to coincide with the Harmonie grid. Data assimilation is used in Harmonie.

Coupled and control (uncoupled) runs over a two month period in the winter of 2013/14 are presented. The general tendency of the coupling is to decrease wave heights and wind speeds, with the largest effects for areas/times of high wind speeds and wave heights. For one particular event a decrease of wind speed and wave height in the order of 10% (from > 25 m/s and > 12 m, respectively) is shown for a large area between Scotland and Norway.

When compared to measurements, modelled wave heights, both in coupled and uncoupled mode, are worse than those from the coarser operational model run at MetNo. The authors state that there is a problem with the north-south propagation of the waves on the rotated grid. This problem must be solved before further conclusions can be drawn.

In general the reduction of wind speeds in the coupled model leads to a reduction of forecast errors. However, high wind speeds tend to be underestimated. The authors speculate that this may be a consequence of not accounting for the drag reduction at very high wind speeds (Sterl, 2017).

3.1.4 Shimura et al. (2017)

atmosphere: MRI-AGCM (1.125°)
waves: WW3 (1.125°)
ocean: -
domain: global

The impact of wave-dependent roughness length on the climate of an AGCM is investigated. Seven climate runs for the period 1990-2014 are performed with prescribed SST and sea-ice extent. Five of them use a Charnock formulation for z_0 (i.e., eq. (4), no coupling to a wave model) with different values for the Charnock parameter α (0.001, 0.005, 0.01, 0.02, and 0.03). The other two runs employ two different wave-dependent roughness length parameterizations, namely those of Taylor and Yelland (2001) and Drennan et al. (2003). In the first one the roughness length depends on wave steepness,

$$\frac{z_0}{H_s} = A_1 \left(\frac{H_s}{L_p}\right)^{B_1}, \tag{10}$$

where H_s is the significant wave height and L_p is the peak wavelength of the wave spectrum, and $A_1 = 1200$ and $B_1 = 4.5$ are tuning coefficients. In the second case z_0 depends on the wave age,

$$\frac{z_0}{H_s} = A_2 \left(\frac{u_*}{c_p}\right)^{B_2}, \tag{11}$$

where c_p is the peak phase speed of the wind-sea component, and the tuning coefficients attain the values $A_2 = 3.35$ and $B_2 = 3.4$. Note that both parametrisations only depend on an integral property of the spectrum (respectively L_p and c_p), while (9) depends on the spectrum itself.

Using the wave-dependent roughness length increases U_{10} in the tropics by up to 15%, leading to a closer correspondence with observed winds. The changed winds result in changes of the Hadley circulation and, consequently, precipitation patterns. The reason for the large impact

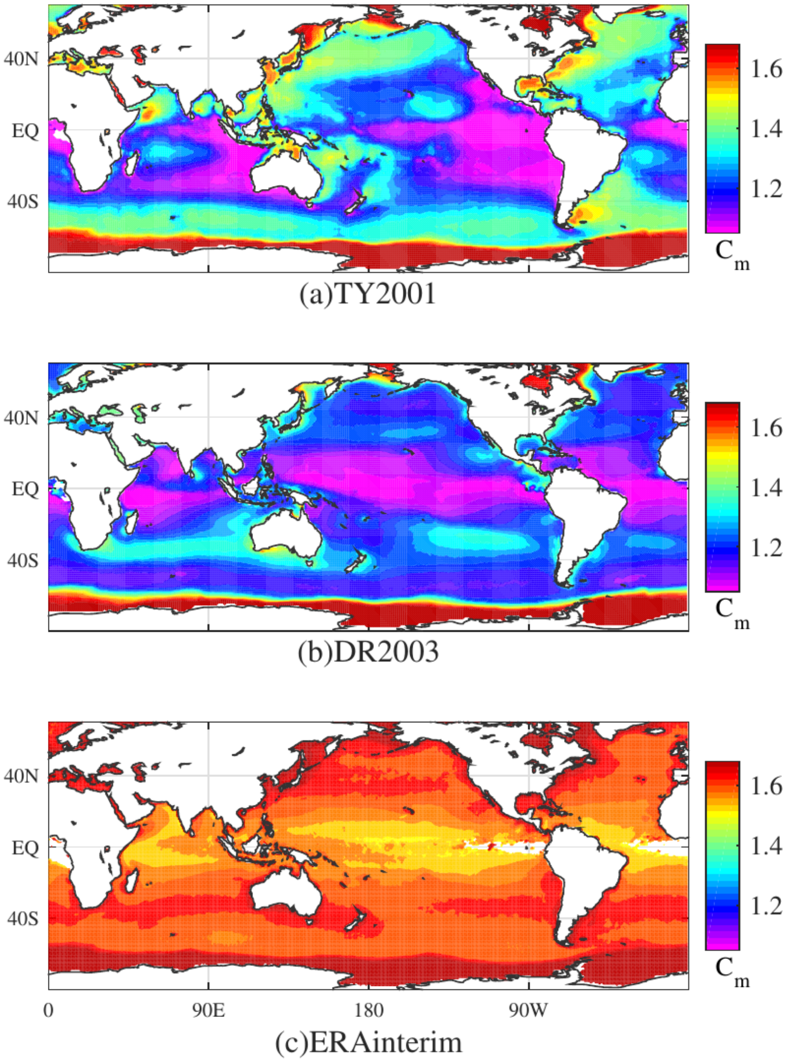

Figure 5: The spatial distribution of C_D climatology for wind speeds under 10-10.25 m/s for (a) the Taylor and Yelland (2001) parameterization, (b) the Drennan et al. (2003) parameterization, and (c) ERA-Interim. (This is Figure 3 of Shimura et al., 2017.)

in the tropics is that they are dominated by swell, which is relatively smooth and not steep, so that z_0 decreases.

While wind speeds in the tropics are better simulated with wave-dependent roughness length, they are deteriorated in the mid to high latitudes. The authors attribute this mixed result to the fact that "the global ocean displays a wide range of climatology and wave characteristics. There are swell dominated areas, wind-sea dominated areas, high and low wave age areas, high and low wave height (wind speed) areas, and so on." They conclude that "ocean wave-dependent roughness parameterizations applicable to the global ocean with better performances need to be developed".

The authors compare the drag coefficients that they obtain with the two wave-dependent parameterizations with those from ERA-Interim (Dee et al., 2011), which parametrizes z_0 according to (9) and note that their values are lower and spatially much more variable than those from ERA-Interim (Fig. 5). Unfortunately, they fail to show a comparison between their winds and those from ERA-Interim.

3.1.5 Summary atmosphere-wave coupling

The available papers on atmosphere-wave coupling show a large impact of coupling on modelled wind speeds and wave heights. Both of them are decreasing, and the model performance when compared to observations increases in the coupled case. The effect of coupling is larger at high wind speeds, when a lot of young (steep) waves are generated, and larger in the open sea. In coastal areas resolution seems to be more important than coupling.

The reviewed papers focus on wave height and wind speed, but do not mention stress. However, it is reasonable to assume that compensating effects act to make relative stress changes smaller than wind and wave changes. During a storm more momentum is extracted from the atmosphere at a given wind speed as the surface is rougher than normal. In other words, the same stress is exerted at lower wind speeds (see also Sect. 5). At this stage it is therefore impossible to quantify the impact of coupled atmosphere-wave effects on storm surges. This knowledge-gap needs to be filled.

3.2 Waves-ocean

3.2.1 Alkyon (2009)

atmosphere: -
waves: SWAN
ocean: Delft3D
domain: Eastern Wadden Sea / Eems-Dollard estuary
resolution: ?

The paper analyses the performance of SWAN and Delft3D during the two-day period around the storm of 9 November 2007. Its focus is on the performance of SWAN, which suffers from problems with representing the propagation of low frequency storm-waves into the Eastern Wadden Sea and an under-prediction of wave growth in depth-limited situations. Including effects of wave-current interactions has only a marginal effect on modelled wave heights. However, inclusion of wave effects (radiation stress) significantly improves the simulation of water levels (Fig. 6). Breaking waves add momentum to the water, leading to a higher transport and thus higher water levels. This finding is consistent with the results of Staneva et al. (2016, 2017) (Sects. 3.2.3 and 3.2.4).

3.2.2 Bircheno et al. (2013)

atmosphere: WRF
waves: WAM (1.8 km)
ocean: POLCOMS
domain: Irish Sea
doc: `http://cobs.noc.ac.uk/modl/polcoms/`
result: "The combination of high-resolution atmospheric forcing and a coupled wave-surge model gave the best result."

Although there are three models involved in this research, only the wave (WAM) and the surge (POLCOMS) model are coupled. There is no feedback from the ocean to the atmosphere. The paper gives no details on the coupling. Instead, reference is made to an earlier paper (Brown et al., 2010) which suggests that coupling is mainly achieved through the impact of varying water levels and currents on wave evolution, and wave information is used to change the surface roughness.

The latter "coupling" is a bit strange: WRF is not coupled to the combined ocean-wave model, so the calculation of wind speed is *not* influenced by the wave conditions. However, when calculating the stress acting on the ocean models, this effect is taken into account. In this way an inconsistency between the stress in the atmosphere model and the stress forcing the ocean is created (cf. Van Nieuwkoop et al., 2015).

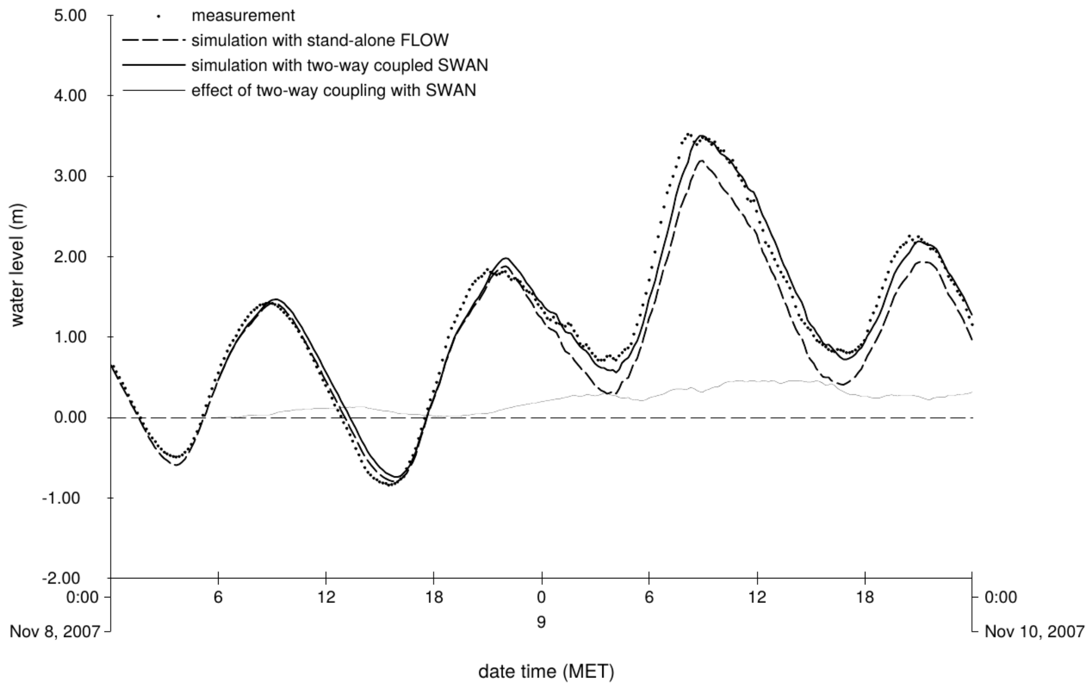

Figure 6: Comparison of simulated and observed water levels at station Schiermonnikoog between stand-alone Delt3D-FLOW and two-way coupled FLOW-SWAN simulations. (This is part of Fig. 3.8 of Alkyon, 2009).

The conclusion that "The combination of high-resolution atmospheric forcing and a coupled wave-surge model gave the best result" seems to refer to the effect of the wave-dependent Charnock parameter (although the description in the paper is not very clear).

3.2.3 Staneva et al. (2016)

atmosphere: -
waves: WAM (cy 4.5.4) – 5 km + 1 km (German Bight) – 200 m (Wadden Sea)
ocean: GETM (5.5 km – 1 km (German Bight) – 200 m (Wadden Sea))
domain: North Sea (60°N)
result: coupling improves model results

Flooding and drying of shallow sand plates (Wadden Sea) is taken into account. The wave model contains a parameterization of depth-induced wave breaking via the radiation stress. It is coupled to the hydrodynamic model via Stokes drift. (The description of the coupling is not very clear.)

Wave heights, wave periods, and currents from the coupled model compare better with observations than the corresponding results from uncoupled runs. The differences are largest in coastal areas, where wave variability increases by up to 30%. During storm Xaver (*Sinterklaasstorm* in the Netherlands; 5-6 December 2013) the coupled model produces water levels that are up to 40 cm higher than in the uncoupled ocean model (Fig. 7).

3.2.4 Staneva et al. (2017)

atmosphere: -
waves: WAM (3.7 km)
ocean: NEMO (3.7 km)

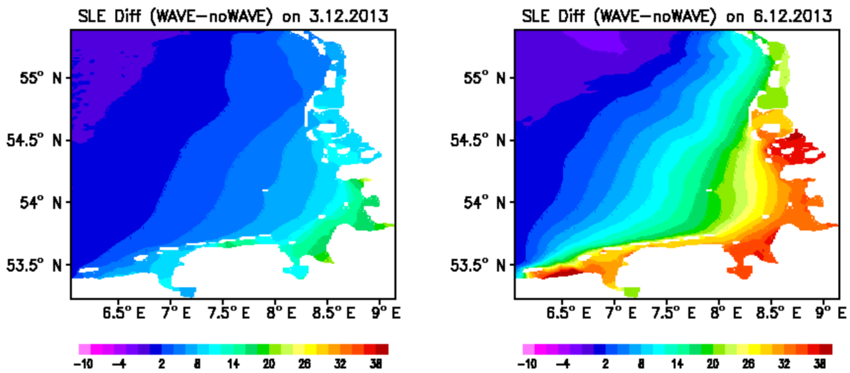

Figure 7: Sea level elevation difference (cm) between the coupled wave-circulation model (WAMGETM) and circulation only model (GETM) for the German Bight on 3 December 2013 at 01:00 UTC (left) and during the storm Xavier on 6 December 2013 at 01:00 UTC. (This is Fig. 6 of Staneva et al., 2016).

domain: North Sea (60°N) – without Wadden Sea
result: including wave effects increases surge heights and improves tidal currents

WAM and NEMO are coupled over the North Sea south of 60°N. Runs are performed for the period October-December 2013 (same as in Wahle et al. (2017), Sect. 3.1.2). In addition to the usual four source terms (wind input, non-linear interaction, white capping, bottom friction), WAM also contains a source term for depth-induced wave breaking.

Three wave effects that influence the ocean are considered,

- the Stokes-Coriolis forcing (STCOR), i.e., the impact of the Coriolis force on the Stokes drift,
- the air-sea momentum flux is sea state dependent according to (9), and the ocean-side stress is given by (8), i.e., the stress associated with the generation and dissipation of waves is accounted for in forcing the currents (TAUOC),
- sea-state dependent input of turbulent kinetic energy (TKE) into the mixed layer because of wave breaking (for details see Breivik et al., 2015).

Five runs are performed: A control run (CTRL), in which NEMO is run without coupling to WAM, a fully coupled run (ALL), in which all three processes mentioned are included, and one run for each of the processes. Note that the effects of the three processes do not add up linearly to the results of ALL.

The atmospheric forcing is obtained from "subsequent short-range forecasts from the regional atmospheric model COSMO-EU, operated by the German Weather Service (DWD)". No further details are given. As COSMO-EU is not coupled to the wave model, the wave-induced stress does not feed back on the atmospheric flow, probably leading to inconsistencies of the stresses (cf. Van Nieuwkoop et al., 2015).

The coupled model (ALL) produces up to 50 cm higher surge levels than the uncoupled model (CTRL) along the west coast of Jutland during storm Xavier (Fig. 8), and in the Elbe estuary during storm Christian (26-20 October 2013). The higher surge levels from ALL correspond better with observations than those from CTRL (Fig. 9). The largest contribution to the higher surges comes from TAUOC. As the difference is highest near the coast, the effect is probably due to the momentum input by wave breaking rather than the partitioning of the wind stress between waves and current.

Current velocities are also better reproduced by the coupled model.

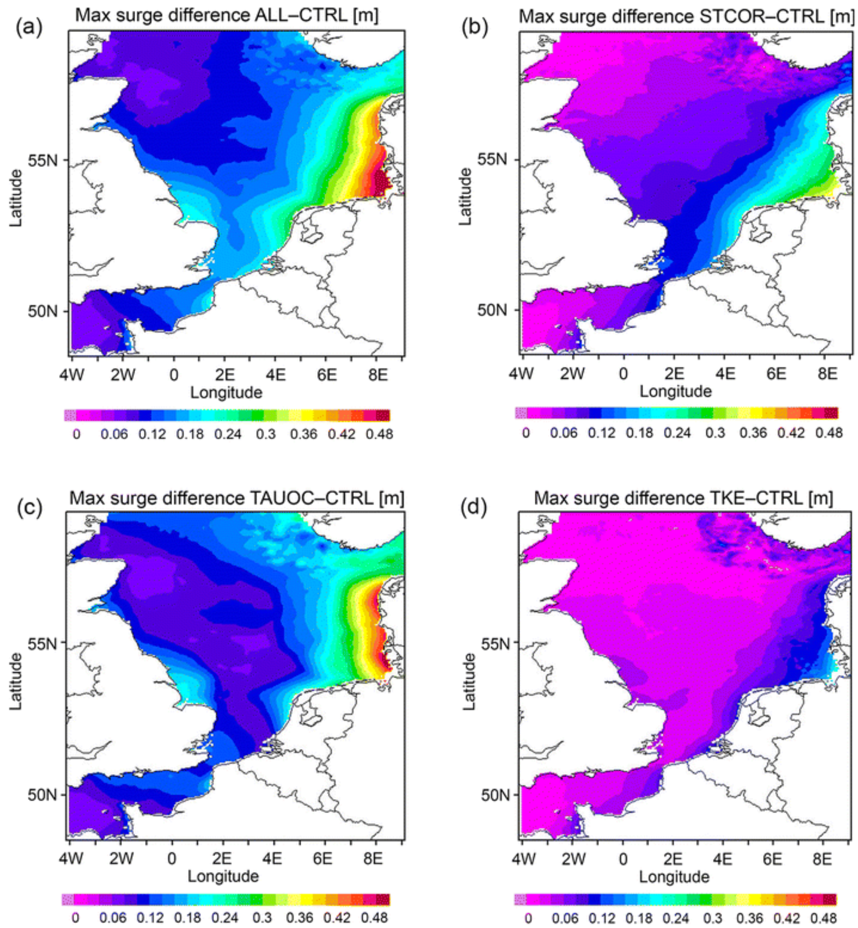

Figure 8: Maximum surge difference (m) during storm Xaver (5-6 December 2013) between (a) ALL and CTRL runs, (b) STCOR and CTRL runs, (c) TAUOC and CTRL runs and (d) TKE and CTRL runs. (This is Fig. 12 of Staneva et al., 2017).

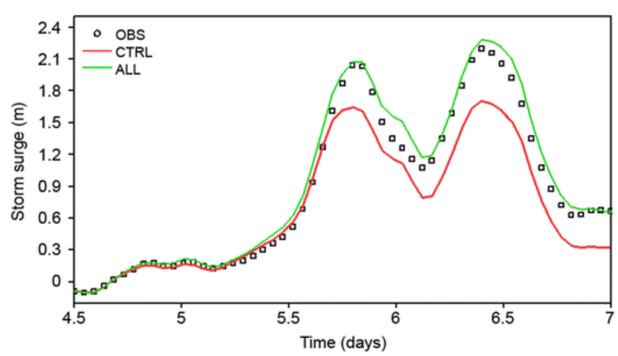

Figure 9: Observed (black squares) against computed storm surges for the circulation model only (CTRL run – red line) and the coupled wave-circulation model (ALL run – green line) during storm Xaver at station Helgoland. The x-axis corresponds to the time in days from 01 December 2013. (This is Fig. 10 of Staneva et al., 2017).

3.2.5 Arns et al. (2017, 2015)

atmosphere: -
waves: MIKE 21 FM HD
ocean: MIKE 21 FM HD
domain: North Sea (14°W, 64°N) (1 km)

Although Arns et al. (2017) use a coupled wave-ocean model, coupling effects are not the focus of this paper. Rather, it deals with the effect of mean sea level rise (SLR) on tides, surge heights and wave heights, and the resulting consequences for the height of coastal defence systems. It is assumed that the bathymetry does not change with mean SLR, resulting in relatively deep water along the coastline. The main conclusion is that extreme wave heights and water levels at the coast increase more than SLR (see Fig. 10). Therefore, coastal protection systems have to be strengthened more than to be expected purely from SLR. These results are backed by those from a preceding paper (Arns et al., 2015) in which only the surge-part of MIKE 21 FM was used. Increasing the global mean sea level by 54 cm resulted in an extra 15 cm of surge height in the shallow areas of the German Wadden Sea.

The result arises from a balance of some competing contributions.

- In deeper water, the atmospheric forcing acts over a larger water depth ($\vec{F}_{\text{atm}} = \frac{1}{h}\frac{\vec{\tau}_{\text{atm}}}{\rho_a}$), *reducing* the current speed.
- Similarly, the impact of bottom friction is reduced and the current speed *increased*.
- As the propagation speed c of the tidal wave depends on water depth ($c \approx \sqrt{gh}$), the tidal peak occurs earlier.
- The deeper water decreases off-shore wave breaking, allowing more waves to reach the shore, *increasing* wave set-up.

The reduced dissipation of the tidal wave due to the higher water depth leads to an increased tidal range.

Although dealing with externally imposed water level changes, these papers underscore the need for properly accounting for water level changes during a storm. During a storm, the water level is not externally imposed, but generated as part of it. Using a coupled model makes it possible to properly account for its effect.

At first sight, this result seems to be at odds with Sterl et al. (2009) and references therein, who find that surge height and mean water level add linearly. However, they use a surge model with a horizontal resolution of 8 km × 8 km that hardly resolves the shallow areas of the Wadden Sea, while Arns et al. (2017) use a horizontal resolution of 1 km × 1 km. So the result of Sterl et al. (2009) holds for coasts that are directly exposed to the open sea with relatively steep bathymetry, but not for shallow regions like the Wadden Sea.

3.2.6 Vatvani et al. (2012)

atmosphere: -
waves: SWAN
ocean: Delft3D
domain: Gulf of Mexico (0.1°) + 0.02°along coast of Louisiana (nested)
result: including wave effects increases surge heights

The main topic of this paper is the evaluation of different parametrisations of the drag coefficient (see Sterl, 2017) at high (hurricane strength) wind speeds. However, using a coupled wave-ocean model the authors note that "For scenarios where the surge compares best with data,

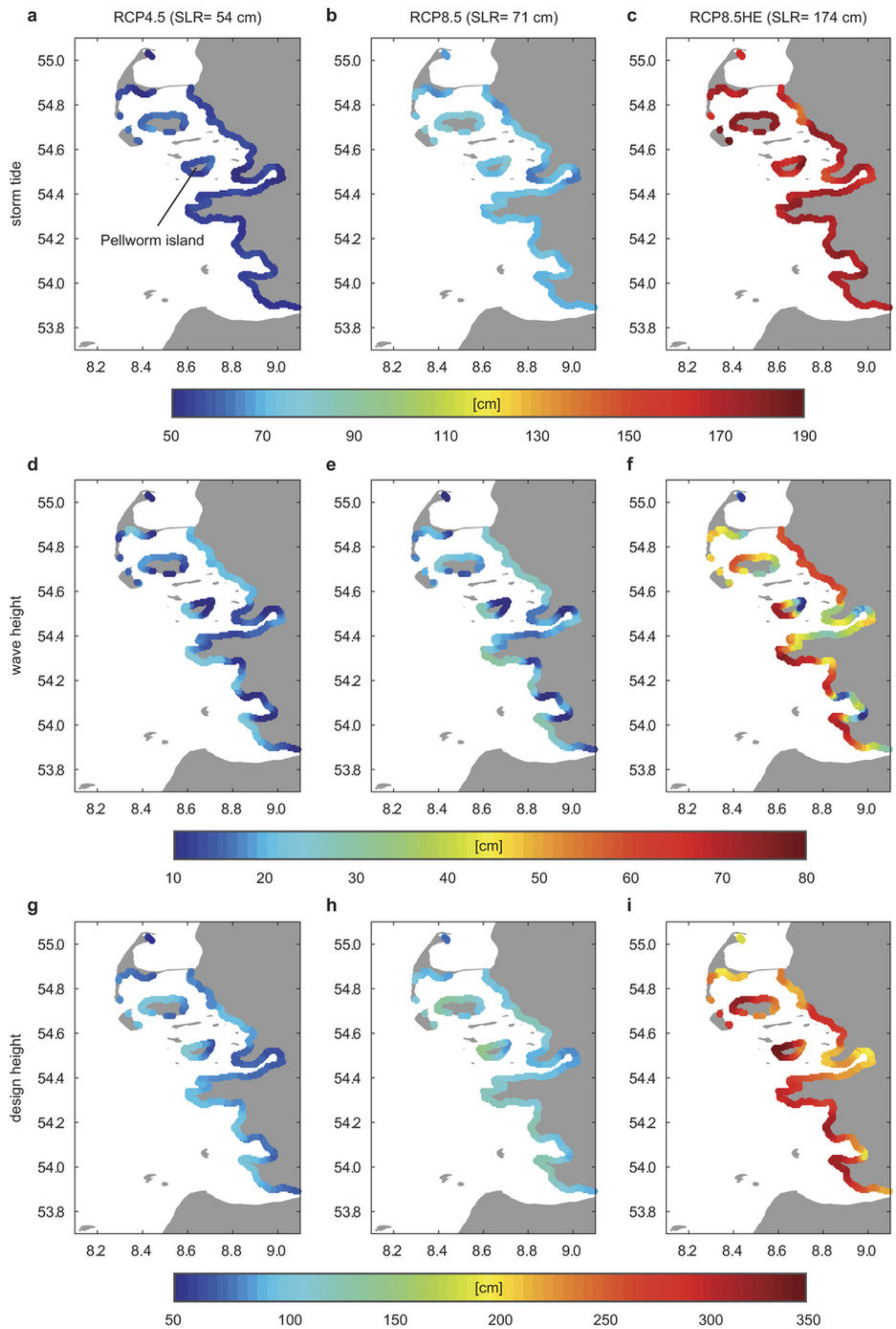

Figure 10: Absolute changes in the ARI_{100} (100-year average return interval) compared to historical (1970-2013) conditions (HIS) under RCP4.5 (*left*), RCP8.5 (*middle*), and RCP8.5HE (*right*; HE: high-end, including rapid ice melt in Antarctica) for storm tides (a-c), wave heights (d-f), and design heights (g-i). Note the different ranges in the colourbars. (This is Fig. 3 of Arns et al., 2017).

the contribution of the wave towards the setup in water level can reach up to 30% of the total surge." The coupling between waves and currents is thus very important. Note, however, that the maximum wind speeds used in these experiments exceed 70 m/s. This is much higher than wind speeds to be expected in the North Sea, and the wave impact on surge height might be much lower there.

3.2.7 Clementi et al. (2017)

atmosphere: -
waves: WW3 ($^1/_{16}$°)
ocean: NEMO ($^1/_{16}$°)
domain: Med Sea

The wave and the ocean model are coupled via surface currents. Wind forcing is calculated from operational ECMWF winds, taking into account the wave-induced stress as obtained from the wave model (i.e., using eq. (9)), as well as a stability correction. The latter decreases (increases) the driving wind speed in stable (unstable) situations and leads to decreased (increased) wave growth.

In the coupled model the wave-output verifies slightly better against observations than in the uncoupled WW3 model. This improvement is mainly due to the stability correction. The impact on the ocean model (current) is small and only visible during a high-wind event. The impact on water levels is not described.

3.2.8 Mao and Xi (2017)

atmosphere: -
waves: SWAN
ocean: ADCIRC (barotropic model) or FVCOM (3D model)
domain: Lake Michigan
resolution: unstructured grid; 340 m – 7.6 km

The aim of the paper is to investigate the impact of different forcings on model results, and to investigate wave-current-surge interactions (WSCI). To this end, SWAN/ADCIRC and SWAN/FVCOM are driven by winds from various sources and using different bulk formulas to translate wind into stress.

The general conclusions are that the inclusion of coupled effects slightly improves the modelled wave-induced setup and wave heights. Improvements in shallow areas are larger than those in deep water.

3.2.9 Wandres et al. (2017)

atmosphere: -
waves: SWAN
ocean: ROMS
domain: Indian Ocean off south-west Australia
resolution: 1 km

This paper studies the interaction between the waves and the strong Leeuwin Current that flows southward along the coast of south-western Australia, reaching surface velocities of more than 1 m/s. While the waves in this region usually propagate north-eastward, the Leeuwin Current forms large meanders, so that surface currents are sometimes running against the waves, and sometimes parallel to them. The model results reveal that the relative direction between waves and current can alter wave heights by up to ±25% (increasing for counter-currents, decreasing for aligned currents), and their direction by up to ±20%.

3.2.10 Other papers on wave-ocean coupling

The results on ocean-wave coupling presented in the preceding subsections are backed by several others. Sabatino et al. (2016) investigate coupling effects along the east coast of Scotland using the MIKE 3 FM / 21 SW combination. They find a strong impact of the coupling with wave height changes up to 2 m close to the coast. Hashemi and Neill (2014) and Hashemi et al. (2015) use a coupled ROMS-SWAN model to investigate the impact of tides (= water level) on wave power availability. They find a large improvement of the coupled model in simulating wave parameters at the west coasts of Ireland and Scotland, but hardly any impact in the North Sea.

3.2.11 Summary wave-ocean coupling

The reviewed papers report significant impacts of wave-ocean coupling on currents, wave heights and water levels (not all papers consider water level), which in general improve model behaviour. The effects are negligible in the open sea where currents are slow and relative depth changes due to varying water levels are small. At the coast, however, the impact on water level can be of the order of 10%. Sufficient horizontal resolution is needed to capture the coupling effects as they depend on water depth and current speed, which both depend on the resolution of the bathymetry.

3.3 Other papers

3.3.1 Ridder et al. (2018)

This paper investigates the impact of differences in atmospheric forcing fields on the performance of the WAQUA/DCSMv5 (Dutch Continental Shelf Model) surge model. It solves the two-dimensional shallow water equations for the North Sea basin to predict water levels along the coast of the North Sea. The model has a horizontal resolution of $1/12^\circ \times 1/8^\circ$, equivalent to ≈ 8 km $\times$ 8 km. Note that at this resolution the Dutch Wadden Sea is not resolved properly.

The surge model is driven by winds derived from the ERA-Interim reanalysis (Dee et al., 2011), which is available at a nominal resolution of ≈ 80 km at 6-hourly time steps. The resolution is degraded in space and time by smoothing, as well as upgraded by dynamical downscaling using the RACMO atmosphere model. This results in five different combinations of space-time resolution. These five wind fields are translated into stress using a constant Charnock parameter of $\alpha = 0.032$. This high value has been recommended before for use in the North Sea by Mastenbroek et al. (1993). In an additional experiment, using the nominal resolution, the stress is derived using a variable Charnock parameter according to (9) and (6). This variable Charnock parameter is also provided by ERA-Interim.

The main finding of the paper is

> We find no significant change in model performance due to the application of a more realistic representation of the drag coefficient using a wave-state dependent Charnock parameter which is in agreement with findings of previous studies (Mastenbroek et al., 1993). We do, however, find a clear improvement of model performance in regards to the reproduction of annual maxima, particularly those with high return periods, when applying dynamically downscaled forcing fields, which lead to a correction of the model low bias.

In other words, the resolution of the forcing wind field is much more important than the details of the stress parametrization.

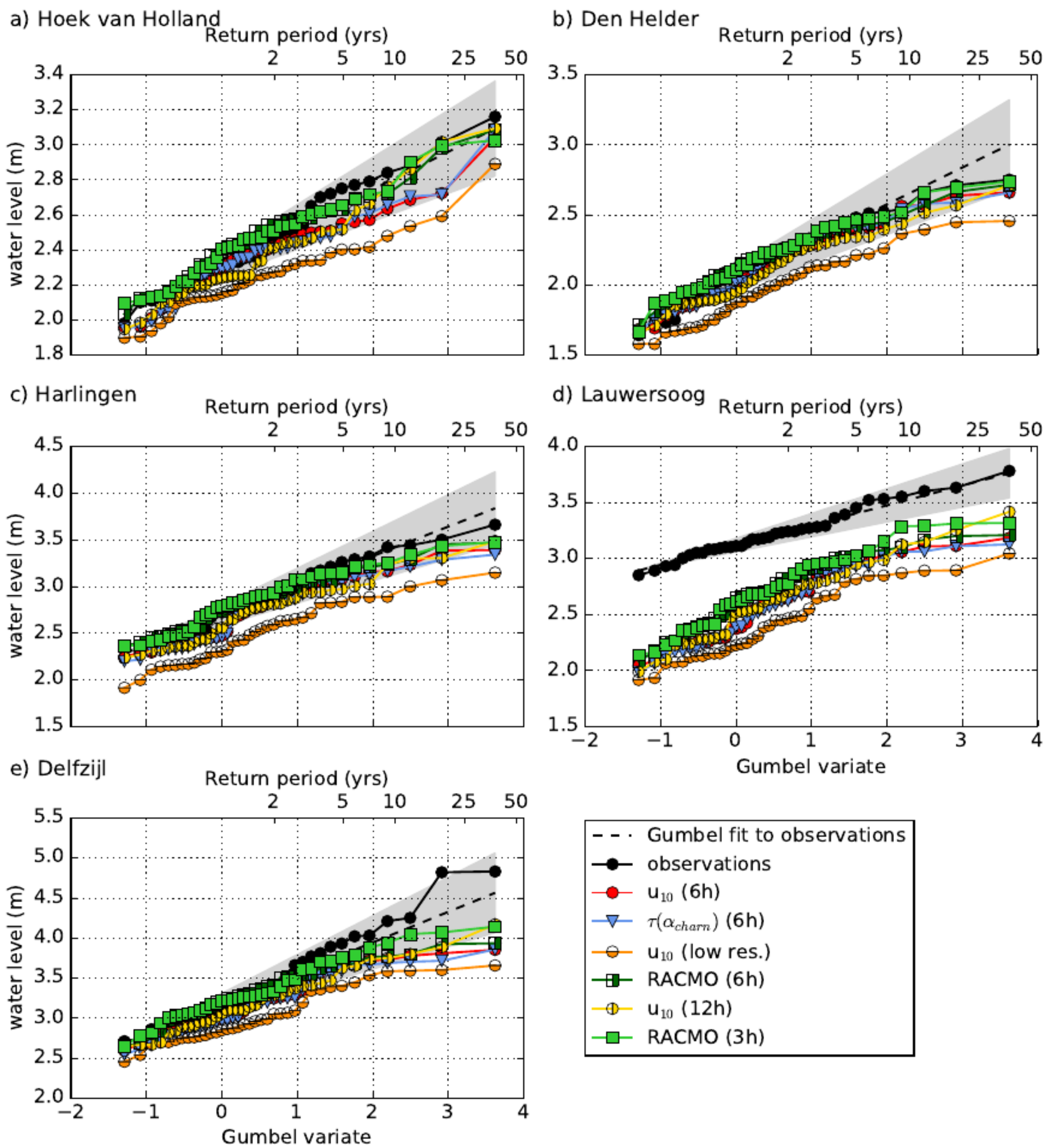

Figure 11: Gumbel plots of observed annual maximum total water levels (black circles) compared to the different experiments (u10(6h): nominal resolution, 6-hourly; $\tau(\alpha_{char})$(6h): wave-dependent Charnock parameter; u10(low res.): coarse resolution, 6-hourly; RACMO(6h): downscaled, 6-hourly; u10(12h): nominal resolution, 12-hourly; RACMO(3h): downscaled, 3-hourly) at five Dutch stations during the 37 years of the modelled period (1979-2015). The grey shaded area indicates the confidence interval of the Gumbel fit (dashed black line) to observed annual maximum total water levels. Note the different scale of the y-axes between the panels. (This is Fig. 4 of Ridder et al., 2018).

This conclusion is illustrated by Fig. 11, where the annual maxima of water level for five Dutch stations are plotted in a so-called *Gumbel plot*. In a Gumbel plot, the x-axis is the *Gumbel variate*, a variable so chosen that a straight line indicates that the annual maxima are following a Gumbel distribution. The Gumbel variate is directly related to the return time, which is also indicated in the figure. From the figure it is clear that the two runs which use dynamically downscaled wind fields produce the best results. On the other hand, time-resolution seems to be of minor importance, as the results from u10(6h) and u10(12h) are nearly indistinguishable, as are those of RACMO(3h) and RACMO(6h). Repeating the analysis for the surge component instead of the total water level yields the same result.

The results of this study suggest that the details of the atmosphere-ocean interaction and the ensuing stress are not important for modelling the surge heights along the North Sea coasts. The spatial resolution of the forcing field appears to be more important, corroborating the findings of Wahle et al. (2017). Note, however, that the shallow Wadden Sea is not properly resolved.

3.3.2 Deltares

In a series of memoranda (Zijl, 2015, 2016a,b, 2017) Deltares have investigated the performance of the DCSMv6 water level model (Zijl et al., 2013). DCSMv6 is a barotropic (depth-averaged, 2D) model of the north-west European shelf area, including the North Sea, which is operationally used by RWS to forecast water levels along the Dutch coast. It is the successor of WAQUA/DCSMv5, that is used by Ridder et al. (2018). Its standard resolution is $1/60° \times 1/40°$ (roughly 1 nm). To better represent the shallow and spatially highly variable Wadden Sea and the estuaries along the Dutch coast, a version with a decreased grid size ($\approx$ 200 m $\times$ 400 m) in the southern North Sea is used. This version is referred to as DCSMv6-ZUNOv4. The model is usually forced by winds generated from a numerical model.

The results reported in these memoranda can be summarized as

Zijl (2016a) Reducing the grid size in the Ems-Dollard estuary to $\approx$ 50 m $\times$ 100 m generally improves the simulation of water levels and surge heights as compared to the standard DCSMv6-ZUNOv4 model. However, this is not true for the *skew surge* during the most extreme events.

Zijl (2015) DCSMv6 is forced by winds which are translated into stress using a Charnock relation (4) with a constant of the Charnock parameter. If DCSMv6 is forced by HIRLAM winds, the HIRLAM value $\alpha = 0.25$ is used, guaranteeing consistent stresses between the two models.

When DCSMv6 is forced by ECMWF winds, the Charnock parameter is set to $\alpha = 0.41$ to improve forecast accuracy. However, a constant value for α is inconsistent with the way the wind is determined in the ECMWF model, which relies on a wave-dependent, spatially and temporally varying Charnock parameter according to (9). Zijl (2015) replace the constant value by the variable Charnock parameter according to (9), restoring the consistency between the stress from the atmosphere model and the stress used in DCSMv6. This improves modelled surge heights, especially for the most extreme events. The improvement is largest in the southernmost part of the Dutch coast and decreases to the North. Note that this result differs from the findings of Ridder et al. (2018) (Sect. 3.3.1), who find no impact on water level when using a variable Charnock parameter. Possible reasons are the higher resolution used by Zijl (2015) and the different values of the constant Charnock parameter (0.41 *vs.* 0.32).

Zijl (2016b) Instead of using wind forcing with a variable Charnock parameter as in Zijl (2015), DCSMv6 is forced directly by the stress from the ECMWF model. Two cases are considered,

- only the stress going to the ocean is used[1],
- the total stress is used.

While the results of the first case are worse than those of the variable Charnock parameter case (Zijl, 2015), those of the second case are better under most conditions. However, for the highest 0.2% of skew surges, the results are mixed. Using the stress slightly improves model results in some places, while slightly deteriorating them at other locations. From the memorandum it is not clear

- if and how the inferred stress is partitioned in the variable Charnock parameter case. For consistency, it should be partitioned between waves and ocean as is done for the stress in the direct forcing case.
- what is happening to the momentum (stress) transferred to the waves. It should be released when waves are breaking, potentially increasing water levels (see Sect. 3.2.4).

Zijl (2017) The *relative* wind is used to calculate the stress. The surface currents needed to achieve this are taken either from DCSMv6 (2D case), or from the 3D D-flow FM North Sea model. Using the the relative wind improves the modelled tide, surge, and water level. However, the modelled skew surge deteriorates under storm conditions. Using a 3D model to determine the water movement without taking the relative wind into account improves the highest skew surges. Adding the relative wind effect again leads to a deterioration in these cases. The following issues emerge from this memorandum

- The 3D-model runs where forced with winds from a model with coarser resolution than was used for the 2D calculations. This might compromise the comparability of the results.
- The partitioning of the stress between ocean and waves has not been taken into account.
- If the stress is based on the relative wind, the momentum extracted from the atmosphere changes. As a result, the wind would change. A coupled model is needed to take this feedback into account. A coupled model is also needed to provide the atmosphere model with the current speed to determine the relative wind.

Together these results show the importance of details in the stress calculation, which should be made as consistent as possible between all models involved. Using a variable Charnock parameter when translating wind to stress improves model results (Zijl, 2015), and directly using the stress to couple the models, thus avoiding the detour via the wind, improves the results even more (Zijl, 2016b). Finally, using the relative wind in calculating the stress also improves model behaviour in most cases (Zijl, 2017), but at the expense of consistency.

Despite showing a general improvement, results are mixed (Zijl, 2016b), or even deteriorate (Zijl, 2017) for the highest 0.2% or so of skew surges. It is tempting to speculate that this is caused by an inadequate use of the relative wind. In Zijl (2016a) it is not used at all, and in Zijl (2017) it is used inconsistently between atmosphere and ocean. To investigate this problem further, a coupled model is needed in which the calculation of the air-side stress $\vec{\tau}_{\mathrm{atm}}$ is based on the relative movement between atmosphere and water, and where this stress is used directly, i.e., without invoking the wind as an intermediary, to force the water movement.

[1] Unfortunately, no details are given. Presumably, a partition according to (7) is meant. The results of this experiment may be compromised as the ECMWF output of $\vec{\tau}_{\mathrm{oce}}$ contains a bug (J. Bidlot, pers. comm., 2017).

4 Consistency

Apart from neglecting feedback effects between different models, the current modelling practice contains some inconsistencies.

- Different models in a modelling chain use different drag parameterizations. This leads to inconsistencies when wind speed is used as the variable linking the models (Van Nieuwkoop et al., 2015). No coupled model is needed to avoid this inconsistency. It suffices to use the same drag parametrisation in all models, or to use the stress to couple them.

- The temperature and pressure dependence of density is not accounted for when the stress is calculated. The effect on modelled water levels is probably only a few percent, but the effect should be investigated in more detail. This can be done without coupling.

- Wave and surge models are usually forced by the *same* stress (vertical momentum transport), without taking the partitioning according to (7) into account. While Staneva et al. (2017) touch on this topic, the results presented are inconclusive. A coupled wave-ocean model is needed to investigate this question further.

5 Summary and Conclusions

Various feedback processes between atmosphere and ocean have been investigated in the analyzed papers. In general, they report a reduced model-observation difference when coupled effects are taken into account.

On the open sea only one of the coupled phenomena is important, namely the feedback between increasing surface roughness due to growing waves and the driving wind. Coupling leads to a $\approx 10\%$ reduction of wind speeds and wave heights over large areas during storms, and a better agreement with observations. From the papers considered it is unclear if and how the stress changes, and how this change would impact the water levels. While the results of Ridder et al. (2018) suggest that details of the stress parameterization are of minor importance, Zijl (2015, 2016b) find an improved representation of modelled surge heights when atmosphere-wave coupling is taken into account.

Several feedbacks involve water level. Not surprisingly, their effects are only significant in shallow waters, where *relative* water level variations are large. However, as coastal waters are shallow waters, these effects are important for risk assessments. Coupled effects tend to *increase* surge heights and wave heights due to smaller frictional losses in deeper water, and due to depth-induced wave breaking and the ensuing wave radiation stress.

Spatial resolution, both of the forcing fields and the hydrodynamic models, is found to be of great importance, probably more so than coupling. This is consistent with the finding that coupling effects are largest in shallow waters, where water depth is spatially highly variable.

Generally, the assessed papers only consider feedback processes between two phenomena (atm-waves, atm-ocean, waves-ocean). Coupling between all of them simultaneously may lead to new processes that may enhance or dampen the effects discussed here. Only further research can shed light on the effects of these interactions.

This summary leads to the following recommendations:

- Investigate the impact of atmosphere-wave coupling on stress, and the ensuing effect on water levels.

- Investigate the effects of momentum released from waves near the coast on water levels. This includes the effect of the wave radiation stress and the accompanying wave set-up.

- Increase the model resolution along the coast and invest in the coupling of different models (atmosphere, waves, currents), taking shallow-water effects and relative wind effects into account.

The first recommendation can be implemented relatively easily by running an existing model (e.g., IFS/WAM of ECMWF) with and without coupling. Performing this experiment is important as from the existing literature the impact of atmosphere-wave coupling on stress is not clear.

A coupled wave-ocean model is needed for the second recommendation. Special attention should be given to the transfer of momentum from the waves to the currents in shallow water. The wave radiation stress leads to increasing water levels. It is only significant directly along the coast.

The implementation of the third recommendation asks for a long-term effort to investigate improved model parameterizations, coupling, and increased resolution and their mutual impact. The models existing at Deltares (Sect. 3.3.2) should be used, building on their extensive experience.

One point that has not been mentioned so far is the saturation of the drag coefficient at high wind speeds (> 30 m/s; see Sterl, 2017). This saturation is not included in any of the stress formulations discussed in this report (i.e., (4), (9), (10), or (11)). Experiments could start with uncoupled runs using WAQUA/DCSM to see the primary effect, but must be repeated with a coupled atmosphere-wave model with the saturation effect included if the effect turns out to be substantial.

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Koninklijk Nederlands Meteorologisch Instituut

Postbus 201 | 3730 AE De Bilt
T 030 220 69 11 | www.knmi.nl