2. Appendix B. D1.2

Implementation of wave stress in the atmospheric model WRF

Jianting Du et al.

The surface stress (or the momentum flux from the atmosphere to the ocean) is one of the most important factors that impact the air-sea interactions. The goal of the present study is to investigate the state of the art of the air-sea momentum flux, and to improve the simulation the storm wind by taking into account of the waves impact. In section 1, we describe how the surface stress impacts the atmospheric boundary layer in WRF model. In section 2, the Wave Boundary Layer (WBL) model according to Hara & Belcher (2004) and Moon (2004) is implemented to the 3rd generation wave model SWAN to better predict the waves and to better estimate the surface stress.

1. The stress method in the atmospheric model

The MYNN is described in detail in Nakanish (2001-2009). Here we briefly go through the equations that directly impacted by the surface stress. The one-dimensional equations for ensemble-averaged variables are given by:

$$\frac{\partial U}{\partial t} = -\frac{\partial}{\partial z}\langle uw\rangle + f(V - V_g)$$
$$\frac{\partial V}{\partial t} = -\frac{\partial}{\partial z}\langle vw\rangle - f(U - U_g)$$

In which the turbulent flux $\langle uw\rangle$are solved by the Turbulent Kinetic Energy (TKE) equation:

$$\frac{dQ}{dt} - \frac{\partial}{\partial z}\left[LqS_q\frac{\partial Q}{\partial z}\right] = 2(P_s + P_b - \varepsilon)$$

Where $Q = q^2$ is twice TKE. On the left hand side is the time dependence and vertical diffusion. And on the right hand side is the shear production, buoyancy production and dissipation term respectively. Then the

$$-\langle uw\rangle = K_m\frac{\partial U}{\partial z}$$
$$-\langle vw\rangle = K_m\frac{\partial V}{\partial z}$$

$$K_m = LqS_m$$

Where master length scale L and q are calculated from the TKE equation, and S_m is solved by MYNN level 2, level 2.5, and level 3 methods which are also functions for L and q. The surface stress impact the solution of the TKE equation by two ways. One of them is kinetic way by changing the sheer production P_s which is described as follows:

The surface stress (τ_s) is represented by the friction velocity (u_*). $\tau_s = \rho_a u_*^2$, ρ_a is the air density. It directly impacts the first model level of the sheer production by:

$$\frac{P_{d1}+P_{d2}}{2} = \frac{u_*^3}{\kappa z}\left(\phi_m - \zeta\right)$$

Where $P_{d1} = (P_s + P_b)_1$ is the sum of the sheer and buoyancy production at the first model level.

$$\phi_m = \begin{cases} 1 + (5-1)\,\zeta, & \zeta \geq 0 \\ \frac{1}{\sqrt[4]{1-16\zeta}} & \zeta < 0 \end{cases}$$

In neutral condition, $\varsigma \sim 0, \phi_m \sim 1$, and the production at the first model level will only depend on u_* and the production at the second model level. The impact will transfer to higher levels by the diffusion terms in the TKE equation.

The other way that u_* impacts the solution of TKE equation is by changing the master length scale:

$$\frac{1}{L_k} = \frac{1}{L_S} + \frac{1}{L_T} + \frac{1}{L_B}$$

Where $L_k$is the master length scale at level k, L_T and L_B are the length scale dependent on the depth of ABL and buoyancy. L_S is the length scale in the surface layer which is written as:

$$L_s = \begin{cases} \kappa z/3.7, & \zeta \geq 1 \\ \kappa z\left(1+2.7\zeta\right)^{-1}, & 0 \leq \zeta < 1 \\ \kappa z\left(1-\alpha_4\zeta\right)^{0.2}, & \zeta < 0 \end{cases}$$

$$\zeta = \frac{z}{L_m}$$

Where L_m is the Monin-Obukhov length, and it is directly impacted by u_*

$$\frac{1}{L_m} = \begin{cases} \frac{B_r \ln\left(\frac{z_{\frac{1}{2}}+z_0}{z_0}\right)}{z_{\frac{1}{2}}}, & B_r = 0, u_* < 0.01 \\ \frac{\kappa g T_*}{\theta_{\frac{1}{2}} u_*^2} & B_r \neq 0 \end{cases}$$

If the roughness method is applied, u_* is estimated diagnostically from the roughness length (z_0):

$$u_*^{n+1} = \frac{u_*^n + \kappa u_{\frac{1}{2}}/\psi_x}{2}, \quad \psi_x = \ln\left(\frac{z_{\frac{1}{2}}+z_0}{z_0}\right) - \psi_m$$

Here u_* at the present time step is the average of the previous value (u_*^n) and the new estimation from z_0 to avoid sudden changes.

When the stress method is applied, the value of u_* at the present time step is directly received from the wave model. Thus it uses fewer assumptions than the roughness method. The method to calculate u_* in the wave model is described in the next section.

2. The stress estimation method in the ocean wave model

In the third generation ocean wave model, the evolution of the wave spectrum is governed by the action balance equation:

$$\frac{dN}{dt} = S_{in} + S_{nl} + S_{ds}$$

On the right hand side of the action balance equation are the three source functions of wind-wave generation in deep water condition. Those are: wave growth by the wind S_{in}, nonlinear four-wave interaction S_{nl}, and wave dissipation due to white capping S_{ds}. The surface stress is estimated in the wind-input source functionS_{in}. There are various ways to estimate the surfaces stress. The simplest but mostly used way is to use a drag relation that fits to previous measurements. For example, in SWAN default setting, it uses the 2nd order fit according to Zijlema (2012):

$$C_d = \left(0.55 + 2.97\tilde{u} - 1.49\tilde{u}^2\right) \times 10^{-3}, \quad u_*^2 = C_d u_{10}^2$$

There are also other parameterizations which use Charnock relations to parameterize z_0 and also take into account of the wave impact. (e.g. Oost 2005, Drennan 2003, Fan 2012). Some of them are applied to coupling systems (e.g. COAWST), but they are rarely used in the wave models. Thus, numerically they are coupled, but physically they are not fully coupled because the wave model and atmospheric model use different surface stresses.

One remarkable approach for coupling is according to Janssen (1991). The wave model utilize the Janssen's (1991) wind-input source function and transfer the z_0 which considers the impact of wave induced stress (τ_w) to the atmospheric model. Thus both of the two models share the same z_0 which is physically more complete than the others. Such an approach is implemented in the COAWST coupling system for this project before. Now, the u_* calculated from this approach is also enabled to transfer to the atmospheric model (stress method). Thus it requires fewer assumptions in the atmospheric side. Although this approach is physically more reasonable, as we showed before, it results in much too high surface stress under high wind speed conditions that is inappropriate to be used in the coupling. Hens a more advanced approach is needed to improve the surface stress estimation.

Among the others the WBL model is chosen to be used for the following reasons:

It implicitly takes account of the sheltering effect. That is the longer waves will absorb the stress from the atmosphere so that the growth of shorter waves will be reduced. Thus the total surface stress which is integrated from the wind-input source function is also reduced compare to Janssen's (1991) scheme.

It follows the momentum conservation low so that the momentum loss from the atmosphere is always equals to the momentum gain by the waves and currents.

It follows the energy conservation low so that the wind profile change within the WBL due to the wave impact is also taken into account.

The WBL model (Hara & Belcher, 2004; Moon, 2004) has been used in several studies (e.g. Moon, 2007; Fan 2009; Reichl, 2014). But it is usually used as a post-processing tool and has never been used as a wind-input source function before in the ocean wave model. The WBL model is described as follows.

The momentum conservation at the lower part of atmospheric boundary layer above the sea surface can be expressed as:

$$\tau_{tot}\left(z\right) = \tau_t\left(z\right) + \tau_w\left(z\right) = constant$$

It means that the total turbulent stress equals to the sum of the turbulent stress τ_t and wave-induced stress (τ_w). Where the wave induced stress at height z is equal to the integration of momentum flux to the waves within the range of $\sigma_{min} < \sigma < \sqrt{g\delta/z}$:

$$\tau_w\left(z\right) = \rho_w \int_{\sigma_{min}}^{\sqrt{g\delta/z}} \int_{-\pi}^{\pi} \beta_g\left(\sigma,\theta\right)\sigma^2 N\left(\sigma,\theta\right) d\theta d\sigma$$

Then the turbulence can be expressed as:

$$\begin{aligned}\tau_t\left(z = \frac{g\delta}{\sigma^2}\right) &= \tau_{tot} - \rho_w \int_{\sigma_{min}}^{\sigma} \int_{-\pi}^{\pi} \beta_g\left(\sigma,\theta\right)\sigma^2 2N\left(\sigma,\theta\right) d\theta d\sigma \\ &= \tau_\nu + \rho_w \int_{\sigma}^{\sigma_{max}} \int_{-\pi}^{\pi} \beta_g\left(\sigma,\theta\right)\sigma^2 N\left(\sigma,\theta\right) d\theta d\sigma\end{aligned}$$

The growth rate function is expressed as:

$$\beta_g\left(\sigma,\theta\right) = C_\beta \sigma \frac{\left|\tau_t\left(z = g\delta/\sigma^2\right)\right|}{\rho_w c^2} \cos^2\left(\theta - \theta_w\right)$$

Based on the energy conservation equation within the WBL:

$$\frac{d}{dz}\left(u\tau_{tot}\right) + \frac{d\Pi}{dz} + \frac{d\Pi'}{dz} - \rho_a \varepsilon = 0$$

The wind profile near the sea surface can be expressed as:

$$\begin{cases} \frac{\mathbf{du}}{\mathbf{dz}} = \frac{u_*}{\kappa z} \frac{\tau_{\mathbf{tot}}}{\left|\tau_{tot}\right|}, & z \geq \frac{g\delta}{\sigma_{min}^2} \\ \frac{\mathbf{du}}{\mathbf{dz}} = \left[\frac{\delta}{z^2}\tilde{F}_w\left(\sigma = \sqrt{g\delta/z}\right) + \frac{\rho_a}{\kappa z}\left|\frac{\tau_t(z)}{\rho_a}\right|^{\frac{3}{2}}\right] \times \frac{\tau_{\mathbf{t}}(\mathbf{z})}{\tau_{\mathbf{t}}(\mathbf{z})\cdot\tau_{\mathbf{tot}}}, & \frac{g\delta}{\sigma_{max}^2} \leq z < \frac{g\delta}{\sigma_{min}^2} \\ \frac{\mathbf{du}}{\mathbf{dz}} = \frac{\rho_a}{\kappa z}\left|\frac{\tau_\nu}{\rho_a}\right|^{\frac{3}{2}} \times \frac{\tau_\nu}{\tau_\nu\cdot\tau_{\mathbf{tot}}}, & z_\nu \leq z < \frac{g\delta}{\sigma_{max}^2} \end{cases}$$

The program starts with a first guess of the viscus stress (τ_v) and calculate the growth rate, wave induced stress and turbulent stress over the whole spectrum. Then the wind profile is calculated from the viscus sublayer to the top of the WBL until 10 meters height. The output of 10 meters wind speed (u_{10}^{out}) is compared with the input of 10 meters wind speed (u_{10}^{in}). If they does not equal to each other, the program will start again with an updated estimation of viscus stress using Newton-Raphson method until u_{10}^{out} equals to u_{10}^{in}. Currently the WBL model has been tested in the idealized case and will soon be tested for real storm application.

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3. Appendix D: M1.5

M1.5 Implementation of a coupler

Rodolfo Bolaños, Jianting Du, Xiaoli Larsen

The coupler MCT is in function in the successfully implemented “online” coupling system COAWST, through which we use the atmospheric model WRF and the wave model SWAN in nested domains.

Previously, in the interim report (2014/08), a state of the art review on couplers and coupled models was presented, summarizing the main two approaches for “Online” coupling: a) using a coupler, b) coupling using a file base approach.

The COAWST system was presented in previous project meeting; COAWST is a system that by using a coupler puts together the atmospheric model WRF (used by DTU) and the wave model SWAN (with similar physics to MIKE 21 SW). Because of the time consuming efforts required to implement such kind of coupler in a new set of models, it was decided to use the COAWST system within the project framework to assess the physical processes that we are working on. This allows focusing on the physics of the wave and atmosphere interactions rather than the technicalities of numerics and software (re-)writing and adaptation. In parallel, a PhD student at DHI (Nikhil, N. who did a visit to DTU and DHI during Sep-Dec 2015) is developing a file based coupling between WRF, MIKE21SW and MIKE3.

Figure A shows a diagram of both systems, COAWST being used by the X-WiWa’s PhD student and MIKE coupling being developed by the DHI “external” PhD student. This combined approach is optimal for the project as it allows the identification of physical processes of relevance (within the framework of the X-WiWa’s PhD student) and prepares the bases for further development of MIKE-WRF with more focus on specific processes identified with COAWST and of potential relevance for Danish waters.

It has to be noted that the use of a coupler or a file based coupling is only relevant for “online” coupling approach, where exchange of information between atmospheric and wave model occurs on a short model time scale. While, in “offline” coupling, exchange of information occurs as input to models and not as a dynamic exchange during the simulation. Online coupling being more CPU and technically demanding than offline coupling. Here comes the importance of using COAWST to identify any physical process that may require online coupling and under which environmental circumstances.

From the tests done so far (“offline” and “online” coupling via sea surface roughness), we can derive some preliminary conclusions:

For wave hindcast in North Sea, CFSR reanalysis wind fields are a good input. A coupling with high resolution WRF has not shown obvious improvement for relatively open sea conditions.

Although improvement of wave source terms can be based in coupling fundaments (eg. use of Fan et al. (2012) roughness formulation), it is not immediately clear that an “online” coupling system provides added values, at least when the interface exchange between the atmospheric model and the spectral wave model is done through the roughness length.

The very similar wind fields from WRF through various roughness length parameterization through coupling are because the values of roughness length from these approaches are close to each other and they are in a range where the winds are not sensitive to it. However, if the roughness length value through a certain scheme (e.g. Oost et al. at strong winds) is beyond this range, the wind field can be significantly different. The challenge is then to obtain the correct values for example at coastal areas with shallow environments. Parametrization of roughness length in WRF is through the 10-m wind speed, which is often a reasonable approximation for open sea conditions. It is expected that a wave model, with high resolution bathymetry, water level and fetch conditions considered, can provide improved surface wave properties and therefore better surface conditions as input to the atmospheric modeling.

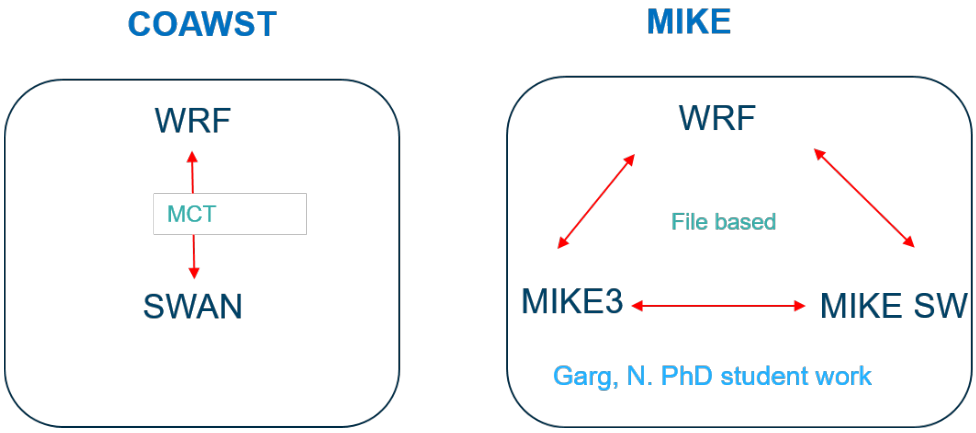


Figure A. Diagram of COAWST and MIKE coupled systems.

4. Appendix C. D1.11

D1.11 Report on the strategy and efficiency of the methodology

Rodolfo Bolaños, Xiaoli Larsén, Jianting Du

The methodology means the way we couple the atmospheric and wave modeling. We are close to finishing the development of the coupling method between the atmospheric and wave model through stress, instead of through roughness length as done previously. Therefore, the current report will be updated to include the impact of this approach to wind, waves and their type of coupling (online versus offline).

Here we differentiate the physics (main concern of the project) from the numerics (intrinsic in any numerical work).

Numerics

As mentioned in M 1.5, two approaches are being done in parallel regarding "online" system. One is the use of an already coupled system (COAWST) to study the physics and the second one is the development of a file base coupling system using MIKE. When referring to online systems, the use of COAWST is numerically more efficient than the file based systems because it allows parallel running and avoid the writing of files frequently for exchange of information. Additionally the online system so far is available for PC computer and not HPCs via Python subroutines.

Physics

The ultimate questions we need to answer are: Where do we expect benefit from wave input in the atmospheric modeling? What are the "wanted" wave parameters for wind, and especially storm wind modeling, in open sea as well as in coastal? Can the online coupling contribute to better wind and wave estimations compared to the more standard offline coupling?

One of the main concern of the project is the "online" coupling between wind and waves. The tests of the online and offline via the surface roughness showed no difference. Figure B shows the typical drag coefficient (left panel) and roughness length values (right panel) over the ocean. Figure C shows time series of WRF modeled roughness length using three different formulations, which fall in the range as given by Figure B. Within this range, as often observed in several water bodies of open sea condition, the atmospheric model did not show to be sensitive to changes of roughness. These results suggest that it is not expected to obtain improvement in the wind modeling for the open sea conditions if we use the roughness length as the exchange parameter. Here it is relevant to mention the recent work of Shabani et al. (2014) who measured wind stress and drag coefficient over the surf zone, although their measured larger values for relatively low winds (see their figure 22, figure D in the present report) the magnitude of drag is still within the range shown in Figure B.

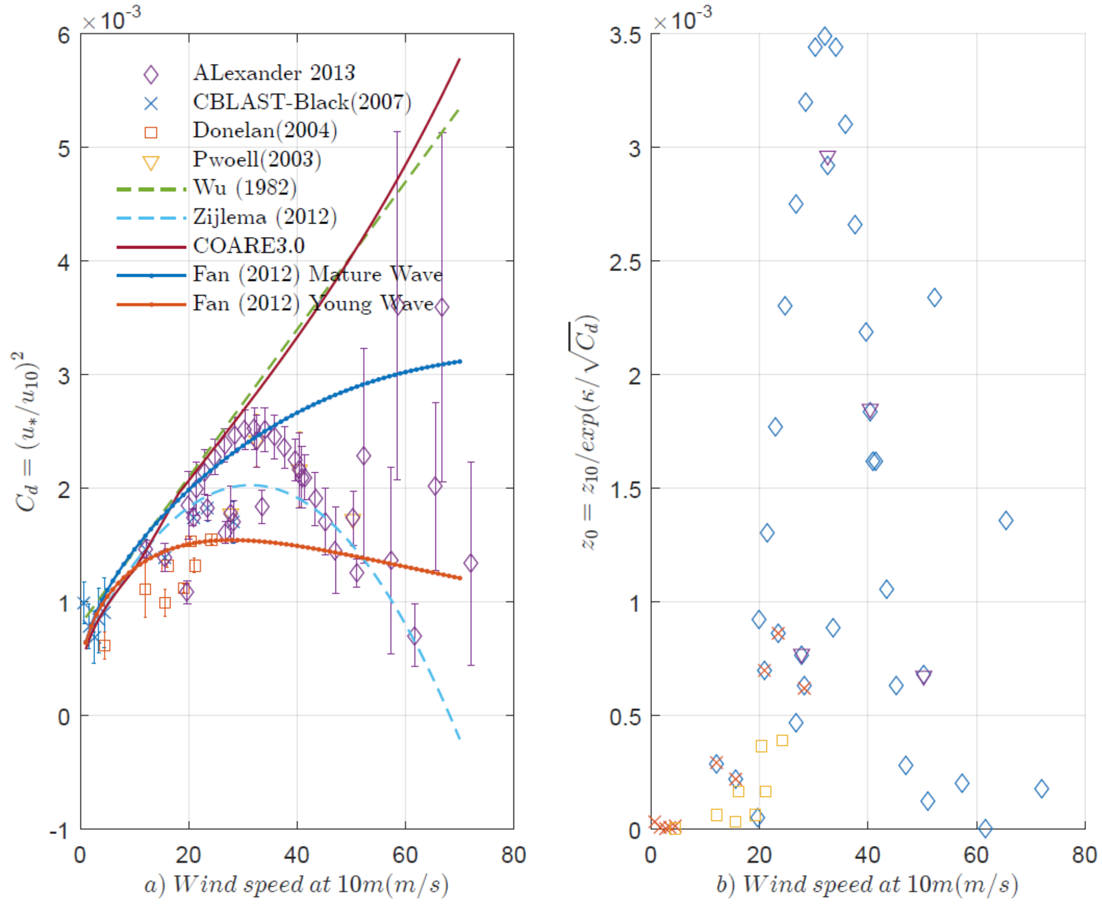
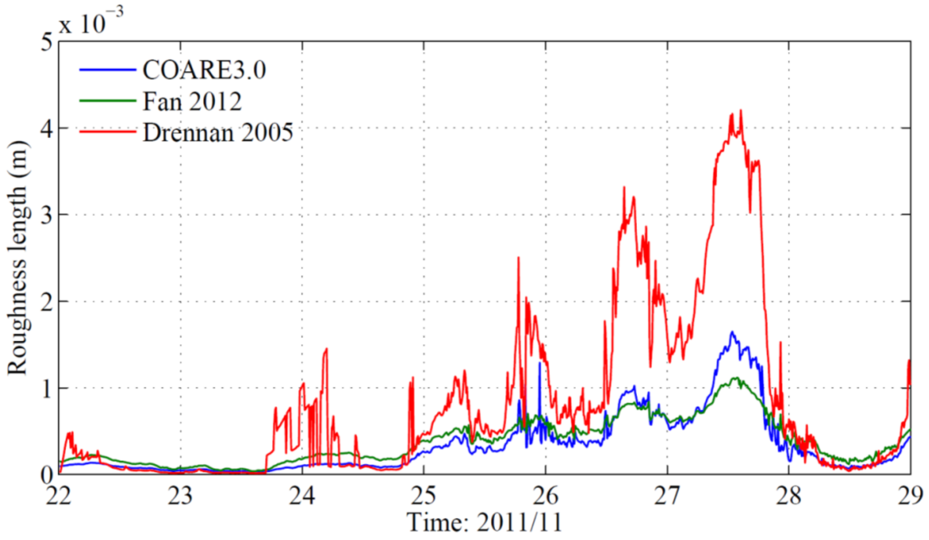


Figure B. Example of drag coefficient (left) and associated roughness length (right) over the ocean for a wide range of wind conditions.



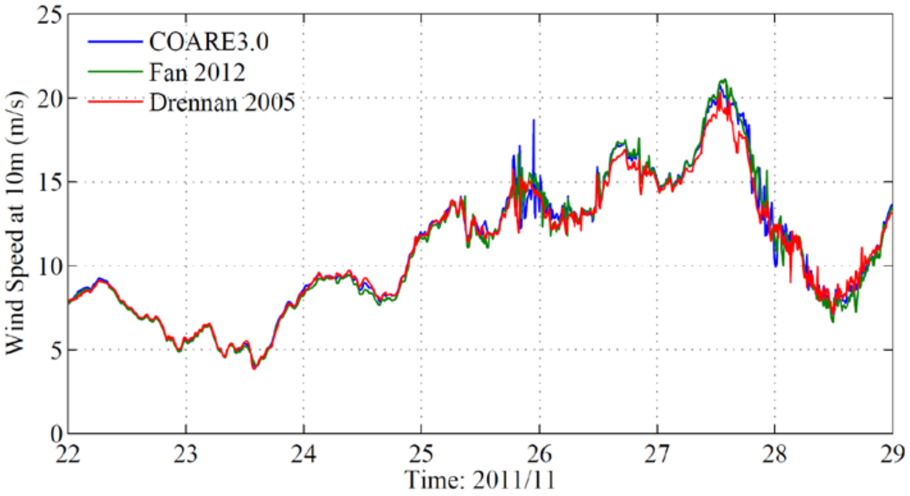


Figure C. Time series of modelled roughness length in WRF from different formulations (top panel) and associated modelled wind speed (bottom panel).

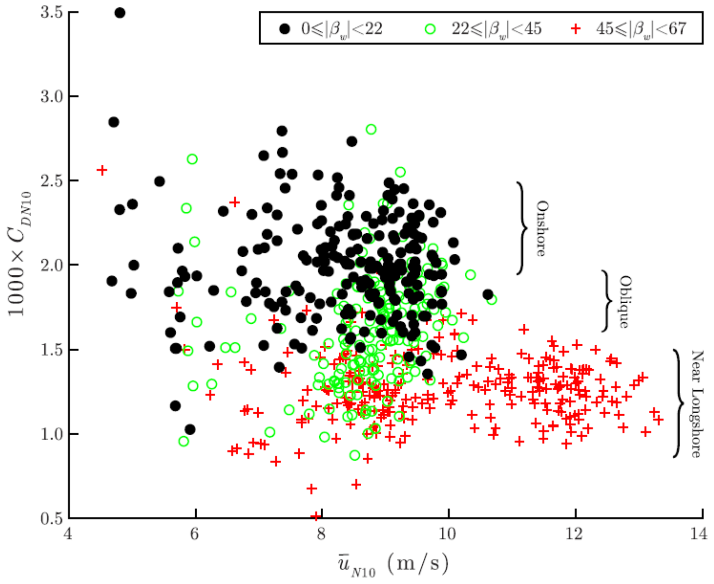


Figure 22. Neutral drag coefficient (C_{DN10}) versus the 10 m neutral wind speed ($\bar{u}_{N10}$). Each data point corresponds to a 15 min data run. The plot contains only near-neutral data points ($|L| \geq 100$ m). The data from both anemometers are included. The data points are binned into different groups, each shown by a separate symbol, according to their $|\beta_w|$.

Figure D. Drag coefficient measurements over the surf zone by Shabani et al., (2014)

Currently, developments of the stress exchange (WBL) are being done by considering an interaction between the wave boundary layer and the wind. This approach involves the development of modified wave source functions that potentially can improve wave results and provide a better description of the bottom boundary layer to the atmospheric model. The effect of this in an online or offline system still need to be assessed in real events. Fetch limited test show that the wave model behavior is closer to empirical curves for short fetches and intense winds (Figure E) while at the same time it gives values of drag coefficient within the expected range (Figure E).

We expect the experiment with the stress coupling method, together with the best setup for both wave and atmospheric modeling to shed lights on the questions given at the beginning of this section.

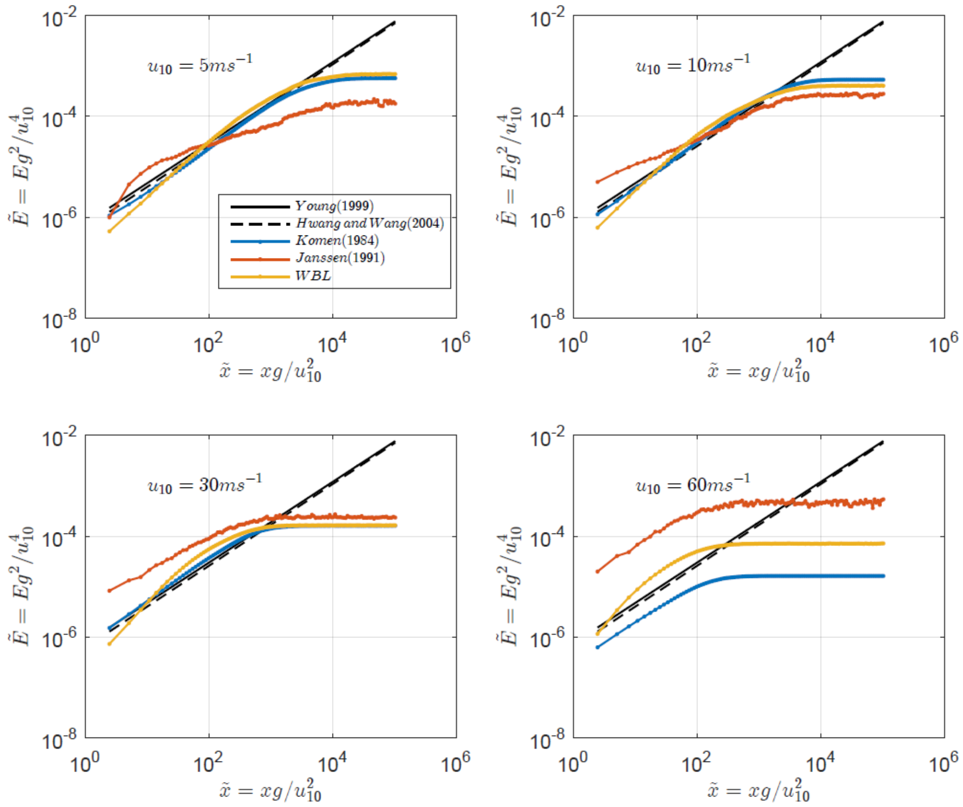


Figure E. Preliminary results of fetch limited idealized cases using the WBL model.

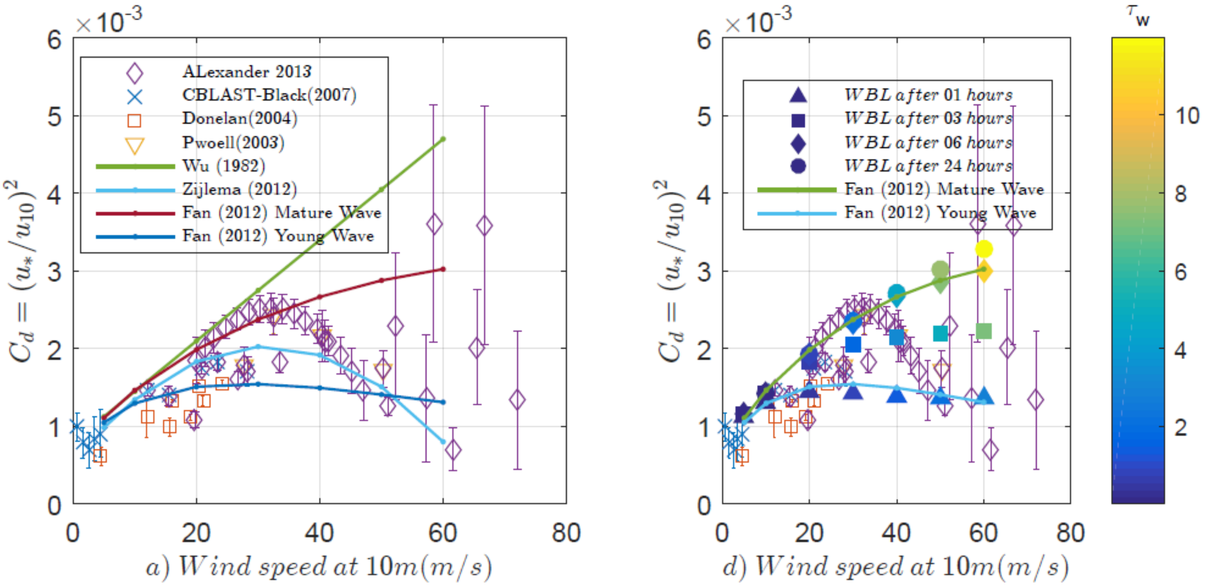


Figure F. Example of drag coefficient measured over the ocean (left panel). Preliminary results of drag coefficient estimated using the WBL model (right panel).

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