Roughness length for coastal waters from wave boundary layer model

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15th Sep. 2016

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--Danish ForskEL X-WiWa (PSO-12020)

16th EMS Annual Meeting & 11th European Conference on Applied Climatology (ECAC) |
12–16 September 2016 | Trieste, Italy

Outline

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- State-of-the-art
- Methodology
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- Results
  - Idealized fetch-limited wave growth
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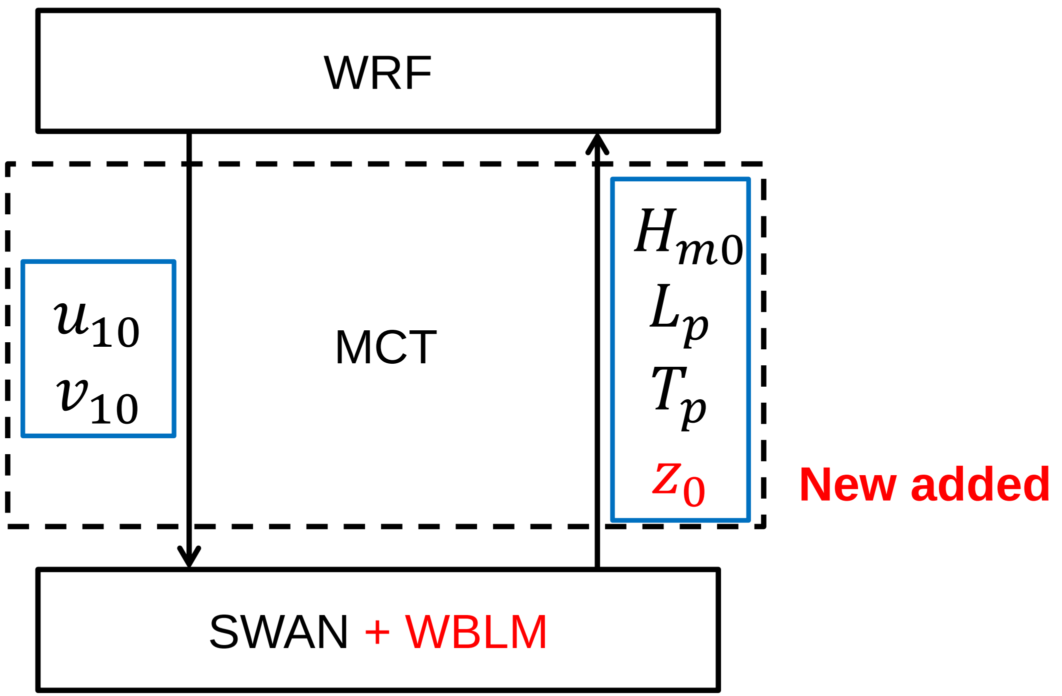
- Conclusion

1. Motivation

To improve the wind and wave simulations during storms by coupling the atmospheric model and the ocean wave model.

COAWST



COAWST: **C**oupled-**O**cean-**A**tmosphere-**W**ave-**S**ediment **T**ransport Modeling System

WRF: **W**eather **R**esearch and **F**orecasting Model

MCT: **M**odel **C**oupling **T**oolkit

SWAN: **S**imulating **WA**ves **N**earshore

DTU

2. State-of-the-art

Parameterization method

$$(z_0, C_d) = F\left(u_{10}, H_{m0}, L_p, \frac{c_p}{u_*}\right)$$

10 m wind speed (u_{10})
significant wave height (H_{m0})
peak wave length (L_p)
peak wave age $\left(\frac{c_p}{u_*}\right)$

Dynamic coupled interface

The loss of momentum form the airflow must, by conservation of momentum, be accompanied by a growth of the water waves.

--Janssen, P. A. E. M. (1991)

Total stress

$$\boxed{\tau_{tot}} = \boxed{\tau_w} + \tau_t$$

Wind-input

$$\boxed{S_{in}} = C_\beta \frac{\sigma}{\rho_w} \frac{\boxed{\tau_{tot}}}{c^2} \cos^2(\theta - \theta_w) \cdot N$$

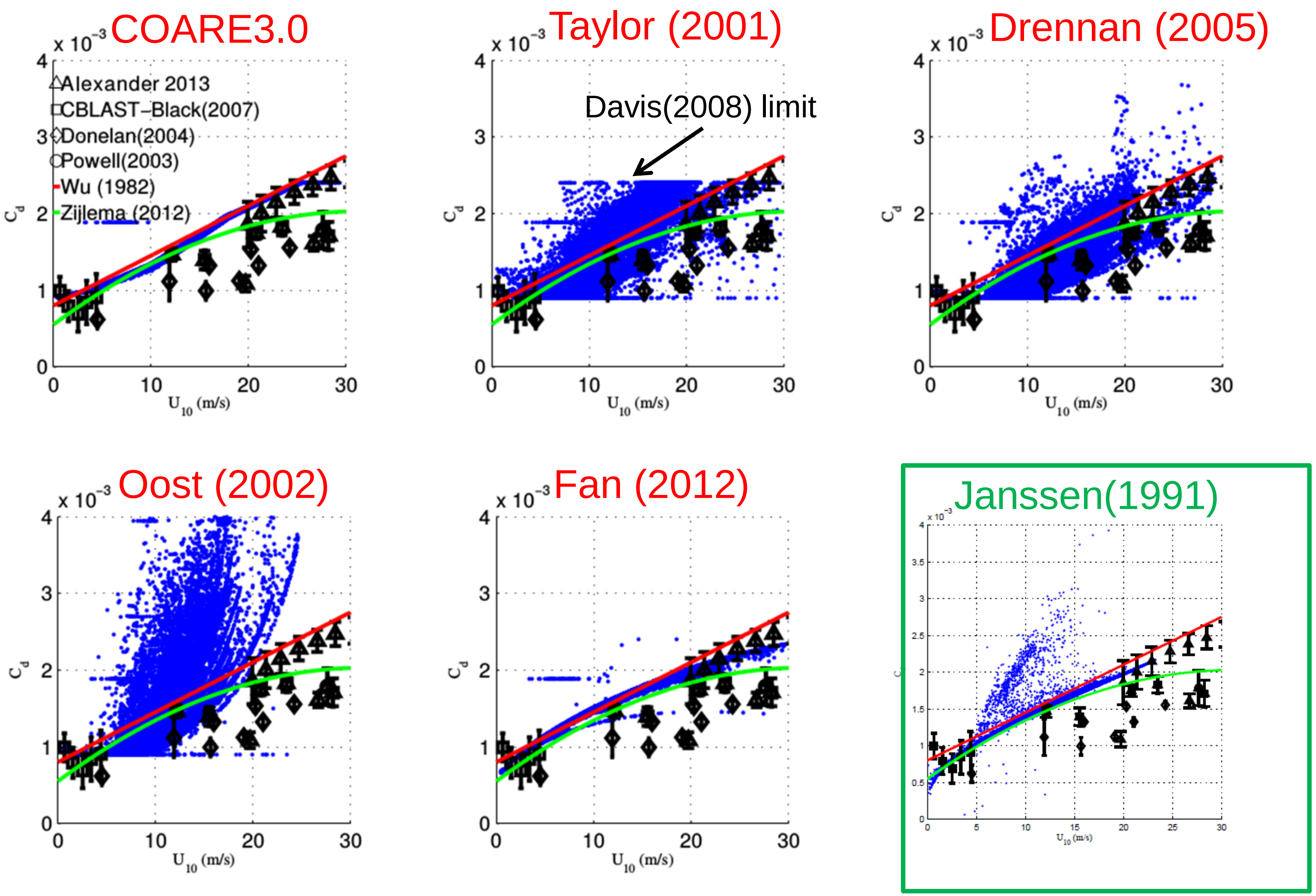
Wave-induced stress

$$\boxed{\tau_w} = \rho_w \iint \sigma^2 \boxed{S_{in}} \, d\theta \, d\sigma$$

2. State-of-the-art

Drag coefficient (C_d) as a function of u_{10}.

- Blue dotes are calculated from **COAWST** during a storm simulation in the North Sea.
- C_d cannot be well parameterized in terms of trend and scatter.
- Janssen (1991)'s method significantly overestimates C_d.



3. Methodology: The Wave Boundary Layer Model (WBLM)

A sheltering mechanism is responsible for generation of the short wind waves, by which wave growth is proportional to the local turbulent wind stress.
-- Chen et. al (2000)

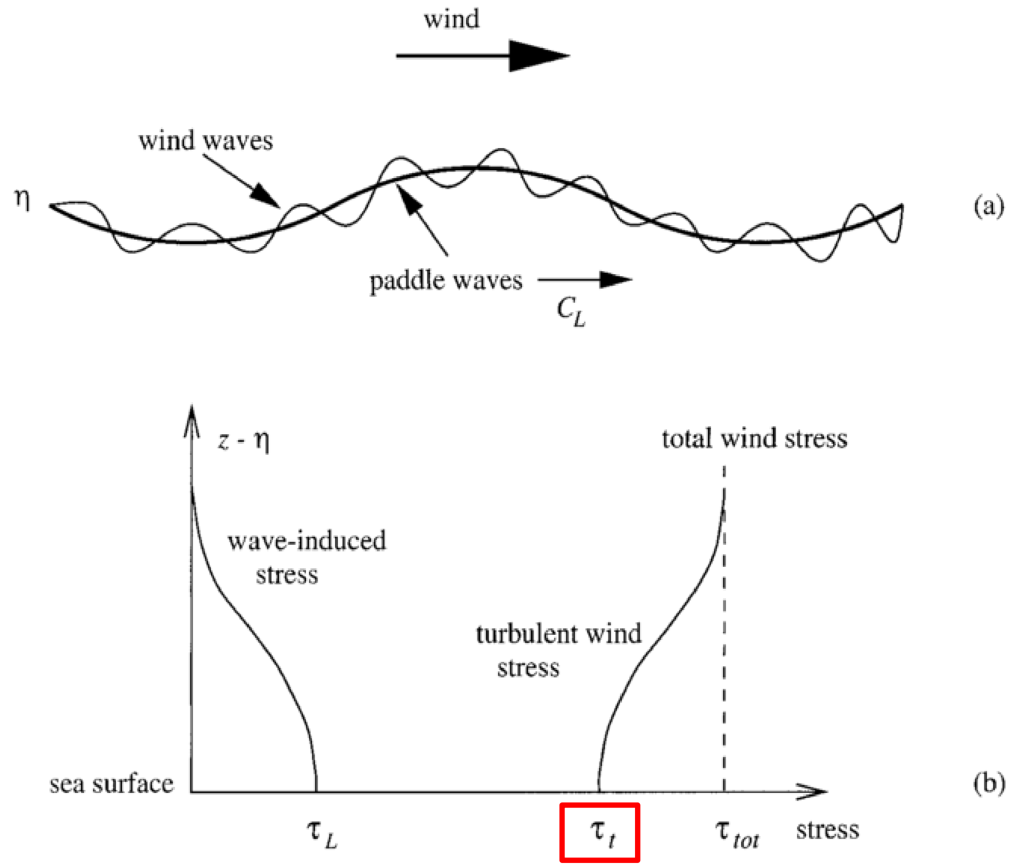


FIG. 1. Schematic of (a) the configuration with wind blowing over wind waves and paddle waves, and (b) the vertical profiles of contributions to the total stress, τ_{tot}.

Chen, G., & Belcher, S. E. (2000). Effects of Long Waves on Wind-Generated Waves. *Journal of Physical Oceanography*, *30*(9), 2246–2256

3. **Methodology:** The Wave Boundary Layer Model (WBLM)

Conservation of momentum :

$$\vec{\tau}_{tot}(z) = \boxed{\vec{\tau}_t(z)} + \vec{\tau}_w(z) = constant \qquad \vec{\tau}_w(z) = \rho_w \int_{\sigma_{min}}^{\sigma_z} \int_{-\pi}^{\pi} \beta_g(\sigma,\theta)\,\sigma^2 N(\sigma,\theta) \frac{\vec{k}}{k} d\theta d\sigma$$

$$\beta_g(\sigma,\theta) = C_\beta \sigma \frac{\rho_a}{\rho_w} \left(\frac{\boxed{u_*^l}}{c} \right)^2 cos^2(\theta - \theta_w)$$

--Wave growth is proportional to the local turbulent stress

Conservation of kinetic energy:

$$\frac{d}{dz}(\vec{u} \cdot \vec{\tau}_{tot}) + \boxed{\frac{d\Pi}{dz}} + \frac{d\Pi'}{dz} - \rho_a \varepsilon = 0$$

Wave-induced energy flux

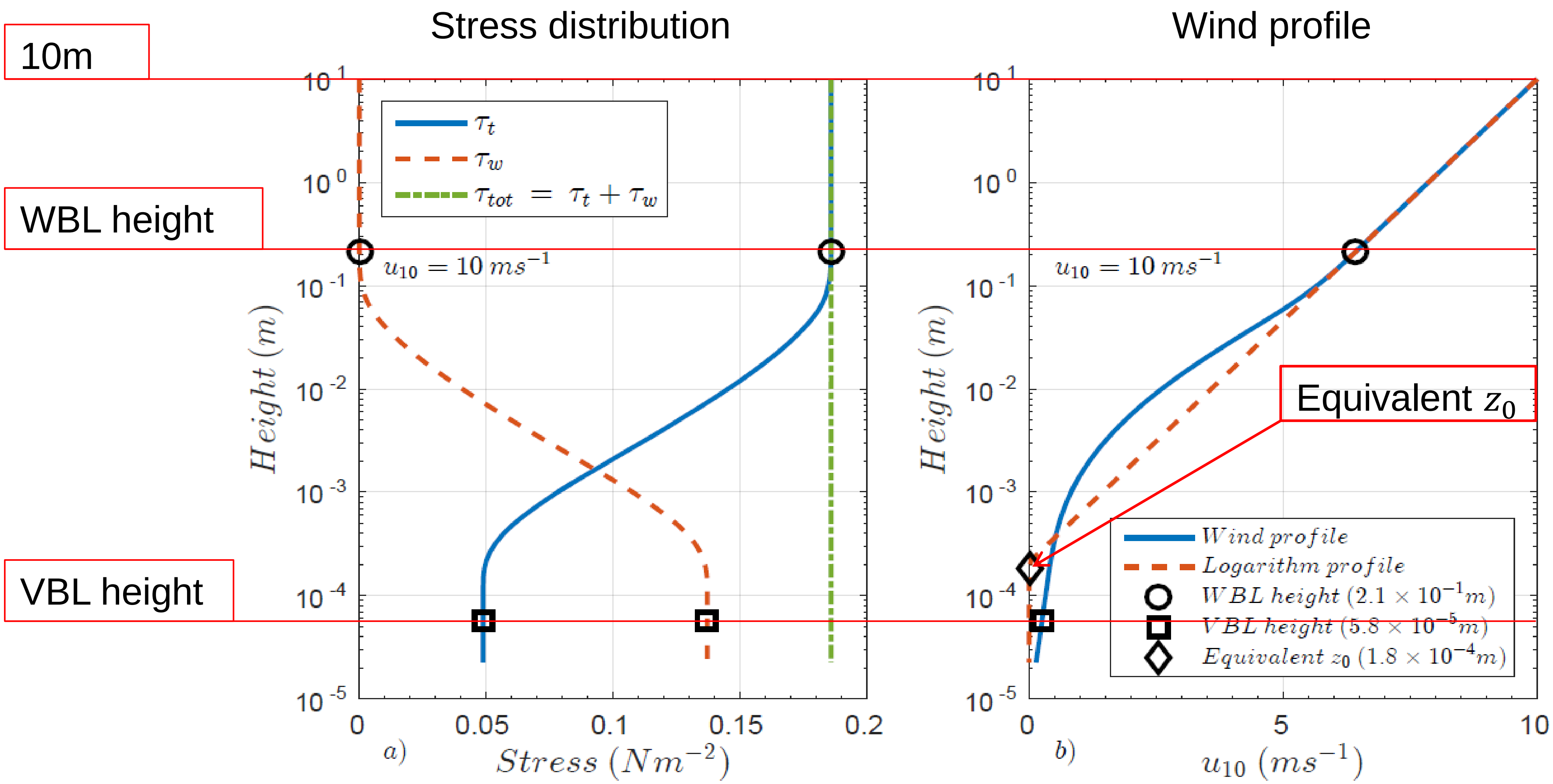
$$\Pi(z) = \int_{\sigma_{min}}^{\sigma} \tilde{F}_w(\sigma)\, d\sigma \qquad \tilde{F}_w(\sigma) = \rho_w \int_{-\pi}^{\pi} \beta_g(\sigma,\theta)\, g\sigma N(\sigma,\theta)\, d\theta$$

$$\frac{d\vec{u}}{dz} = \left[\frac{\delta}{z^2} \tilde{F}_w\left(\sigma = \sqrt{g\delta/z}\right) + \frac{\rho_a}{\kappa z} \left| \frac{\boxed{\vec{\tau}_t(z)}}{\rho_a} \right|^{\frac{3}{2}} \right] \times \frac{\vec{\tau}_t(z)}{\vec{\tau}_t(z) \cdot \vec{\tau}_{tot}}$$

--Wind profile in the wave boundary layer

From Du et al. “The use of a wave boundary layer model in SWAN”, submitted to JGR-Oceans

4. Results: Idealized fetch-limited wave growth



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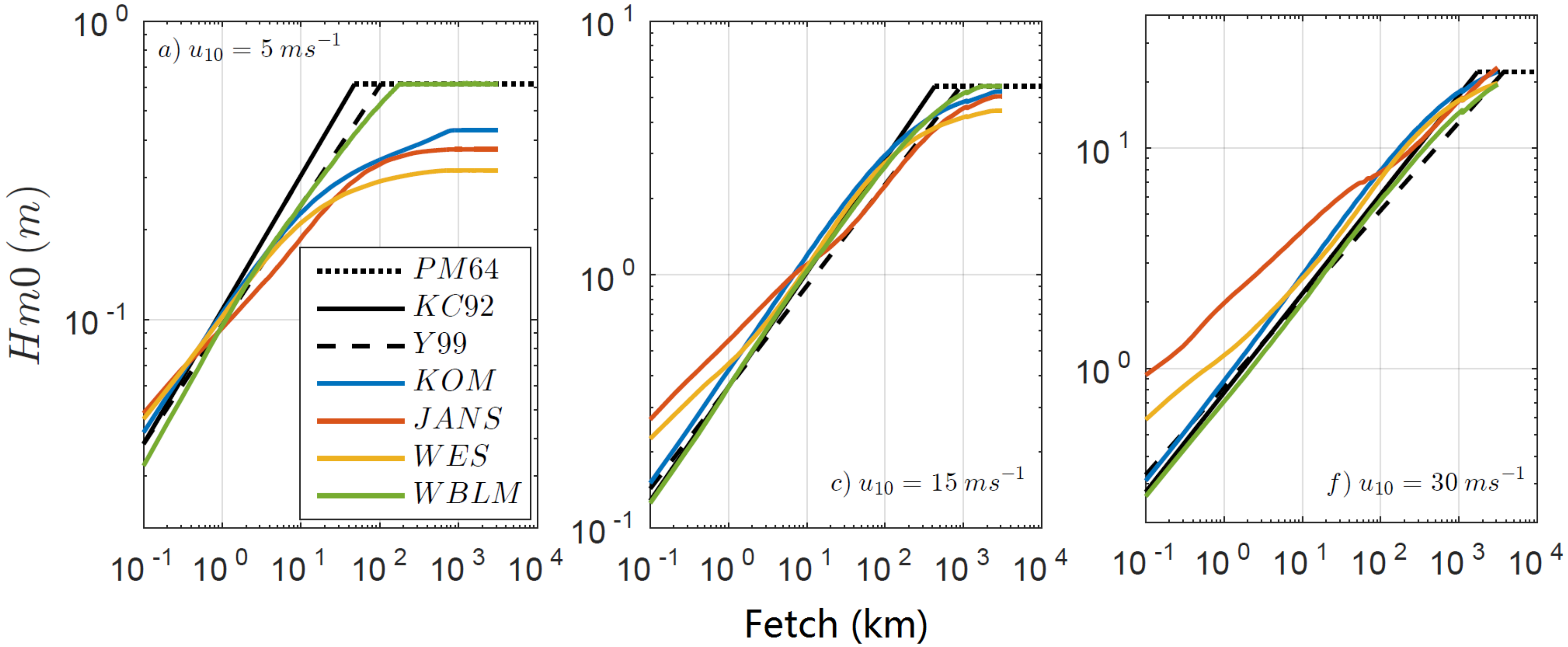

- WBLM closely reproduces the **Kahma and Calkoen (1992) and Young (1999)** curves at all wind speeds and fetches.
- The three original wind-input source functions in SWAN (KOM, JANS, and WES) tend to overestimate/underestimate H_{m0} in short/long fetches.

From Du et al. "The use of a wave boundary layer model in SWAN", submitted to JGR-Oceans

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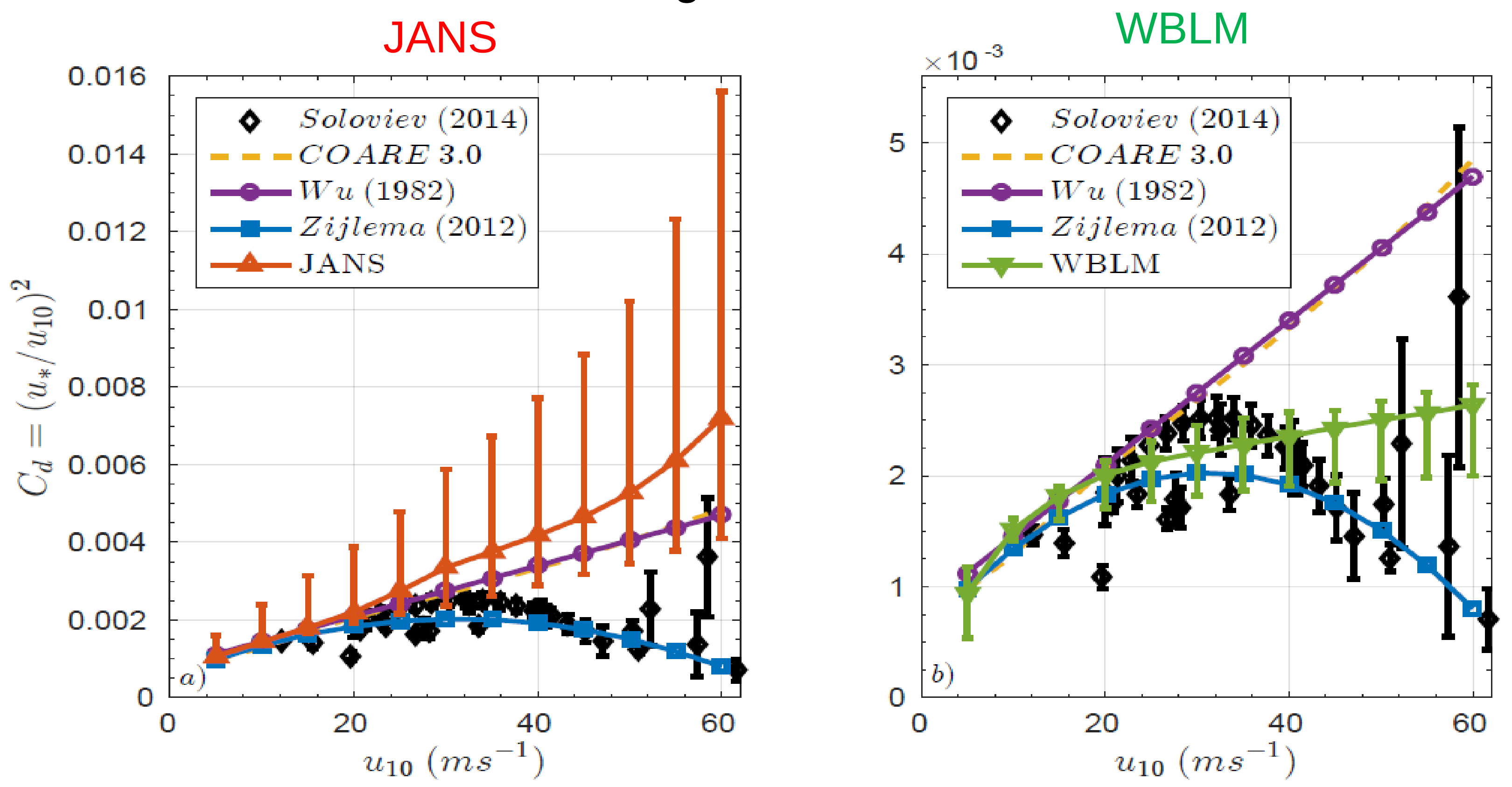

- JANS significantly overestimates C_d.
- C_d of WBLM follows the trend of the measurement data and its distribution gives a wide overlapping with the measurement data for $u_{10} \leq 40ms^{-1}$.

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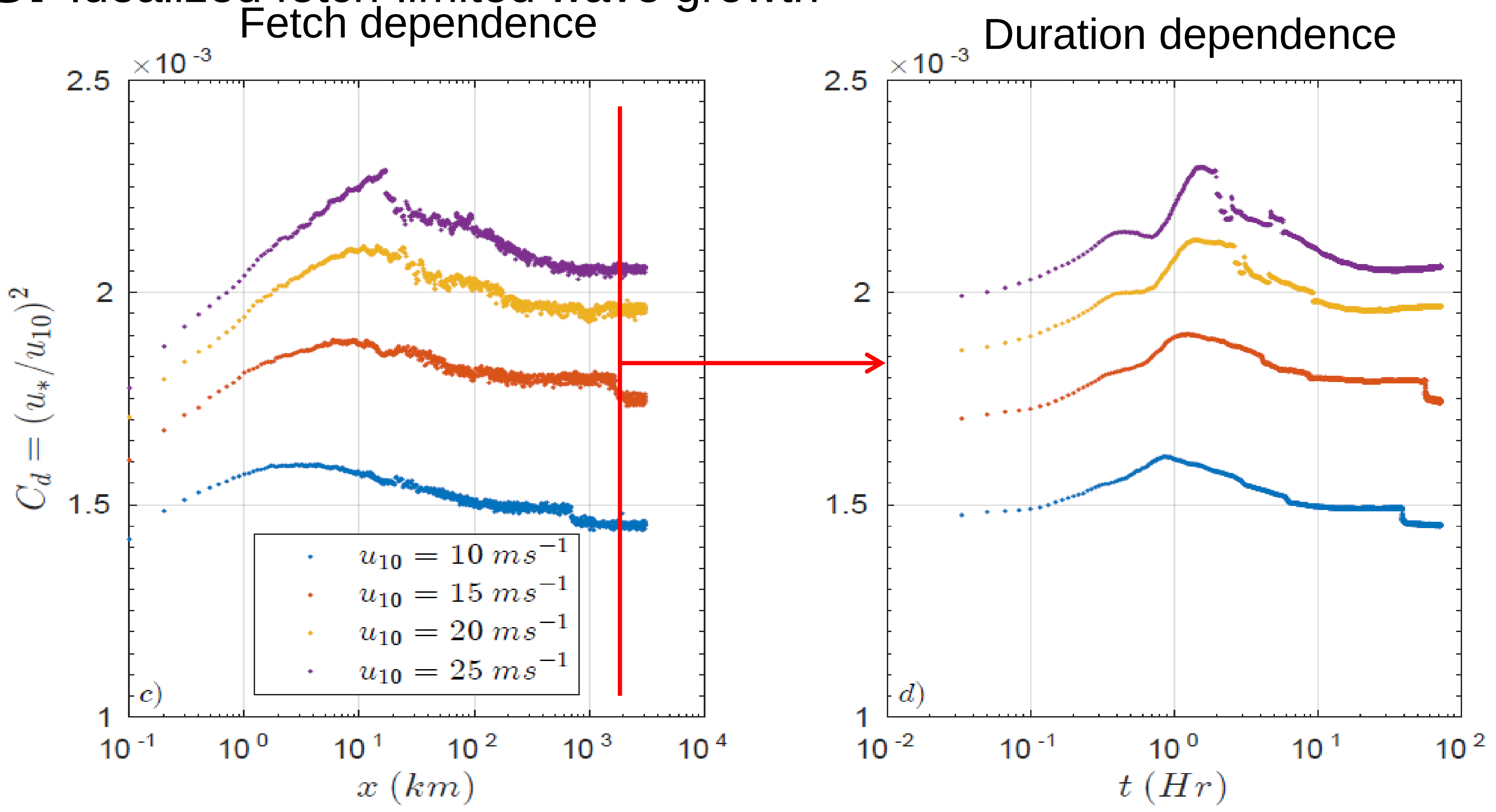
4. Results: Idealized fetch-limited wave growth

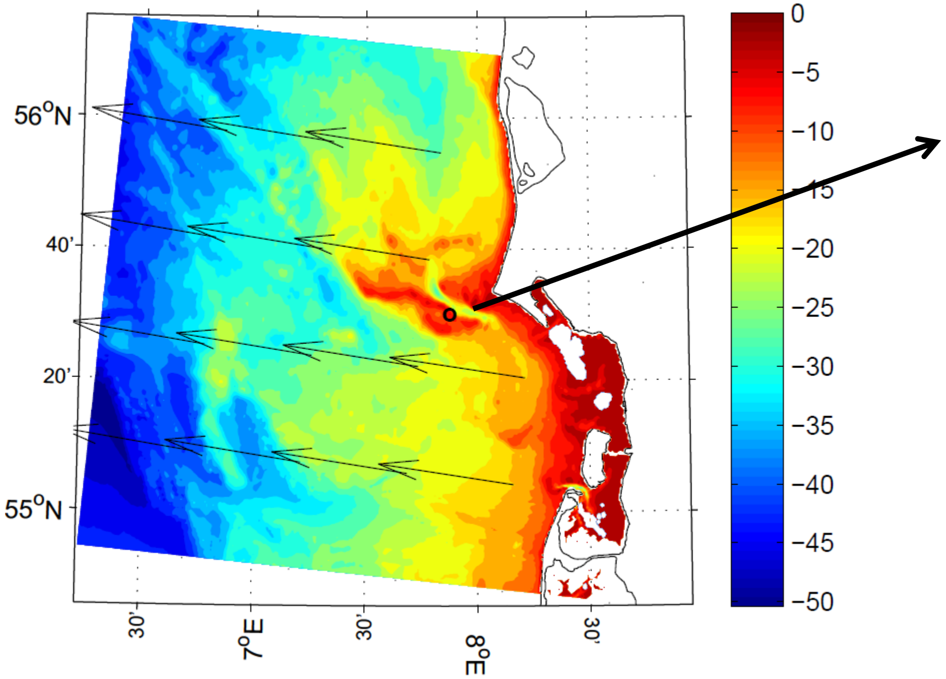


- For fetches shorter than 10 km, C_d increases with fetch; for fetches longer than 10 km, C_d decreases with fetch.
- C_d increases with time in the first 1 or 2 hours and decreases with time afterwards.

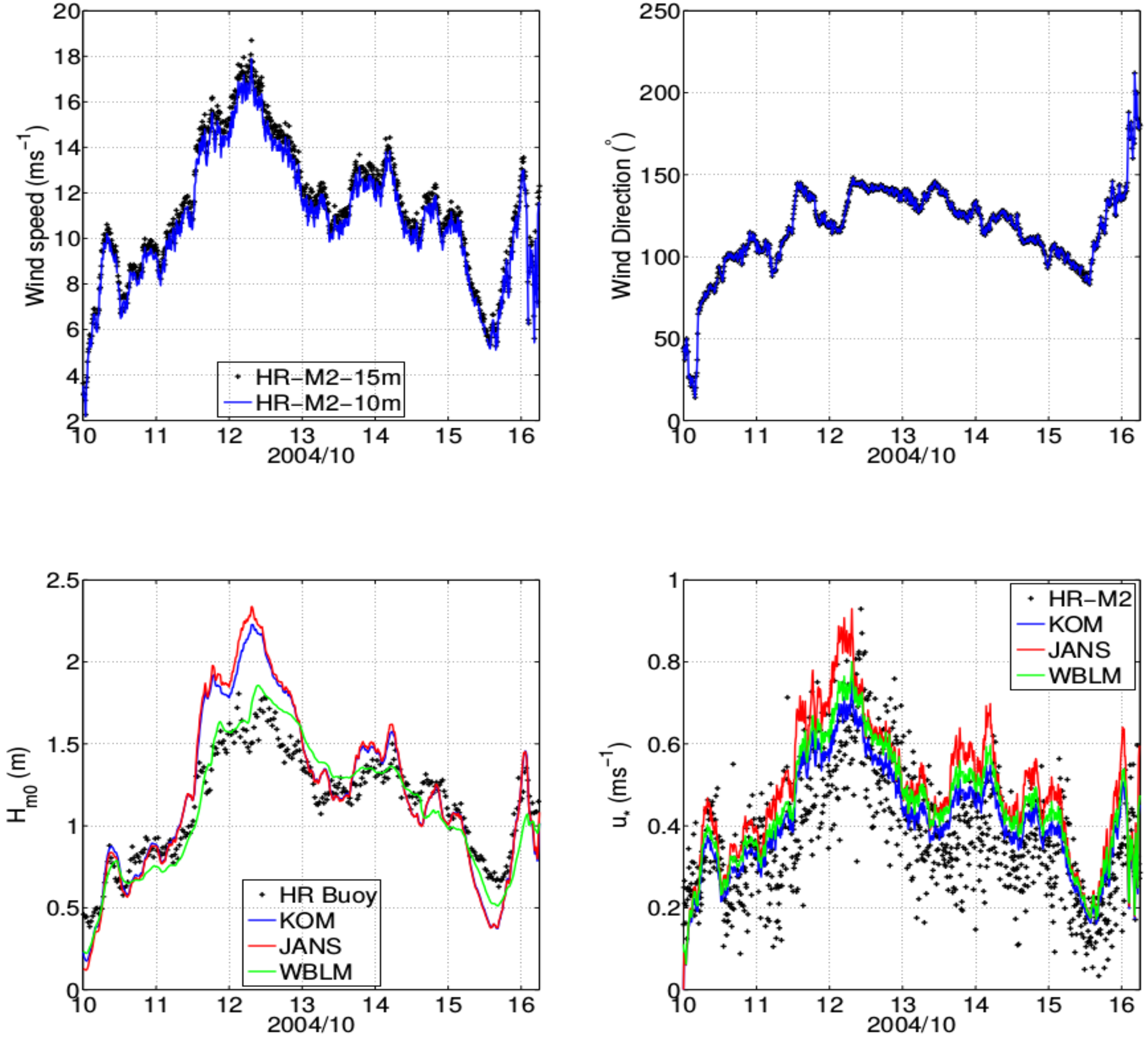
From Du et al. "The use of a wave boundary layer model in SWAN", submitted to JGR-Oceans

4. Results: Real fetch-limited case study

Bathymetry in the model domain (m)



Horns Rev



Storm	Direction at HR	Stability
2002 11 20 - 23	East	Neutral
2002 12 13 - 16	East	Neutral
2002 03 03 - 06	East	Neutral
2004 10 10 - 16	East	Neutral

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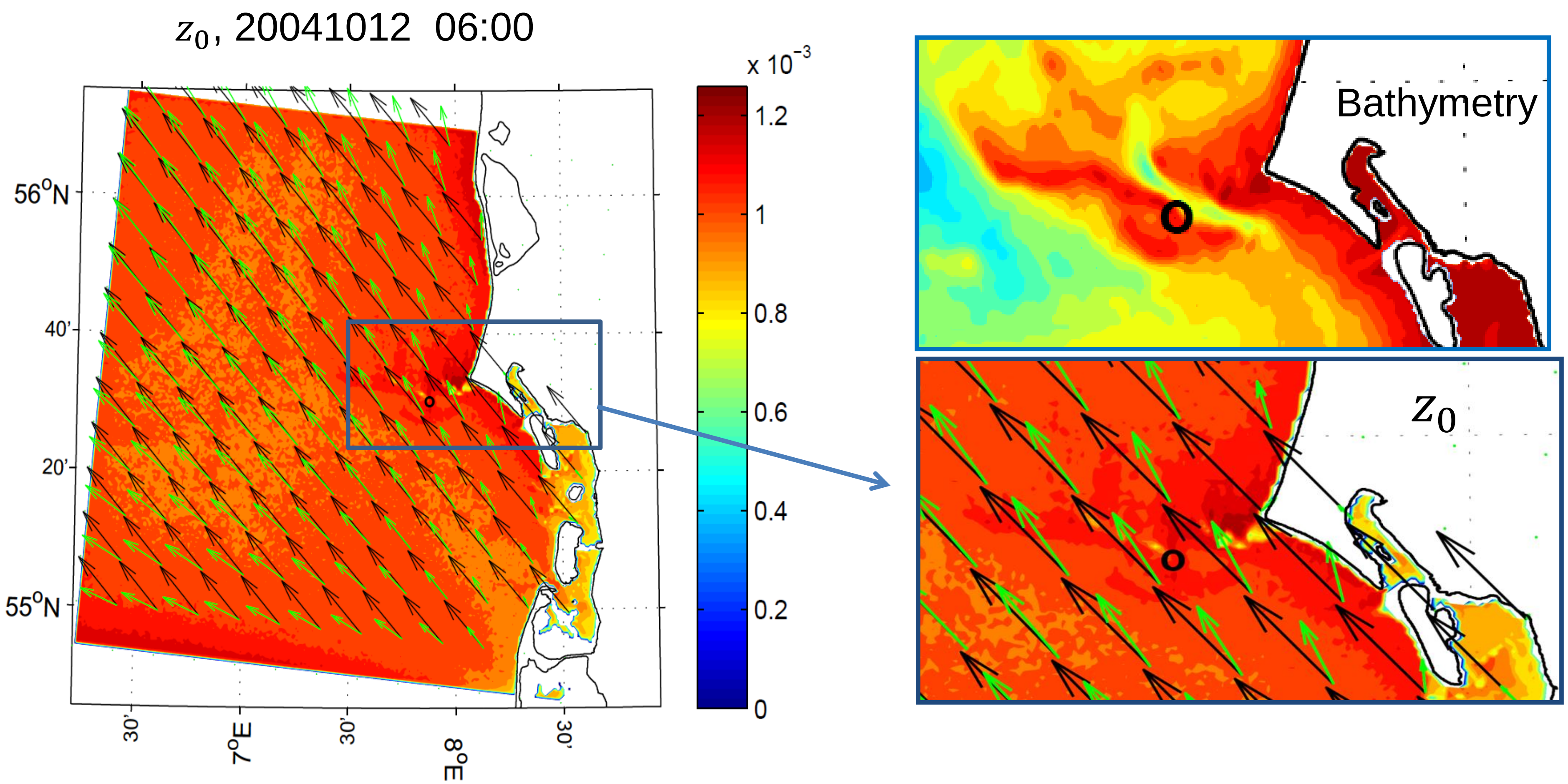

Wind direction
Mean wave direction

- Waves bend to the shore line due to the refraction.
- z_0 calculated from WBLM shows detailed spatial distribution.

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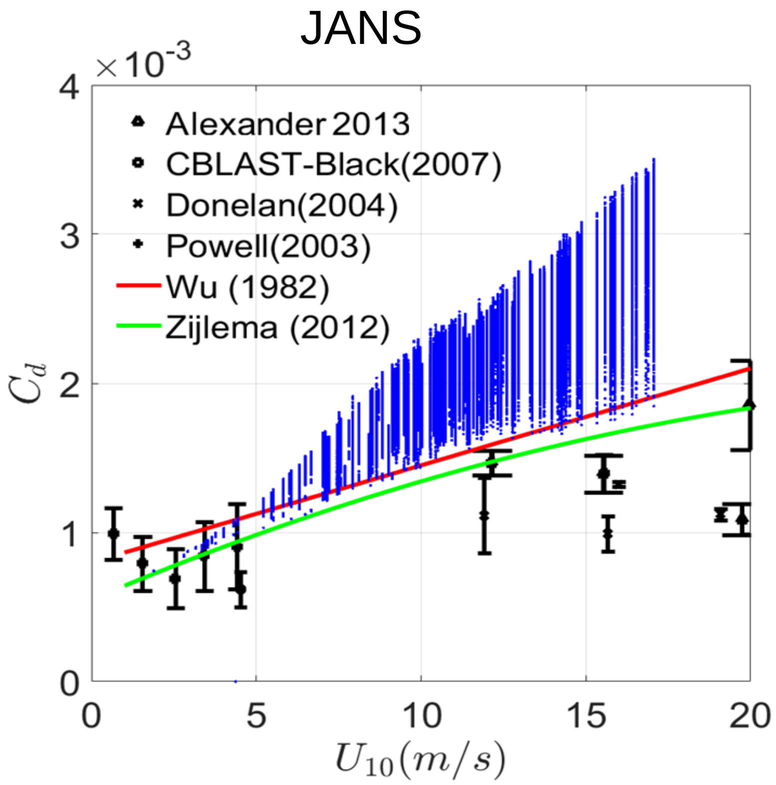

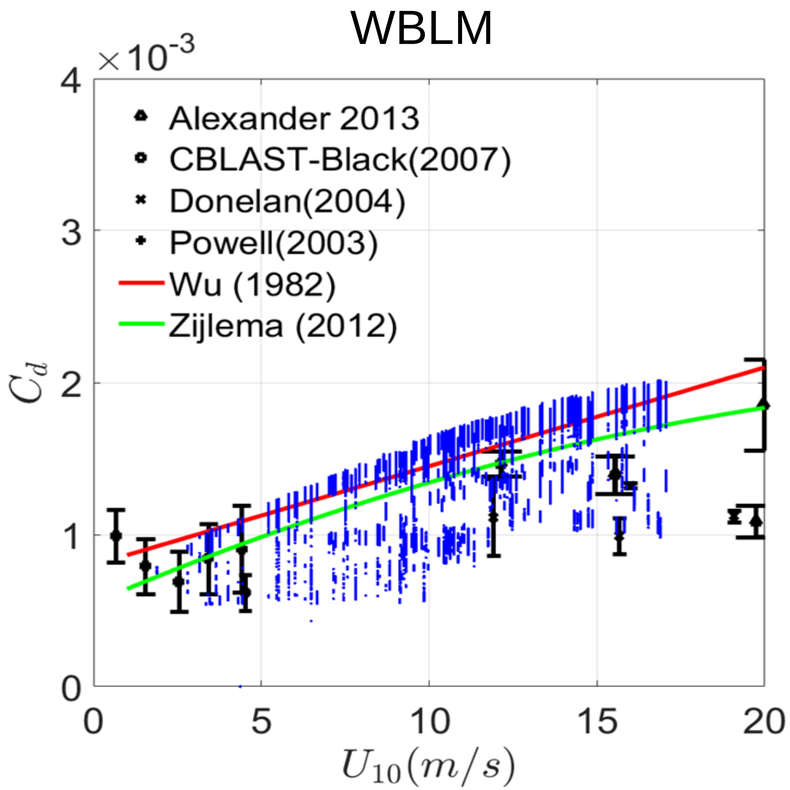

- Blue dotes are calculated from **SWAN** during the experiment.
- Compared with the idealized fetch-limited study, the variance of C_d calculated in **WBLM** covers a wider range of the measurement data.

5. Conclusion

- Sea surface roughness length cannot be properly parameterized by limited wind and wave parameters in complex sea state conditions.

- A Wave Boundary Layer Model (WBLM) is implemented in SWAN as a new wind-input source function, which improves the wave simulation in short fetches.

- The WBLM provides detailed wave characteristics giving more reliable roughness length estimation for coastal zones than the common used parameterization methods.