Surface Wave Impact When Simulating Midlatitude Storm Development

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ABSTRACT

Surface gravity waves, present at the air–sea interface, can affect the momentum flux and heat fluxes by modifying turbulence in the lower layers of the atmosphere. How to incorporate wave impacts into model parameterizations is still an open issue. In this study, the influence of a dynamic roughness length (considering instantaneous wave-induced stress), horizontal resolution, and the coupling time resolution between waves and the atmosphere on storm simulations are investigated using sensitivity experiments. Based on the simulations of six midlatitude storms using both an atmosphere–wave coupled model and an atmospheric stand-alone model, the impacts are investigated. Adding the wave-induced stress weakens the storm intensity. Applying a roughness length tuned to an average friction velocity is not enough to capture the simulation results from “true” wave-related roughness length. High-horizontal-resolution models intensify the simulation of storms, which is valid for both coupled and uncoupled models. Compared with the atmospheric stand-alone model, the coupled model (considering the influence of dynamic roughness length) is more sensitive to the model horizontal resolution. During reasonable ranges, the coupling time resolution does not have a significant impact on the storm intensity based on the limited experiments used in this study. It is concluded that the dynamic wave influence (instantaneous wave influence) and the model resolution should be taken into account during the development of forecast and climate models.

1. Introduction

The exchange of momentum, heat, and moisture at the air–sea interface plays a vital role in the development of atmospheric systems. Midlatitude wind storms, one of the synoptic-scale atmospheric systems, are a serious threat to coastal areas and offshore activities and so are important to model correctly. During the evolution of wind storms, surface fluxes between the atmosphere and the ocean provide (absorb) energy to (from) the atmosphere, leading to the intensification (dissipation) of storms. Surface fluxes in numerical models are usually presented through parameterizations. The accuracy of those parameterizations plays an essential role in windstorm forecasts.

In most atmospheric numerical models, the surface stress τ is calculated using bulk formulation, that is, $\tau = \rho_a C_d U_{10}^2$, where ρ_a is the air density, C_d is the drag coefficient, and U_{10} is the wind speed at 10 m above the sea surface level. Based on the Monin–Obukhov similarity theory (MOST), under neutral conditions, the drag coefficient over the ocean is expressed as

$$C_{dN} = \left[\frac{\kappa}{\ln(10/z_0)} \right]^2, \quad (1)$$

where κ is the von Kármán constant and z_0 is the roughness length. The Charnock formula (Charnock 1955) is used in nearly all atmospheric models, that is, $z_0 = \alpha u_*^2/g$, where α is the Charnock coefficient, g is the acceleration due to gravity, and u_* is the friction velocity. The Charnock coefficient α is generally assumed to lie between 0.015 and 0.035, corresponding to the range reported in observational studies (Powell et al. 2003).

Surface gravity waves, present at the air–sea interface, have significant influences on turbulence in the lower atmosphere. Under different wave conditions (e.g., swell-dominated waves and wind waves), the turbulence structure of the atmospheric surface layer exhibits large differences (Rutgersson and Sullivan 2005; Höglström et al. 2009). Under swell conditions, the swell waves can generate a low-level wind maximum (which has been observed in measurements and numerical models), contrary to the common condition that the wind generates waves (Semedo et al. 2009). The Charnock relationship used in most numerical models is strictly valid only for fully developed wave conditions (Doyle 2002).

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To incorporate the wave state influence on the wind stress, some wave-state-dependent (e.g., wave age, wave steepness) Charnock coefficients have been proposed and applied into many wind stress parameterizations (Taylor and Yelland 2001; Smedman et al. 2003; Guan and Xie 2004; Drennan et al. 2005; Carlsson et al. 2009). As expected, wave-state-dependent parameterizations improve the comparison between measurements and model results of wind stress compared with the traditional Charnock relationship. However, there is still room for improvement in wind stress modeling compared with measurements, especially for complicated wave conditions (e.g., swell and heavy wave conditions). The wave impact under high wind speeds (sea spray, airflow separation caused by breaking waves) and the swell impact on the wind stress are applied to an effective roughness length in numerical models, which improved model performances (Makin 2005; Kudryavtsev and Makin 2011; Liu et al. 2011; Wu et al. 2015b, 2016).

To consider the two-way interaction between waves and the atmosphere, a coupled wave–atmospheric model was developed at the European Centre for Medium-Range Weather Forecasts (ECMWF) in the middle of the 1990s (Janssen 2004). In the coupled model, the Integrated Forecasting System (IFS) is coupled with a wave model to consider the impact of the wave-induced stress. Later, atmosphere–wave coupled models were developed to investigate the influence of wave-induced stress on climate simulations and mesoscale weather systems (Doyle 1995, 2002; Lee et al. 2004; Wen et al. 2006; Zhang et al. 2009). Surface waves not only impact the atmosphere but also the upper-ocean mixing through wave breaking, Stokes drift interaction with the Coriolis force, Langmuir circulation, and stirring by nonbreaking waves (Wu et al. 2015a). Presently, an increased complexity is introduced in the atmosphere–wave–ocean coupled climate and seasonal forecast systems (Fan and Griffies 2014; Breivik et al. 2015; Li et al. 2016). Those systems are also in need of good parameterizations of the wind stress and wave impacts on upper-ocean mixing.

The wave-induced stress may be one of the most important factors, which affects the wind stress significantly over the ocean (Janssen 1989, 1991). It enhances the roughness length under young waves (Doyle 2002). Taking the windstorm as an example, the increased roughness length leads to more energy transferred to the ocean from the atmosphere. Accordingly, the wave-induced stress enhances the decay of the storm, which is demonstrated in some studies (Doyle 1995, 2002). The feedback of the enhanced roughness length caused by wave-induced stress can also affect storm tracks, heat

fluxes, the local planetary boundary layer, etc. (Zhang and Perrie 2001; Doyle 2002; Wen et al. 2006).

To better simulate air–sea fluxes, more efforts should be spent on developing new wave-state-dependent parameterizations of momentum and heat fluxes based on measurements and theory (Högström et al. 2015; Wu et al. 2015b). However, in this study, instead of developing a new wind stress parameterization, we aim to investigate whether having a dynamic response of the surface roughness length is important compared with having a comparable mean surface roughness. In addition, we investigate more technical aspects of the air–sea coupling in terms of coupling time interval (i.e., the time interval that different model components exchange information) and model horizontal resolution. Based on three groups of sensitivity experiment simulations of six midlatitude storms, we investigate the following questions:

- Is the dynamic roughness length influence (instantaneous roughness length) important?
- Which model is more sensitive to the model resolution, coupled or uncoupled?
- Can the coupling time interval affect simulation results?

In some wind stress parameterizations, the wave influence is not explicitly considered (e.g., Andreas et al. 2008). In those parameterizations, the wind stress (roughness length) is solely a function of wind speed, even when the wave spectrum is different. Assuming good performance of those wind stress parameterizations, there still some scatter (perhaps small) due to the inability to solve for the influence of different types of wave spectra. Decades of studies have been done for the tuned parameters for the drag coefficient. Here, we take one step back, investigating the influences of dynamic roughness length, as well as the tuned roughness length parameterizations, on the storm simulation. Are the results from the two experiments same? The results may guide the direction of developing new flux parameterizations over water: should dynamic wave information be considered or is a tuned parameterization sufficient?

Nowadays, atmosphere–wave coupled models are becoming increasingly frequent and applied to weather forecasts and research. With higher-resolution simulations, more detailed structures of weather systems may be resolved, and storm simulation results are generally more intense in atmospheric stand-alone models (Ma et al. 2012; Gentry and Lackmann 2010). The question of whether the coupled model is more sensitive to the model horizontal resolution compared to uncoupled models is investigated based on sensitivity experiments.

In the development of coupled models, the coupling time interval between model components varies according to model designers and the purpose of simulations. Some coupled models exchange parameters every model time step, while other models exchange information less frequently (Zhang et al. 2009; Liu et al. 2011; Wu et al. 2015b). In theory, the coupling time interval determines the time response of waves on atmospheric dynamic processes. Within reasonable coupling interval time ranges, how significant is the coupling interval? Through a group of sensitivity simulations, we investigate this question.

The three questions are addressed based on sensitivity simulations of six midlatitude storms using an atmosphere–wave coupled model and an atmospheric stand-alone model. The paper is structured as follows: the models used in this study are introduced in section 2; the designs of experiments are presented in section 3; the simulation results are analyzed in section 4; finally, the discussion and conclusions are given in sections 5 and 6, respectively.

2. Numerical models

a. Atmospheric model

The Weather Research and Forecasting (WRF) Model (version 3.5) is a three-dimensional nonhydrostatic atmospheric model (Skamarock et al. 2008). In this study, WRF was used as the atmospheric model to simulate storms. The WRF single-moment three-class microphysical scheme (Hong et al. 2004) was used. The Rapid Radiative Transfer Model (Mlawer et al. 1997) and the NCAR Community Atmosphere Model (Collins et al. 2004) were used as longwave and shortwave radiation schemes, respectively. The Noah land surface model (Chen and Dudhia 2001) was used as the land surface model. For the planetary boundary layer model, we used the Yonsei University turbulence scheme (Hong et al. 2006). The Kain–Fritsch scheme (Kain 2004) was used as a cumulus parameterization. The domain of the WRF Model covers all of Europe, shown in Fig. 1 (the inner-box area). The global reanalysis dataset ERA-Interim (Dee et al. 2011) was used to provide the initial and boundary conditions. The resolution and time step of the WRF Model varies between experiments (see section 3). The roughness length in the default WRF Model is expressed as

$$z_0 = \alpha \frac{u_*^2}{g} + \frac{0.11 \times \nu}{\max(u_*, 0.1)}, \quad (2)$$

where ν is the air kinematic viscosity. The Charnock coefficient is expressed as

FIG. 1. The domain of WAM and WRF. The outer box is the domain of coarse WAM, and the inner box is the domain of both the stand-alone WRF Model and the WRF–WAM coupled model.

$$\alpha = 0.011 + 0.007 \times \min\{\max[(U_{10} - 10)/8, 0], 1.0\}. \quad (3)$$

b. Wave model

The Wave Model (WAM; WAMDI Group 1988) is a third-generation full-spectral wave model. In this study, WAM was set up for two nested domains (Fig. 1). The resolution of the outer domain is 0.25° and 0.1° for the inner domain. The outer domain is run to provide boundary conditions to the inner domain. The forcing data of the outer domain are provided by the ERA-Interim dataset (Dee et al. 2011) every 6 h. In WAM, the roughness length is given by

$$z_0 = \alpha \frac{\tau}{g\rho_a(1 - \tau_w/\tau)^{1/2}}. \quad (4)$$

The Charnock coefficient α is set as 0.010 in WAM. The wave-induced stress τ_w is expressed as (Janssen 1991)

$$\tau_w = \rho_w \int \omega \gamma F \cos(\theta - \varphi) df d\theta, \quad (5)$$

where ρ_w is the water density, γ is the growth rate of the waves, ω is the angular frequency, F is the wave spectrum density, θ is the wave direction, and φ is the wind direction.

c. Coupled model

In the atmosphere–wave coupled model, the WRF is used as the atmospheric component model and WAM is the wave component model. The domains of the WRF and WAM in the coupled model are approximately the same (the inner-box area is shown in Fig. 1). In the atmosphere–wave coupled model, the WRF provides the wind field to WAM, and WAM provides the

TABLE 1. The design of experiments. In group I, wrfst0 is the control experiment, wrfcpl is the atmosphere–wave coupled simulation, wrfz0 is the tuned roughness experiment, and the parameterized variation of z_0 for the same friction velocity is added to wrfz0var. In group II, wrfst0 and wrfst0_10km are the control experiments with low and high horizontal resolution, respectively; wrfcpl and wrfcpl_10km are the coupled simulation with low and high horizontal resolution, respectively. In group III, the coupling time interval for wrfcpl, wrfcpl_20m, and wrfcpl_30m is 10, 20, and 30 m, respectively.

	Coupled	Roughness length	Resolution (km)	Time step (s)	Coupling time interval	Group
wrfst0	No	Eq. (2)	20	60		I, II
wrfcpl	Yes	Eq. (4)	20	60	10 min	I, II, and III
wrfz0	No	Tuned z_0	20	60		I
wrfz0var	No	Tuned z_0 with variation	20	60		I
wrfst0_15km	No	Eq. (2)	15	60		II
wrfst0_10km	No	Eq. (2)	10	30		II
wrfcpl_15km	Yes	Eq. (4)	15	60	10 min	II
wrfcpl_10km	Yes	Eq. (4)	10	30	10 min	II
wrfcpl_20m	Yes	Eq. (4)	20	60	20 min	III
wrfcpl_30m	Yes	Eq. (4)	20	60	30 min	III

roughness length calculated from the wave spectrum to WRF. The wave simulations from the outer domain of the stand-alone WAM provide the wave boundary conditions for the coupled model. The coupler OASIS3–Model Coupling Toolkit (MCT; Valcke et al. 2015) is used for communication between WRF and WAM. The coupled time interval varies with experiments; the details are shown in section 3.

3. Experimental designs

Three groups of experiments are designed to investigate the three questions proposed in section 1. To investigate the influence of instantaneous wave information (influence of a dynamic roughness length from waves) on simulations, four experiments are designed in group I: wrfst0, wrfcpl, wrfz0, and wrfz0var (see Table 1). The difference between the experiments is the parameterization of the roughness length z_0 over water. The horizontal resolution of WRF in these simulations is 20 km, using 31 vertical layers. The top model layer locates near the 5-hPa level, and the lowest model layer is approximately 30 m.

In wrfst0 (the control experiment in group I), the default WRF Model is used. The experiment wrfst0 is used to compare with other experiments in this group to investigate influences of a changed z_0 due to waves (wrfcpl, wrfz0, and wrfz0var). The coupled WRF–WAM model is used in experiment wrfcpl, which is treated as the “true” wave-related z_0 (including the dynamic response of waves). In wrfz0, the roughness length is tuned to that from wrfcpl using the regressed equation between u_* and z_0 calculated from wrfcpl. The aim of wrfz0 is to investigate if the simulation results from wrfz0 can agree well with the results from wrfcpl if the tuned parameterization of roughness length agrees well with the average relationship between u_* and z_0 from wrfcpl? Thus, to reduce the impact of the possible

difference relationship between u_* and z_0 for different storms, the regressed equation is based on the u_* and z_0 from wrfcpl over ocean using the hourly output data at the same time and grid points for each windstorm simulation. In the coupled model simulation, the roughness length for the same friction velocity is different due to the impact of wave-induced stress. The standard deviation of z_0 in every friction velocity bin (0.01 m s^{-1}) is regressed using the hourly output data from wrfcpl for each storm. To investigate whether adding the variation of z_0 for a specific u_* changes the results, the standard deviations of z_0 for friction velocity bins are parameterized through random variation in wrfz0var. The z_0 distribution from wrfz0var for one time step is shown in Fig. 2a. One can see there are significant nonphysical features of the roughness length. To reduce the nonphysical roughness length and to provide more slowly varying roughness length, the roughness length in experiment wrfz0var is averaged using the roughness length from the nearest nine sea grid points. Figure 2b shows an example after the roughness length is smoothed from Fig. 2a. The z_0 in wrfz0var can be treated as “fake” instantaneous wave-related roughness length. The comparison between experiment wrfcpl and wrfz0 is used to investigate whether it is enough to use the tuned z_0 parameterization for simulations. From the comparison between wrfcpl and wrfz0var, we want to investigate whether the simulation results from the “fake” instantaneous wave-related z_0 can agree well with the simulation results from the “true” instantaneous wave-related z_0 (wrfcpl).

Figure 3 shows the change in the roughness length with friction velocity for the six storms of the experiments in group I. For experiment wrfst0 (blue dots), the roughness length increases with friction velocity; that is, the roughness length for the same friction velocity is the same, even though the wave state is different [Eq. (3)].

FIG. 2. The example of the roughness length on a logarithmic scale (m; color bar) (a) before and (b) after smoothing in experiment wrfz0var.

The roughness length calculated from WAM (red dots) is more than 3 times larger than that from wrfst (blue dots) during high friction velocity (i.e., high winds). For the same friction velocity, the z_0 from wrfcpl has large variation caused by different wave states (wave-induced stress). The influence of wave-induced stress can be considered in the Charnock coefficient to show its explicit impact. Following Eq. (4), the effective Charnock coefficient in WAM can be expressed as

$$\alpha_e = \frac{\alpha}{(1 - \tau_w/\tau)^{1/2}}. \quad (6)$$

For saturated wave states, the wave-induced stress is $\tau_w = 0$, which gives an effective Charnock coefficient $\alpha_e = \alpha = 0.010$. Young waves, which have the fastest growth rate (τ_w is large), give a larger effective Charnock coefficient and a larger roughness length compared with undersaturated waves for the same friction velocity. For the low friction velocity (i.e., low winds), z_0 from wrfcpl is higher than from wrfst. The tuned z_0 parameterization from wrfz0 (pink dots) can simulate the average dependence of z_0 with u_* from the coupled model wrfcpl. For the same friction velocity, in general, z_0

calculated from the tuned parameterization (wrfz0) has the same mean value of z_0 as the results from wrfcpl. However, it cannot simulate the distribution of z_0 at the same friction velocity from wrfcpl. Adding the parameterized variation of roughness length, in general, wrfz0var can simulate the distribution of z_0 at the same u_* to some degree. However, it is fake wave-related roughness length (it is not true wave-state influence, only the approximately same distribution on average). The experiment wrfz0var is used to test the influence of including a variable z_0 with u_* . From the distribution of z_0 for the four experiments in group I, we can see that the four experiments (i.e., wrfst, wrfcpl, wrfz0, and wrfz0var) can satisfy our purpose: control case, true instantaneous wave-induced stress influence, tuned average z_0 parameterization to true wave-induced stress, fake instantaneous wave-induced stress. The tuned z_0 in experiments wrfz0 and wrfz0var is done individually for each of the storms.

To investigate the influence of horizontal resolution on coupled and uncoupled simulations, four more experiments (wrfstd_15km, wrfcpl_15km, wrfst_10km, and wrfcpl_10km) with wrfst and wrfcpl are added in group II (see Table 1). The horizontal resolution of WRF in these additional runs is increased to 15 and 10 km; all other settings are kept equal to wrfst or wrfcpl.

The coupling time interval is also an important issue that needs to be kept in mind when designing coupled models. In group III, together with experiment wrfcpl, two more experiments—wrfcpl_20m and wrfcpl_30m—are added. In wrfcpl_20m (wrfcpl_30m), WAM and WRF exchange information (roughness length and wind field) every 20 (30) min. The other settings are the same as for wrfcpl. In group III, the experiment wrfcpl is treated as the control experiment. The differences between wrfcpl_20m/wrfcpl_30m and wrfcpl are caused by the differences in coupling time interval.

In this study, six midlatitude storms are simulated using the 10 experiments to investigate the three questions proposed in section 1. The six midlatitude storms are Dagmar (Patrick), Emma, Kyrill, Christian (St. Jude), Ulli, and Xaver. All of the six storms attacked Europe, which is included in the model domain. Detailed information about the six storms is available online (at <http://www.europeanwindstorms.org/>).

4. Results

a. Dynamic roughness length

The wind speeds from wrfcpl are compared with experiment wrfst at the same grid point and the same

FIG. 3. The relationship between the friction velocity and the roughness length of different experiments for the different storms: (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver.

time step for every wind speed bin (1 m s^{-1}) using all of the simulation period data. The comparison results between wrfstd and wrfcpl for the six storms are shown in Fig. 4, which shows the influence of the dynamic roughness length. The red line is the bin average from wrfcpl compared with the results from wrfstd (the average of the wind speed bin range from wrfstd is shown on the x axis, and the average of the wind speed on the same grids and time step as the data used in the x-axis bin average is shown on the y axis). The standard deviation in different wind speed bins is shown as error bars. During the low wind speed range of $0\text{--}10 \text{ m s}^{-1}$, the wind speed from wrfcpl is slightly higher than that from wrfstd. During the wind speed range of $10\text{--}20 \text{ m s}^{-1}$, the results from wrfcpl agree well with wrfstd, although there is some scatter. With increasing wind speed ($U_{10} > 20 \text{ m s}^{-1}$), there is less agreement between wrfcpl and wrfstd. Under high wind speed ranges, U_{10} from wrfcpl is lower than that from wrfstd, which is caused by the change in z_0 (in high wind speed, z_0 from wrfcpl is larger than that from wrfstd). The influence of the dynamic roughness length on the wind speed simulation is significant during high wind speeds.

The comparison between wrfcpl and wrfz0/wrfz0var for U_{10} is shown in Fig. 5. During wind speed ranges ($U_{10} < 20 \text{ m s}^{-1}$), U_{10} from both wrfz0 and wrfz0var agree well with that from wrfcpl. This is mainly because the difference in z_0 under low wind speeds (i.e., low friction velocity) is too small (Fig. 3) to make an impact on the simulated wind speeds. However, wrfz0/wrfz0var underestimates the wind speed from wrfcpl when U_{10} is larger than 20 m s^{-1} . This is also caused by the larger variation in z_0 for the same friction velocity under high wind speeds (i.e., high friction velocity). Compared with U_{10} from wrfz0, the results from wrfz0var are slightly closer to the results from wrfcpl (if we do not add the smoothing of z_0 , it is much closer to the results from wrfcpl). The fake wave-related roughness length improves the simulation results concerning U_{10} compared with the tuned experiment, wrfz0; that is, by adding a random variation of the roughness length, the results agree slightly better with the coupled system.

The differences in the minimum sea level pressure are small in group I (figures are not shown). The storm tracks are extracted from the minimum sea level pressure using the data from the simulations. The differences

FIG. 4. The relationship between U_{10} from wrfstd and that from wrfcpl for different storms: (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver. The red line is the bin average (2 m s^{-1}) with standard deviations. The black line is the 1:1 line.

in the storm tracks from the four experiments in group I are small (figures are not shown). The time series of the maximum wind speed at 10 m defined from the square with its center in the storm center and 12° side lengths are shown in Fig. 6. In general, the maximum wind speed at 10 m ($U_{10\text{max}}$) from wrfstd is the highest in group I during the high wind speed period. The wrfz0 has the lowest $U_{10\text{max}}$ on average (0.68 m s^{-1} smaller than wrfstd on average). Adding the parameterized variation to wrfz0, wrfz0var gives the second smallest $U_{10\text{max}}$ on average (0.45 m s^{-1} smaller than wrfstd on average). However, we can see that the wind speed from wrfcpl is higher than from wrfz0/wrfz0var (close to the results of wrfstd) for the high wind speed time period.

To investigate the influence of waves on high wind speed areas, two indices are chosen to show their influences: 1) the area where U_{10} is higher than 17 m s^{-1} (a Beaufort wind scale of approximately force eight) S_{17} and 2) the area where U_{10} is higher than 21 m s^{-1} (a Beaufort wind scale of approximately force nine) S_{21} . The search area of S_{17} and S_{21} is the 12° rectangle, the center of which is the storm center at that time. The time

series of S_{17} and S_{21} are shown in Fig. 7. The average differences of S_{17} and S_{21} between wrfstd and wrfz0, wrfz0var, and wrfcpl are shown in Table 2. On average, S_{17} from wrfstd is the largest and then the experiment wrfcpl. The experiment wrfz0var has the smallest value concerning the average of S_{17} (except for cases Ulli and Christian). The S_{17} from wrfcpl is larger than from wrfz0/wrfz0var. For S_{21} , the average difference between wrfz0 and wrfz0var is not significant. The S_{21} from wrfstd is the largest of the experiments in group I. The S_{21} of wrfcpl is larger than that from wrfz0var on average. The maximum wind speed and high wind speed area S_{17} and S_{21} indicate that the tuned z_0 experiment (wrfz0) has a lower wind speed and a smaller high wind speed area compared to that from wrfcpl. Adding the parameterized random z_0 (fake wave-related roughness length) makes the results closer to the results from wrfcpl; however, there are still some random differences when comparing the time series of $U_{10\text{max}}$, S_{17} , and S_{21} (see Figs. 6 and 7).

To investigate the spatial distribution differences of parameters, some specific time steps for four chosen

FIG. 5. The relationship of U_{10} in different experiments (wrfcpl, wrfz0, and wrfz0var) for different storms: (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver. The red (blue) line and the error bars are the results from wrfz0 (wrfz0var) with bin average to the results from wrfcpl. The black line is the 1:1 line.

storms are shown. The four chosen time steps are 1) 1200 UTC 25 December 2011 for Dagmar, 2) 1200 UTC 29 February 2008 for Emma, 3) 0600 UTC 18 January 2007 for Kyrill, and 4) 1200 UTC 27 October 2013 for Christian. Figure 8 shows the logarithmic distribution of roughness length from the four experiments in group I for the chosen four specific time steps. The distribution of z_0 for the experiments in group I is similar. However, z_0 from wrfstd is much smaller compared with the other three experiments for high wind speed areas. The pattern of z_0 from wrfz0 agrees reasonably with wrfcpl. However, in some areas, z_0 from wrfz0 is larger (smaller) than that from wrfcpl. When adding the variation of z_0 (wrfz0var), it adds some random scatter compared with wrfz0. This illustrates the unphysical behavior of adding a random component to the roughness length.

Figure 9 shows the U_{10} from wrfcpl, as well as the U_{10} differences between wrfstd/wrfz0/wrfz0var and wrfcpl. Compared with z_0 (the main difference is shown in the high wind speed areas), the differences of U_{10} in relatively low wind speed areas are also significant (see

Fig. 9). The differences in heat flux are caused by the differences in wind speed as well as the roughness length (the roughness length will affect the transfer coefficient for heat fluxes). In general, the heat fluxes from wrfstd/wrfz0/wrfz0var are larger than that from wrfcpl. The differences between wrfz0 and wrfcpl are larger than the differences between wrfstd and wrfcpl. As a secondary effect, changing the roughness length also impacts the precipitation; however, the magnitude varies between the different storm cases (figures are not shown).

b. Horizontal resolution

The time series of $U_{10\text{max}}$ for group II are shown in Fig. 10. The maximum wind speed from the high-resolution experiments is higher than that from the low-resolution experiments, which is valid for both coupled and uncoupled models. Compared with the difference between reference runs (uncoupled models), in general the difference between the high- and low-resolution models is larger for the coupled model than with the uncoupled model. The maximum (mean) difference

FIG. 6. The time series of the maximum wind speed at 10 m simulated from different experiments for storms: (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver.

of $U_{10\max}$ can reach $7.4/5.9 \text{ m s}^{-1}$ ($0.71/0.35 \text{ m s}^{-1}$) for different resolutions of the coupled experiments (wrfcpl_10km–wrfcpl/wrfcpl_15km–wrfcpl). For the uncoupled models, the maximum difference is $6.2/5.6 \text{ m s}^{-1}$ ($0.52/0.34 \text{ m s}^{-1}$) for wrfst_10km–wrfst/wrfst_15km–wrfcpl. At a higher resolution, more details in the storm structure can be resolved, which may be a reason for the higher wind speed in high-resolution models. For the coupled model, the detailed wave influences on the wind stress enhance the wind speed difference compared with the uncoupled models.

The time series of the high wind speed areas (S_{17} and S_{21}) for the experiments in group II are shown in Fig. 11. Compared with the low-resolution simulation results, the S_{17} is smaller in high-resolution simulations for Kyrill, Ulli, and Xaver. However, for the other three storms, the S_{17} from higher-resolution simulations is larger than that from low-resolution simulations. Compared with the uncoupled simulations, the absolute difference between high- and low-resolution coupled models is larger. On average, the S_{21} is larger in high-resolution simulations than that in low-resolution

simulations, which is valid both for coupled and uncoupled models. There are some differences for different storms. Similar to S_{17} , the absolute differences in S_{21} between the uncoupled simulations (wrfst–wrfst_10km/wrfst–wrfst_15km) are smaller than those from coupled simulations (wrfcpl–wrfcpl_10km/wrfcpl–wrfcpl_15km). In some areas, the higher-resolution model increases (reduces) the high wind speed area. Compared with the uncoupled model, considering the dynamic roughness length influence enhances this influence (either increases or reduces differences).

The precipitation in higher-resolution simulations is heavier than that from low-resolution simulations for both coupled and uncoupled simulations. The differences in heat fluxes and total precipitation in the high-resolution simulations (wrfst_10km–wrfcpl_10km/wrfst_15km–wrfcpl_15km) are larger compared to that in the low-resolution simulations (wrfst–wrfcpl). These results are also valid when comparing the high wind speed area differences between the high- and low-resolution runs. All in all, it indicates that the simulations are more sensitive to

FIG. 7. The time series of high wind speed areas: solid lines represent the areas where U_{10} is larger than 17 m s^{-1} , and dashed lines represent the areas where U_{10} is larger than 21 m s^{-1} . (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver.

the wave-related roughness length in high-resolution models.

c. Time resolution of coupling

Based on the six storm simulations, introducing a higher resolution to the coupling time interval (group III) does not have a significant statistical influence on the maximum wind speed (Fig. 12), minimum sea level pressure, or storm tracks for the three experiments in group III listed in Table 1. Similar to $U_{10\text{max}}$, S_{17} , and S_{21} in group III, no significant differences are shown.

However, a higher resolution can have an influence on the distribution of the parameters for specific time steps (results are not shown).

5. Discussion

When modeling midlatitude storms, one could ask whether an atmosphere–wave coupled model is required. Previous studies have shown that it is important to introduce the impact of waves and sea spray generation on wind stress (Wu et al. 2015b). Here we aim to

TABLE 2. Average difference between experiment wrfst0 and the other experiments (wrfz0, wrfz0var, and wrfcpl) for the higher wind speed area (S_{17} and S_{21} ; 10^3 km^2) for the six storms.

	Expt	Dagmar	Emma	Kyrill	Christian	Ulli	Xaver	Mean
S_{17}	wrfstd-wrfz0	10.0	18.9	42.6	13.9	13.0	6.9	11.1
	wrfstd-wrfz0var	21.0	22.3	20.3	11.7	12.4	8.3	16.0
	wrfstd-wrfcpl	4.6	2.3	11.3	19.3	15.1	9.2	10.1
S_{21}	wrfstd-wrfz0	35.9	32.4	43.8	13.4	55.3	36.2	36.2
	wrfstd-wrfz0var	41.5	33.8	53.9	12.4	52.7	33.3	38.0
	wrfstd-wrfcpl	26.8	11.0	31.9	13.9	57.9	34.4	29.3

FIG. 8. Spatial variation of roughness length on a logarithmic scale (m; color bar) calculated from the four experiments in group I for the chosen time steps. (top to bottom) The results from wrfcpl, wrfst, wrfz0, and wrfz0var. (left to right) The chosen time step for Dagmar, Emma, Kyrill, and Christian. The four chosen time steps are 1200 UTC 25 Dec 2011 for Dagmar, 1200 UTC 29 Feb 2008 for Emma, 0600 UTC 18 Jan 2007 for Kyrill, and 1200 UTC 27 Oct 2013 for Christian.

determine whether the dynamic response of a wave model is of importance or whether it is enough to apply an atmospheric model being tuned to a surface roughness length representing the mean wave influence. In this study, taking the wave-induced stress (dynamic roughness length influence) as an example, the dynamic influence of waves on roughness length and the tuned roughness length are studied based on the simulation of six midlatitude storms. The influence of horizontal resolution and the coupling time interval is investigated using an atmosphere–wave coupled model and an atmospheric stand-alone model.

For saturated waves, the wave-induced stress is zero (the effective Charnock coefficient is 0.010), which is smaller than from wrfst [Eq. (2)]. Then in the same friction velocity, the roughness length in saturated waves from wrfcpl is smaller than from wrfst (see Fig. 4). During high wind speeds, in general the wave growth rate is larger (young waves), which leads to the large wave-induced stress. The

large wave-induced stress increases the effective Charnock coefficient [Eq. (6)]. Then at the same wind speed, the roughness length from WAM is much larger than from wrfst during high wind speeds.

In general, the intensities of the storms simulated by the atmospheric stand-alone model (wrfst) are larger than from experiments with some kind of wave information (wrfcpl, wrfz0, wrfz0var). This agrees with the roughness length from wrfst being smaller for high wind speeds. Then the energy transferred from the atmosphere to the ocean in wrfst is smaller than from other experiments and more energy exists in the atmosphere to maintain the intensity of the storms. Under low wind speeds, the simulation results of the wind speed from the tuned z_0 parameterization agree well with the true instantaneous wave influence (from the coupled model). For the high wind speeds, the tuned z_0 model (wrfz0) “underestimates” the wind speed from the results of true instantaneous wave influence. This

FIG. 9. The wind speed (m s^{-1}) at 10 m from different experiments. (top to bottom) The results from wrfcpl (row 1), and the wind speed differences between wrfst (row 2), wrfz0 (row 3), and wrfz0var and wrfcpl (row 4). (left to right) The chosen time steps for Dagmar, Emma, Kyrrill, and Christian.

may be because the tuned z_0 cannot represent the impact of different wave states. Only experiment wrfz0 can represent the mean change of the roughness length with friction velocity. The spatial distribution of roughness length caused by wave states may affect the wind speed, which cannot be simulated by wrfz0/wrfz0var. The feedback from the wind speed impacted by waves from previous time steps can also contribute to the “underestimation.” Adding the variation to the same friction velocity to tuned z_0 parameterization slightly improves the model performance. This may be because, with the parameterized variation of z_0 , the total momentum flux from wrfz0var is somewhat in better agreement with the coupled model. However, the instantaneous difference of z_0 from wrfcpl and wrfz0var still can lead to significant differences concerning the distribution of the surface layer wind speed (see Fig. 9). The high wind speed areas are also significant, which may be

caused by the influence of z_0 , as well as the feedback influence, on the wind speed.

The change of the roughness length also influences the transport of energy between the atmosphere and the ocean; however, it is not enough to change the energy structure of the storm system. In other words, the momentum flux difference around the storm center between the different simulations is not big enough. Additionally, the wind and pressure gradients are not changed enough to significantly affect the storm tracks. The results are consistent with the results of Wu et al. (2015b), who show that the change in the roughness length does not significantly affect the midlatitude storm tracks. In the WRF Model, the heat and moisture flux is calculated using the COARE3.0 algorithm (Fairall et al. 2003). The scalar sea surface roughness length is a function of roughness Reynolds number ($R_r = z_0 u_* / \nu$). The roughness length over the ocean in the coupled models is calculated in WAM, which leads to the change

FIG. 10. The time series of maximum wind speed (m s^{-1}) at 10 m simulated from different experiments in group II for storms (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver.

in heat fluxes and to vapor transportation between the atmosphere and the ocean. These changes will then affect the transportation of moisture in the air, which leads to change in precipitation (the impact magnitude varies among the storm cases).

With the high horizontal resolution, numerical models can resolve more detailed spatial structures of momentum flux, heat fluxes, etc. These detailed spatial structures can affect the gradient forces as well as the wind speed and precipitation. This is a possible explanation for the variation in the maximum wind speed as well as precipitation when changing the model resolution. In the high-resolution models, the small-scale differences in roughness length from WAM caused by the changes in wave states is more than from Eq. (2) (which is related only to the wind speed). This may lead to a greater difference between the coupled and uncoupled models in the high-resolution simulations than in the low-resolution simulations.

A short coupling time interval gives higher-temporal-resolution wave-related roughness length to WRF. Accordingly, the atmospheric model can take the roughness length influence to the simulation more rapidly. Then

the WRF Model can resolve more detailed changes in the roughness length from WAM. The changed roughness length will affect the simulation of the wind field as well as the roughness length in WAM. The feedback affects the model in certain time steps; however, it does not have a significant influence on the time series of maximum wind speed and high wind speed area based on the limited three different experiments (group III). The resolution used in the coupled model is relatively coarse, which is one possible reason why it does not make a significant difference based on the experiments in group III. Also for this study, we used only three coupling time intervals (10, 20, and 30 min) for the simulation of wind storms. One may expect more differences if the range of the coupling time interval is larger (e.g., the difference between 1 and 60 min); however, those are not reasonable coupling time intervals for the storm simulations. For extreme weather systems (e.g., tropical cyclones) and high-resolution models, the exchange of variables between waves and atmosphere should be done frequently to adequately capture the wave feedback. It is also possible that the impact of using different coupling time

FIG. 11. The time series of high wind speed area for group II: solid lines represent the area where U_{10} is higher than 17 m s^{-1} , and dashed lines represent the area where U_{10} is higher than 21 m s^{-1} . (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xavier.

intervals would be larger for an even larger horizontal resolution.

Measurements and theoretical studies have shown that the drag coefficient levels off at very high wind speeds (e.g., Powell et al. 2003; Wu et al. 2015b). The reduced drag coefficient corresponds to the reduced roughness length during high wind speeds. If the sea spray influence is included in the roughness length parameterization, then the drag coefficient under high wind speeds will decrease (Wu et al. 2015b). However, in this study, the sea spray influences are not considered, as it is outside of the scope of this study. Only the influence of the wave-induced stress on the roughness length is the aim of the sensitivity test in this study.

6. Summary and conclusions

In this study, the influence of the dynamic roughness length and the tuned roughness length parameterization was studied through the simulations of six mid-latitude storms using an atmosphere–wave model and

an atmospheric stand-alone model. The impact of horizontal resolution and the coupling time resolution of the simulation of storms was also investigated.

Taking the wave-induced stress (dynamic wave influence) into consideration, the intensity of storms is weaker compared with that from the atmospheric stand-alone model. The tuned z_0 parameterization has good agreement with the coupled model in which the dynamic wave influence is included. However, the agreement for high wind speed ranges is less compared with low wind speed ranges. Adding the parameterized variation of roughness length to the tuned z_0 parameterization (“fake” wave-related roughness length) slightly improves the agreement with the results from “true” wave-related roughness length concerning the wind speed. However, it is still not enough to capture the wave influence. The dynamic roughness length impacts not only the wind speed and storm intensity but also the high wind speed areas.

In general, higher-resolution models intensify the storms and increase the precipitation for both coupled

FIG. 12. The time series of maximum wind speed (m s^{-1}) at 10 m simulated from different experiments in group III for storms (a) Dagmar, (b) Emma, (c) Kyrill, (d) Christian, (e) Ulli, and (f) Xaver.

and uncoupled models compared with low-resolution models. The coupled model is more sensitive to the horizontal-resolution model compared with the uncoupled model when simulating storms.

In reasonable ranges, the coupling time interval does not have a significant statistical influence on the storm intensity or the precipitation based on the limited range of cases used in this study.

From the simulation results, we can conclude that the model resolution and the dynamic wave influence should be taken into consideration in further model development.

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