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Impact of Surface Waves on Wind Stress under Low to Moderate Wind Conditions

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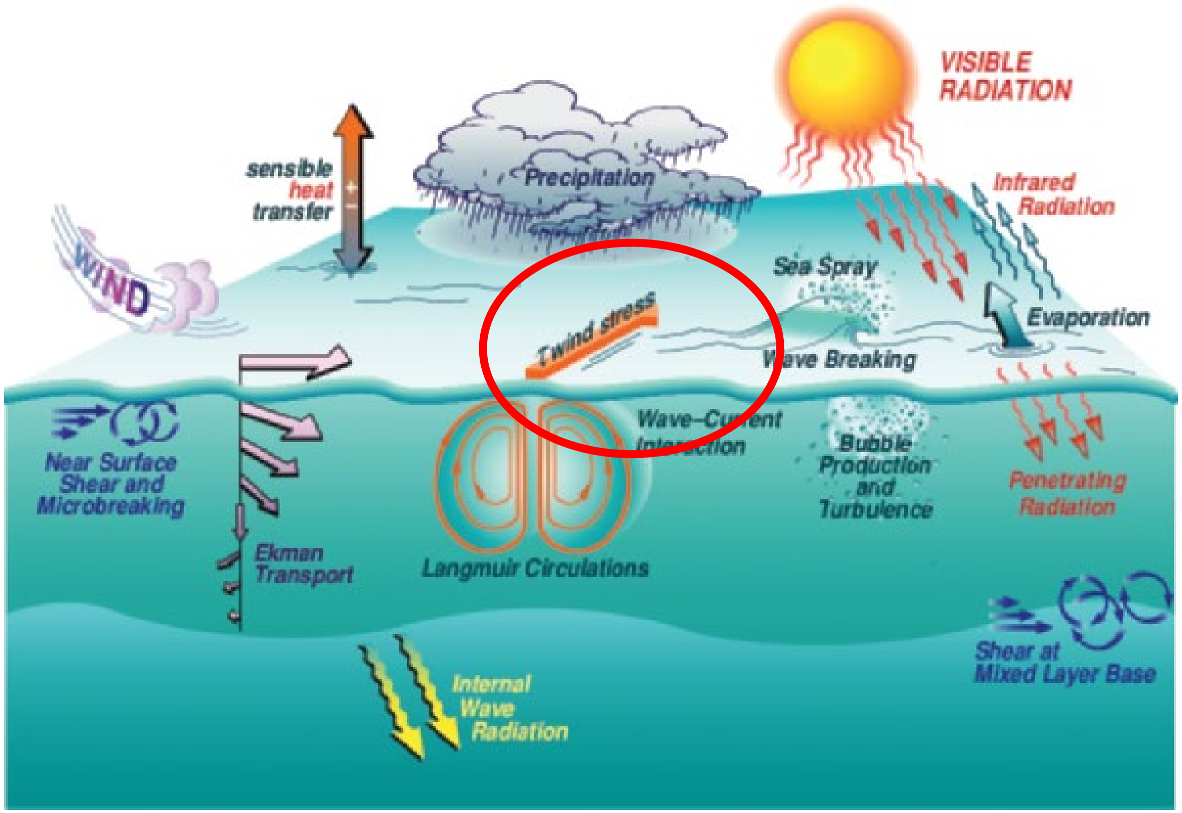
CONTENTS

Background and Aims

Why?



Air-sea interaction processes (Edson et al. 2007)

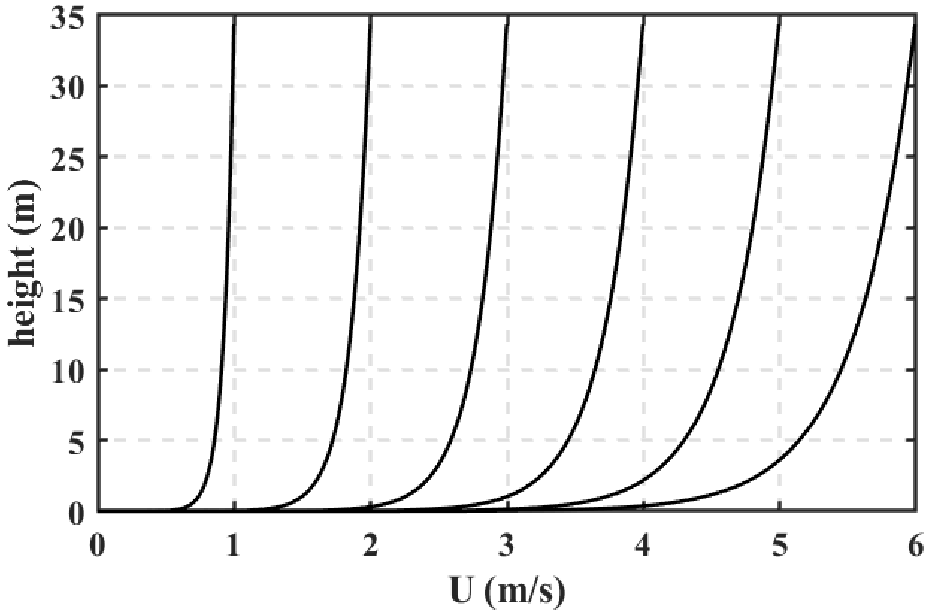
- **Wind stress:**
- **Key parameter**
- **Modeling**
- **Forecasting**
- **Surface is mobile**
- **Surface waves**

Background and Aims

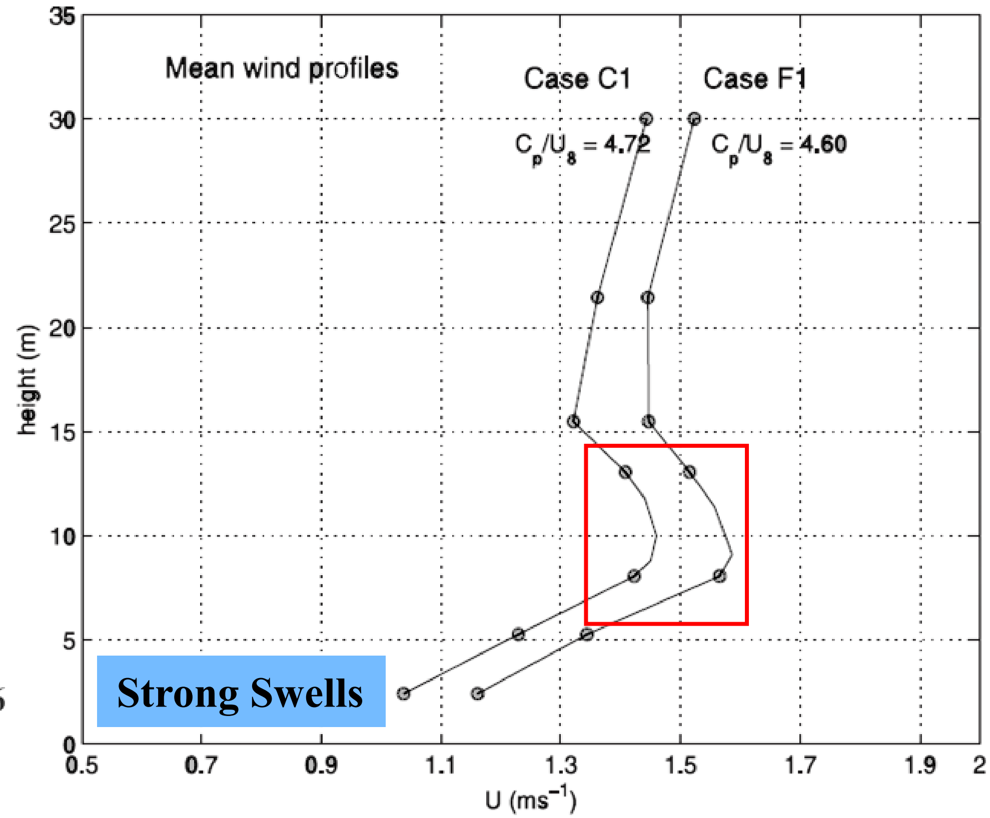
Monin-Obukhov Similarity Theory (MOST)

$$\bar{u} = \frac{u_*}{\kappa}\left[ln\left(\frac{z}{z_0}\right)\right]$$

Logarithmic profile



Validity?



Smedman et al. 2009

- **Invalidity of MOST: Swell √ ; Wind sea ?**
- **Upward momentum flux.**

Background and Aims

Aims

Low to Moderate winds: Swell

Field measurements and model:

- Impact of surface waves on wind stress;
- Validity of traditional MOST;
- Upward momentum flux.

Finally, a preliminary scheme for estimating wind stress.

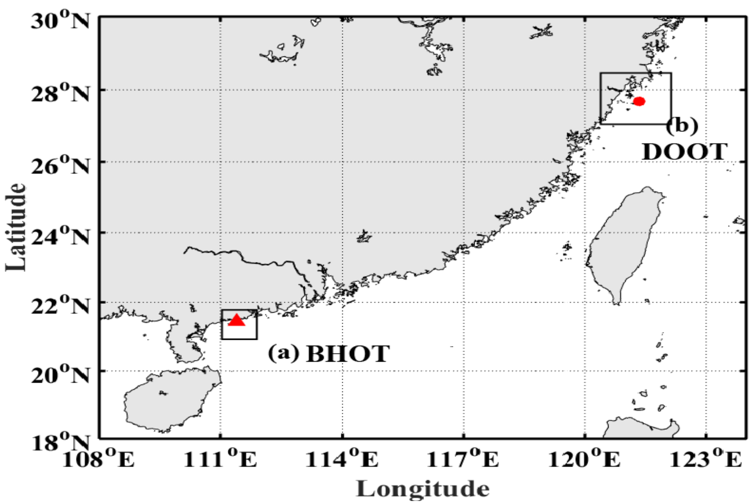
Field Measurements and Datasets

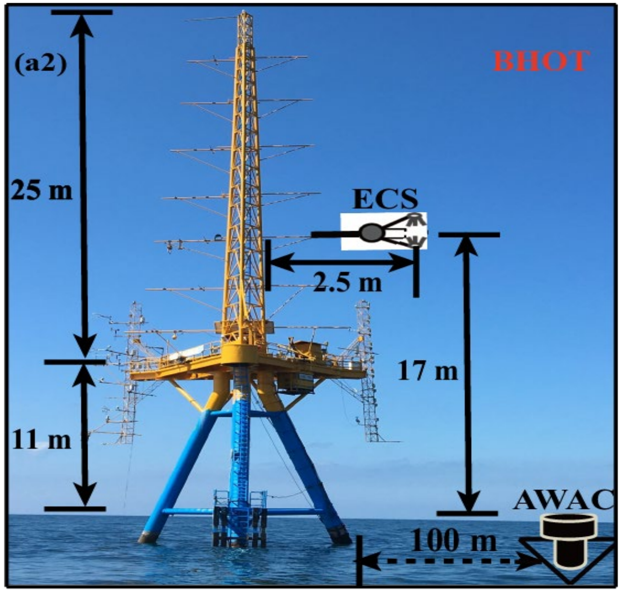
- **BoHe Observation Tower (BHOT)**

Northern SCS; ~**6.5 km** away from the coastline;

Water depth **16** m; Height **17** m, **70°**, 10 Hz, **AWAC**

Datasets: **February 10 to March 11, 2015**



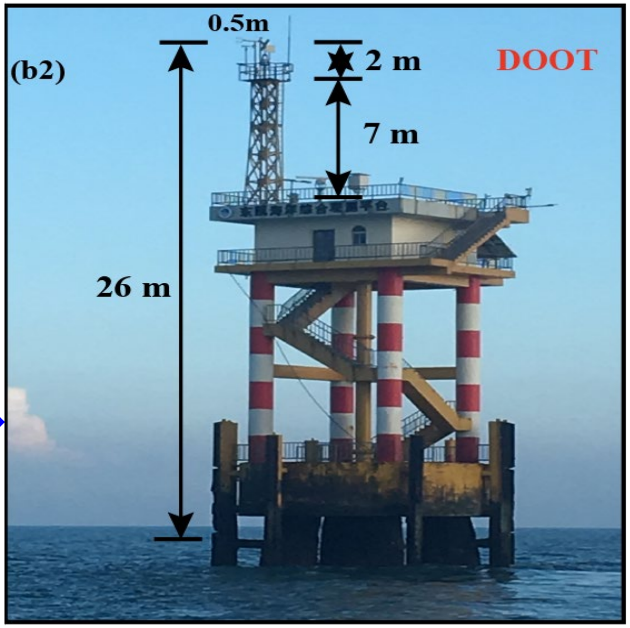


- **DongOu Observation Tower (DOOT)**

Western ECS, **~24 km** away from the coastline;

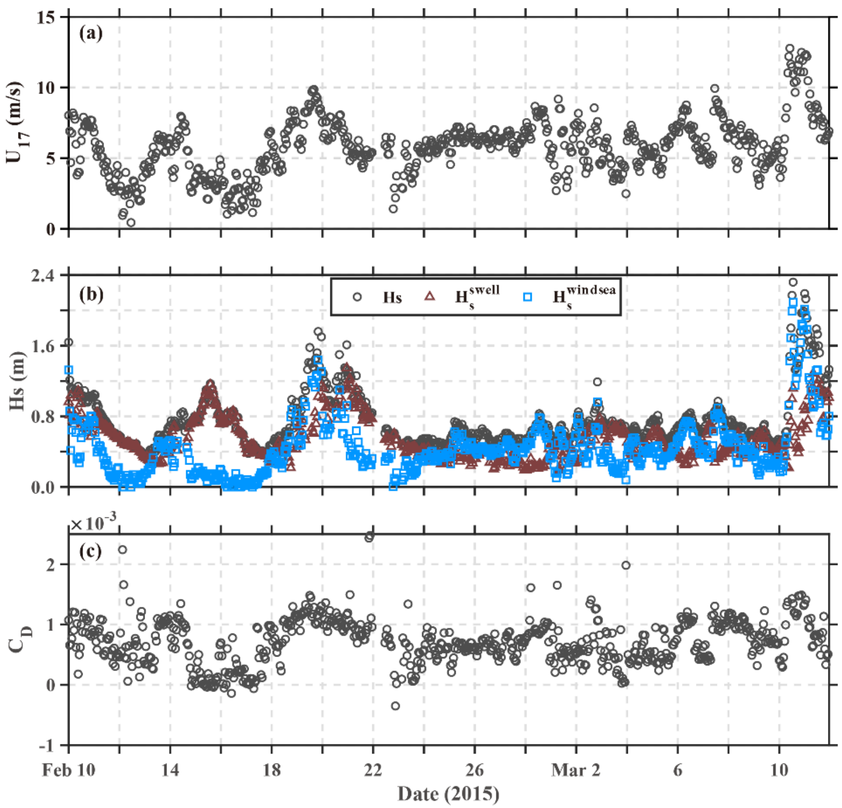
Water depth **28** m; Height **26** m, **30°**, 10 Hz, **AWAC**

Datasets: **April 1 to 30, 2017**

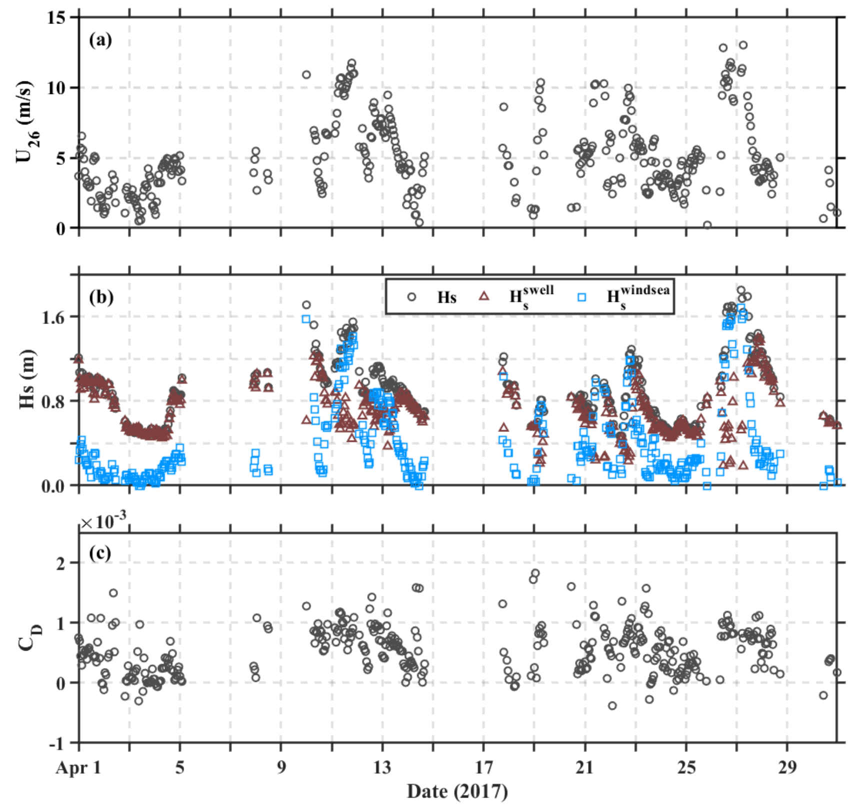


Field Measurements and Datasets

- **BHOT**



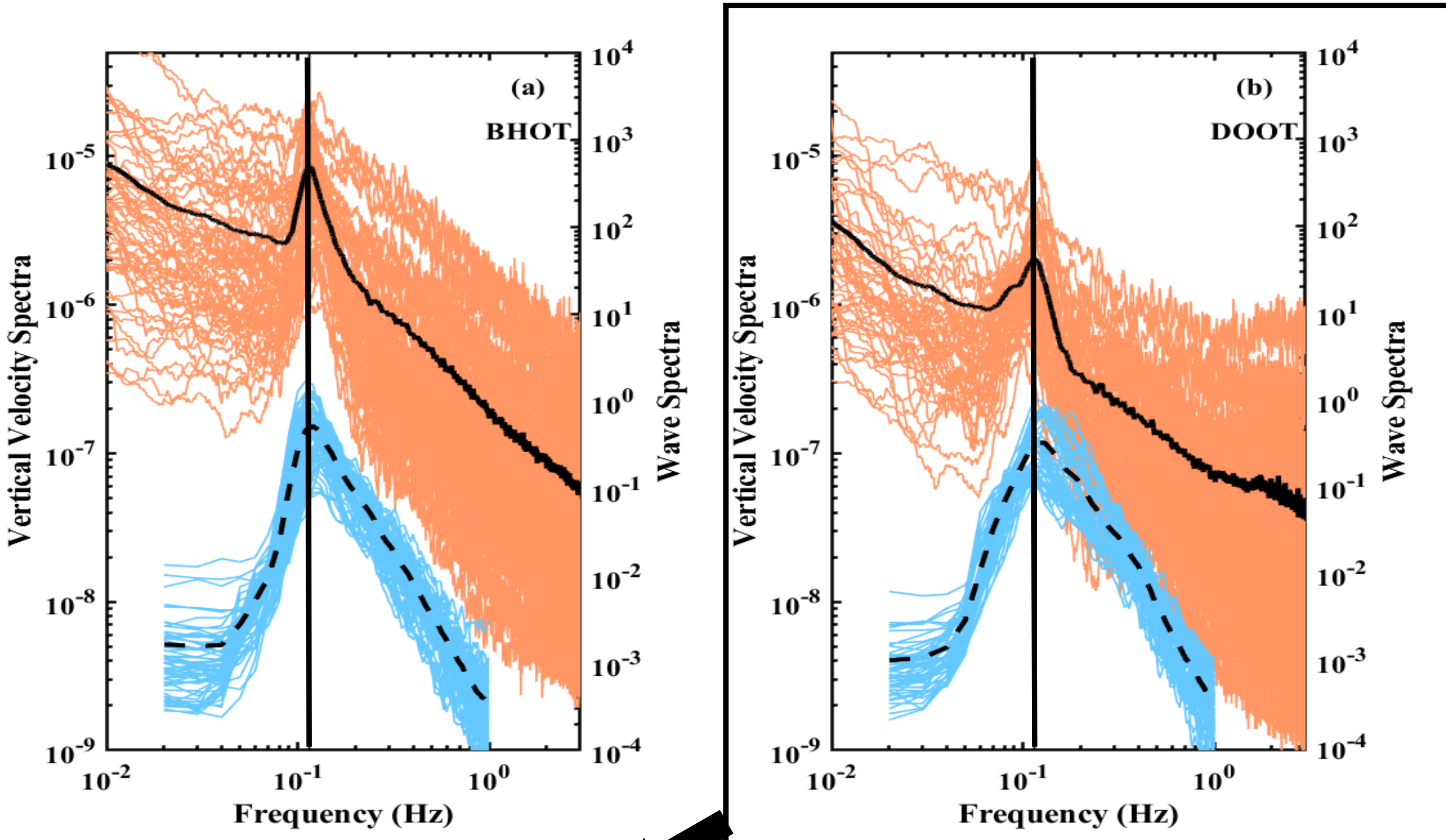
- **DOOT**



- **Low to moderate winds.**
- **Swell dominated.**
- **Negative drag or stress.**

Results and Discussions: Surface Waves

Swell influence on turbulent velocity



- **DOOT: The swell induced perturbation can reach 26 m.**

Results and Discussions: Model

MOST Model Without surface wave effect

- Total stress: $\tau_{tot} = \tau_{turb} + \tau_{visc} = u_*^2$ $\tau_{tot} = \tau_x$, $\tau_{turb} > 0$
- Constant flux assumption: $\frac{d\tau_{tot}}{dz} = 0$
- Turbulent closure model: $\tau_{turb} = K_m \frac{dU}{dz}$ $K_m^l = lu_*$
- **Wind gradient profile under near neutral conditions:**

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

Results and Discussions: Model

TKEW Model **With surface wave effect** **(Semedo et al. 2009)**

- Surface waves, $\boldsymbol{\tau_{tot} = \tau_{turb} + \tau_{wave} = u_*^2}$ $u_* = \sqrt{(|\tau_{tot}|)}$, **Wind seas:** $\tau_{wave} > 0$, **Swells:** $\tau_{wave} < 0$
- $\tau_{wave} < 0$ and $|\tau_{wave}| > |\tau_{turb}|$ → $\boldsymbol{\tau_{tot} = \tau_{turb} + \tau_{wave} < 0}$: **Upward momentum flux**
- $\frac{d\tau_{tot}}{dz} = 0$ & $\tau_{turb} = K_m \frac{dU}{dz}$ → $\boldsymbol{\frac{dU}{dz} = \frac{\tau_{tot} - \tau_{wave}}{K_m}}$ $\qquad \boldsymbol{U(z) = \int_{z_0}^{z} (\tau_{tot} - \tau_{wave}) K_m^{-1} dz}$
- $\boldsymbol{\tau_{wave} = -\langle \tilde{u}\tilde{w} \rangle}$, $\boldsymbol{\tilde{u} \propto e^{-kz}}$, $\boldsymbol{\tilde{w} \propto e^{-kz}}$ → $\boldsymbol{\tau_{wave} = \tau_{wave}^0 e^{-2kz}}$

$\boldsymbol{K_m^e = l\sqrt{e}}$ **(Semedo et al. 2009)**

- **TKE:** $\boldsymbol{\frac{\partial \bar{e}}{\partial t} = \frac{g}{\bar{\theta}_v}\overline{w'\theta_v'} - \left(\overline{u'w'}\frac{\partial \bar{u}}{\partial z} + \overline{v'w'}\frac{\partial \bar{v}}{\partial z}\right) - \frac{\partial(\overline{w'e})}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial(\overline{w'p'})}{\partial z} - \varepsilon}$
- $\boldsymbol{\tau_{tot}\frac{dU}{dz} + F_w - \varepsilon = 0}$

$$F_w = -\frac{1}{\rho_a}\frac{d}{dz}(\langle \tilde{p}\tilde{w} \rangle) \qquad -\langle \tilde{p}\tilde{w} \rangle = -\rho_a c \langle \tilde{u}\tilde{w} \rangle$$

$$F_w = -2kc\tau_{wave}^0 e^{-2kz},\ \varepsilon = \frac{e^{3/2}}{l}$$

➢ $\boldsymbol{{K_m^e}^4 l^{-4} = |\tau_{tot}(\tau_{tot} - \tau_{wave}) + K_m^e F_w|}$

Results and Discussions: Model

$$U(z) = \int_{z_0}^{z} (\tau_{tot} - \tau_{wave}) K_m^{-1} dz$$

$$\tau_{wave} = \tau_{wave}^{0} e^{-2kz}$$

$${K_m^e}^4 l^{-4} = |\tau_{tot}(\tau_{tot} - \tau_{wave}) + K_m^e F_w|$$

TKEW Model

τ_{wave}??

- **Wave induced stress is related to the rate of change of wave energy E:**

$$\frac{\partial E}{\partial t} = \rho_a c \tau_{wave}^{0} = \beta E$$

- $\beta = C_\beta k \frac{\rho_a}{\rho_w} \frac{u_*^2}{c}$ $\quad$ **C_β: wave growth or damping rate coefficient**

$c/u_* < 20$: $C_\beta > 0$

$c/u_* > 20$: $C_\beta < 0$

E

- **Single-frequency wave**: $E = 1/2 \rho_w g a^2$
- **Wave spectrum**: $E = \int_0^\infty S(f) df$

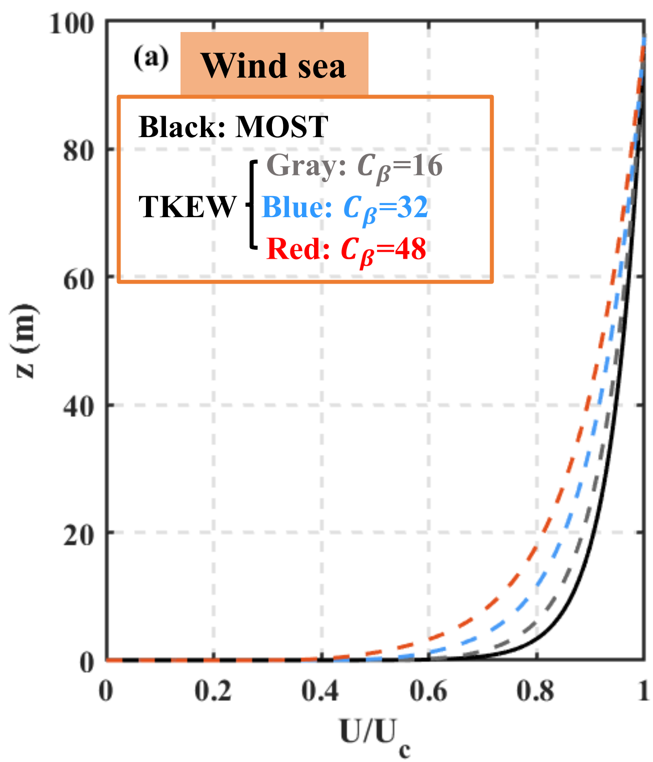
Results and Discussions: Model Results

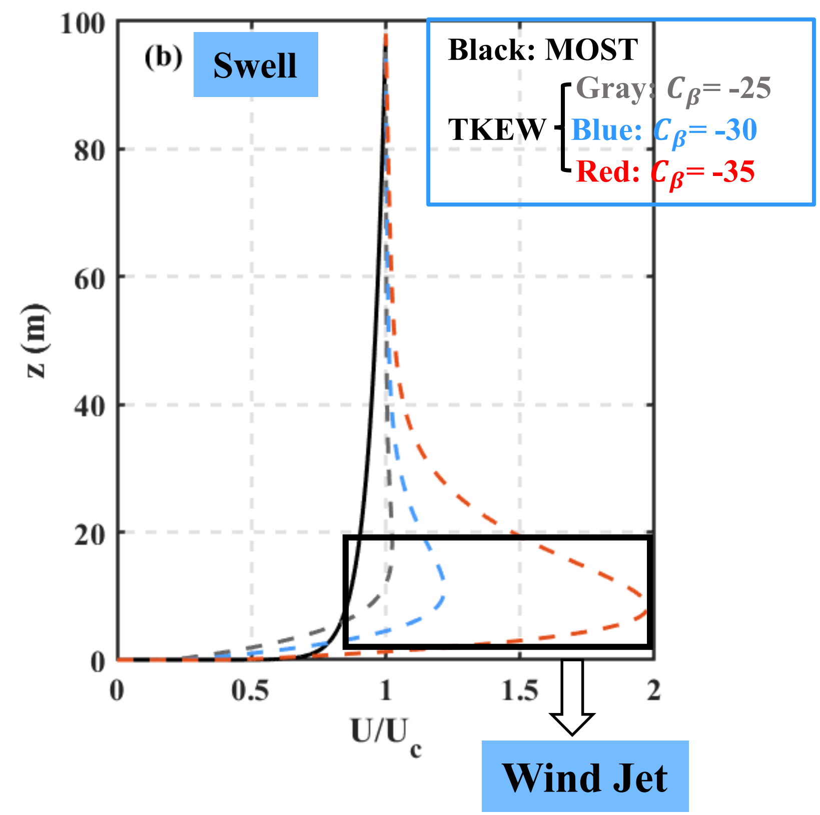
Single-frequency wave

$$\tau_{wave} = \frac{1}{2} C_\beta (ak)^2 u_*^2 e^{-2kz}$$

Deviate;

Invalidity





Normalized wind speed gradient

Results and Discussions: Model Results

Wave Spectrum

$$\tau_{wave} = \int_0^{\infty} \frac{\beta \rho_w g S(f)}{\rho_a c} e^{-2kz} df$$

(Donelan et al. 1985)

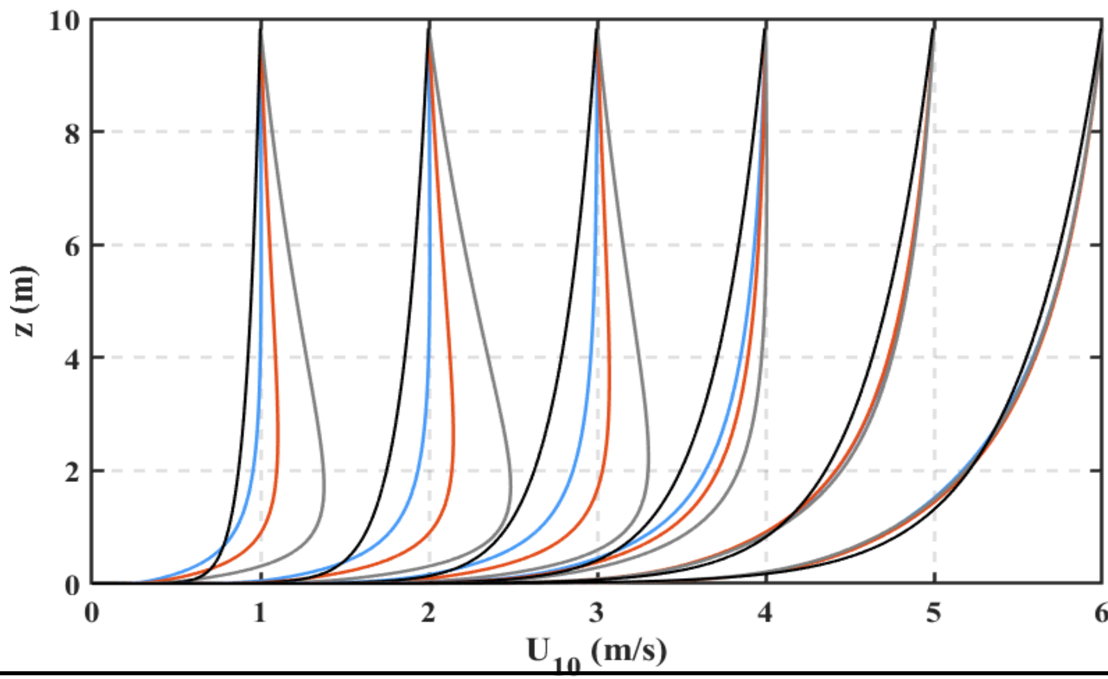
Wind seas: $S(f) = \frac{\alpha g^2 f^{-4}}{(2\pi)^4} f_p^{-1} \exp(-\left(\frac{f_p}{f}\right)^4)\gamma^{\Gamma}$

$C_\beta = 32$

Swells: $S(f) = \frac{\alpha g^2 f^{-4}}{(2\pi)^4} f_p^{-1} \exp(-\left(\frac{f_p}{f}\right)^4)\gamma^{\Gamma} \exp[(\frac{f}{f_0})^3$

$C_\beta = -30$

(Hanley and Belcher,2008)



Black: MOST

TKEW
- Blue: C_p =10 m/s
- Red: C_p =12.5 m/s
- Gray: C_p =15 m/s

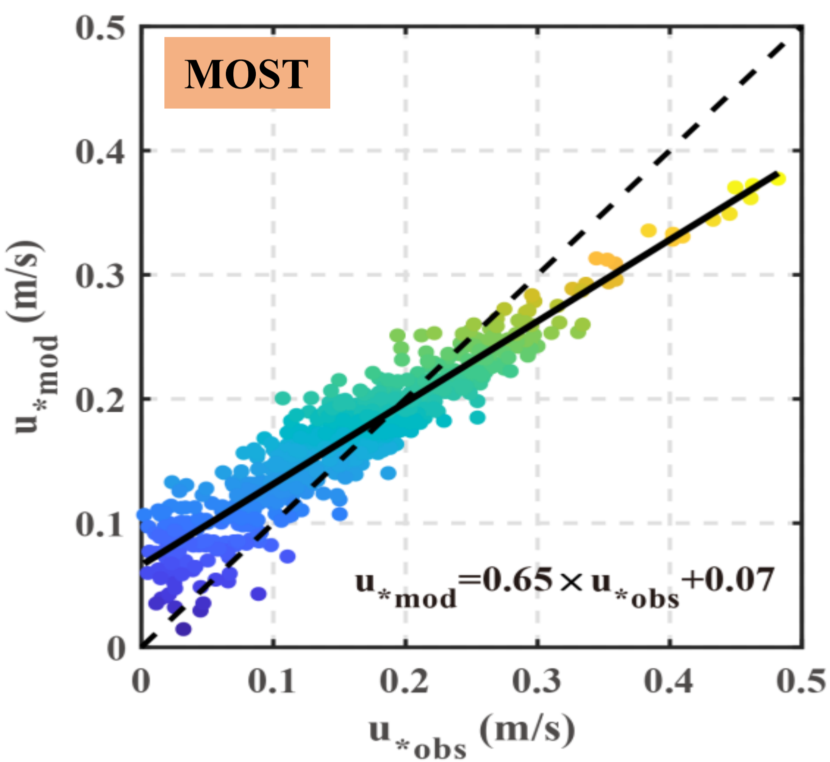
- The wind profiles departed from the traditional logarithmic profiles;
- The deviation increased with the peak wave phase speed.

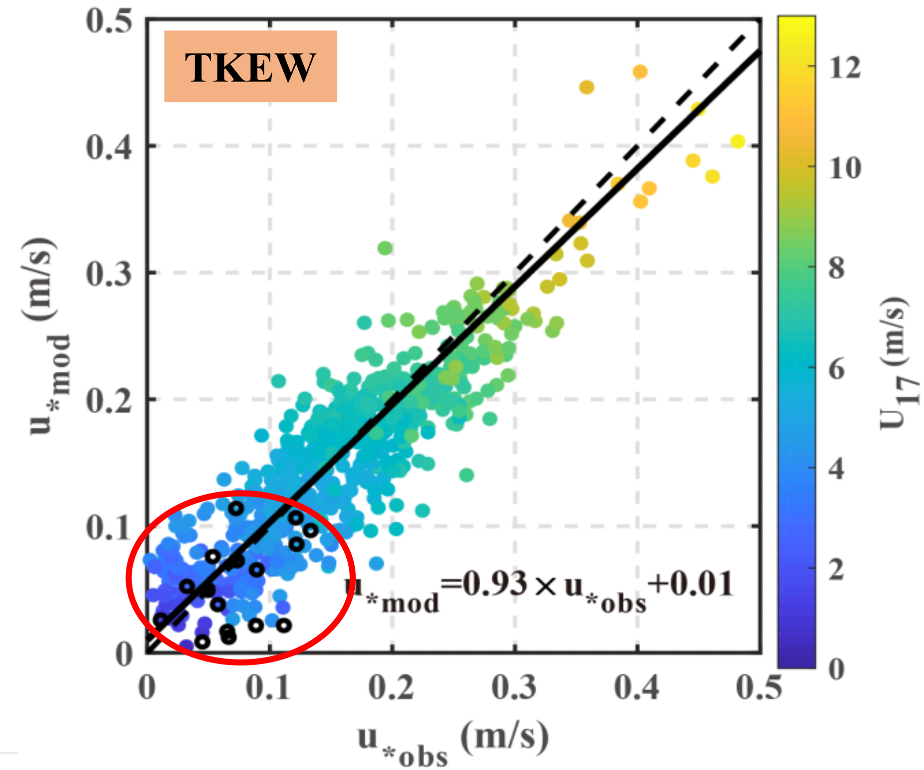
Results and Discussions: Comparison

Comparison for BHOT

- **Input: Wind speeds, Observational height, Water depth, Wave frequency spectra**
- **Wind sea: $C_\beta = 16$; Swell: $C_\beta = -30$**

Bias (m/s)	MOST	TKEW
$u_* < 0.2$ m/s	0.027 →	0.007
$u_* > 0.2$ m/s	-0.026 →	-0.008



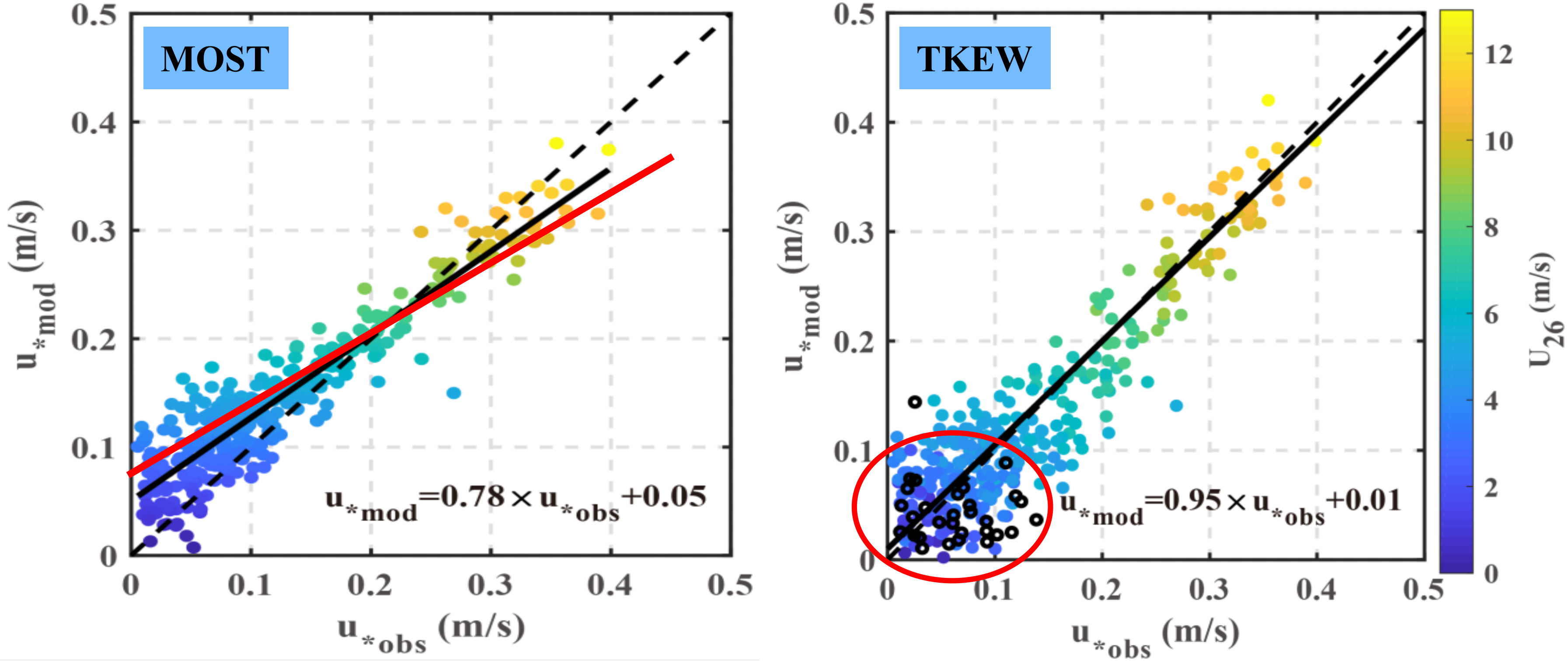


✓ **TKEW model better agreed with the observations with respect to the MOST model.**

Results and Discussions: Comparison

Comparison for DOOT

Bias (m/s)	MOST	TKEW
$u_* < 0.2$ m/s	0.026 →	0.002
$u_* > 0.2$ m/s	-0.014 →	-0.004



- MOST was invalid within the typical observational height (< 30 m).
- The influence of surface waves on wind stress decreased with increasing height.

Conclusions

- **The swell-induced perturbation reached a height of nearly 30 m from the mean sea surface; the influence of swell decreased with increasing height.**
- **With respect to the MOST, the TKEW model better agreed with the observations; TKEW model predicted the upward momentum flux.**
- **Combined wave-induced stress and turbulent stress, a preliminary scheme of wind stress estimation was obtained.**

- ☐ **Directions of the wind, wave and stress;**
- ☐ C_β **is the main source of uncertainty;**
- ☐ **Constant flux layer assumption may be debatable.**

Conclusions

Chen S, Qiao F, Huang C J et al. Deviation of wind stress from wind direction under low wind conditions [J]. Journal of Geophysical Research: Oceans, 2018, 123, doi: 10.1029/2018JC014137.

Chen S, Qiao F, Jiang W Z et al. Impact of surface waves on wind stress under low to moderate wind conditions [J]. Journal of Physical Oceanography, 2019, doi: 10.1175/JPO-D-18-0266.1.

THANKS!