University of Bergen

Geophysical Institute

Numerical Modelling of Wind-Driven Circulation Behind a Large Wind Farm In the presence of Surface Gravity Waves

Presented by

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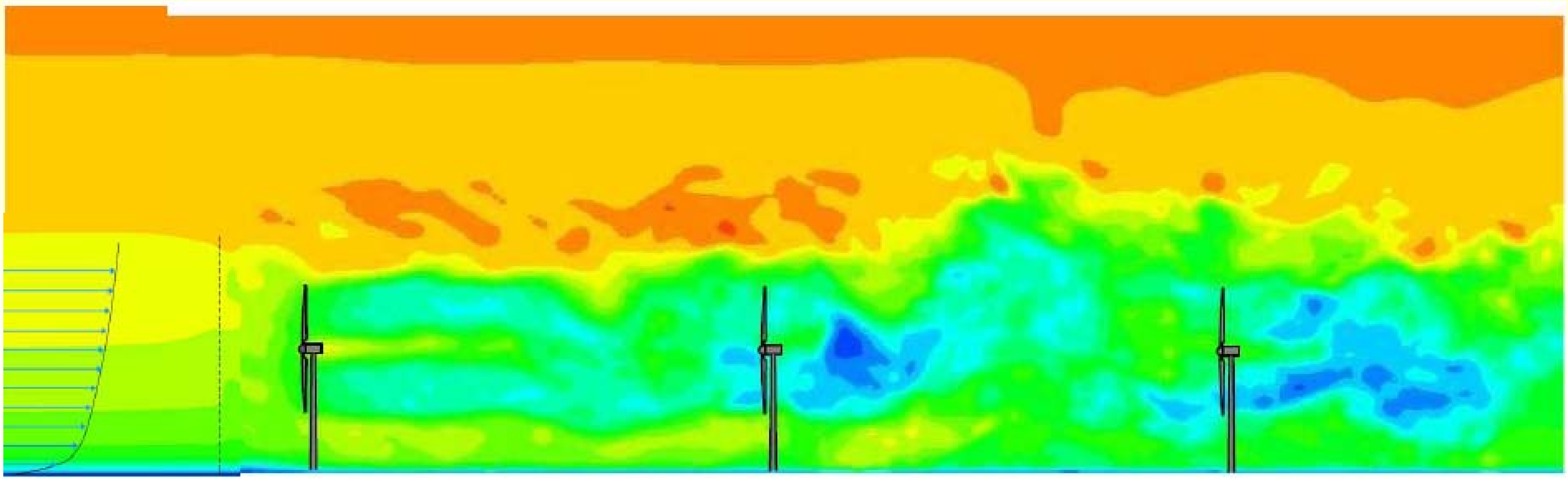
Norway

Outline

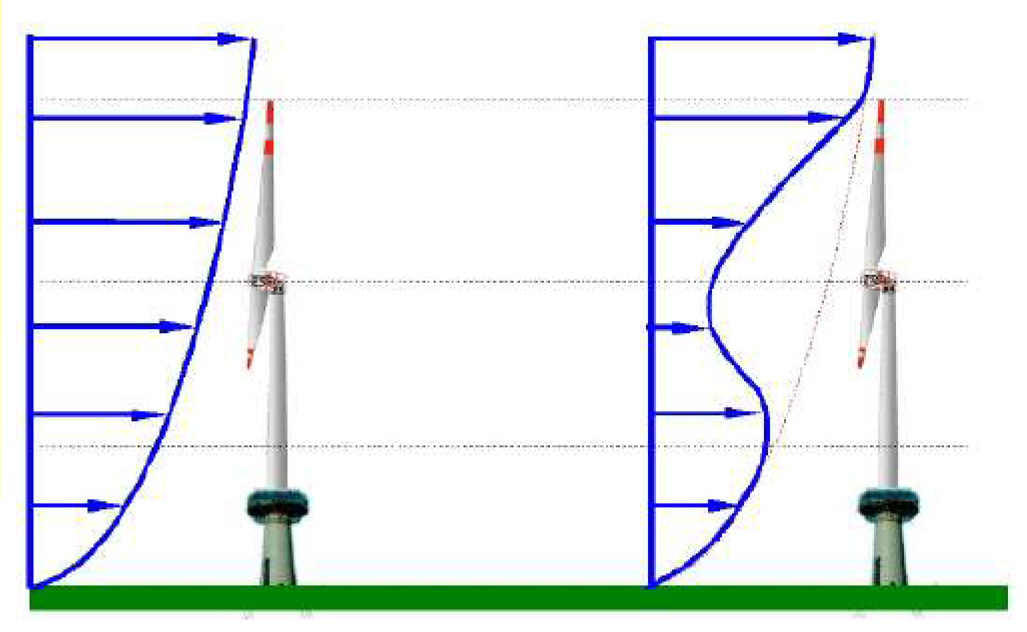
- boundary layer
- Surface gravity waves
- Upper ocean response
- Numerical model
- Instrumentation
- References

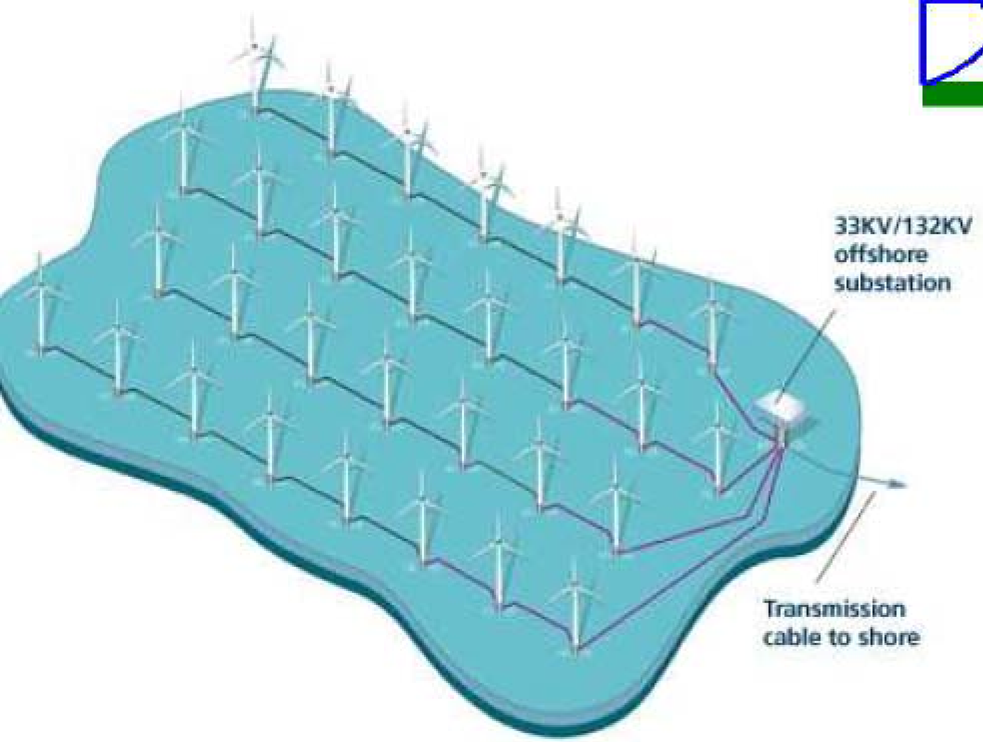
Wind Turbine Farm Interaction with Boundary Layer



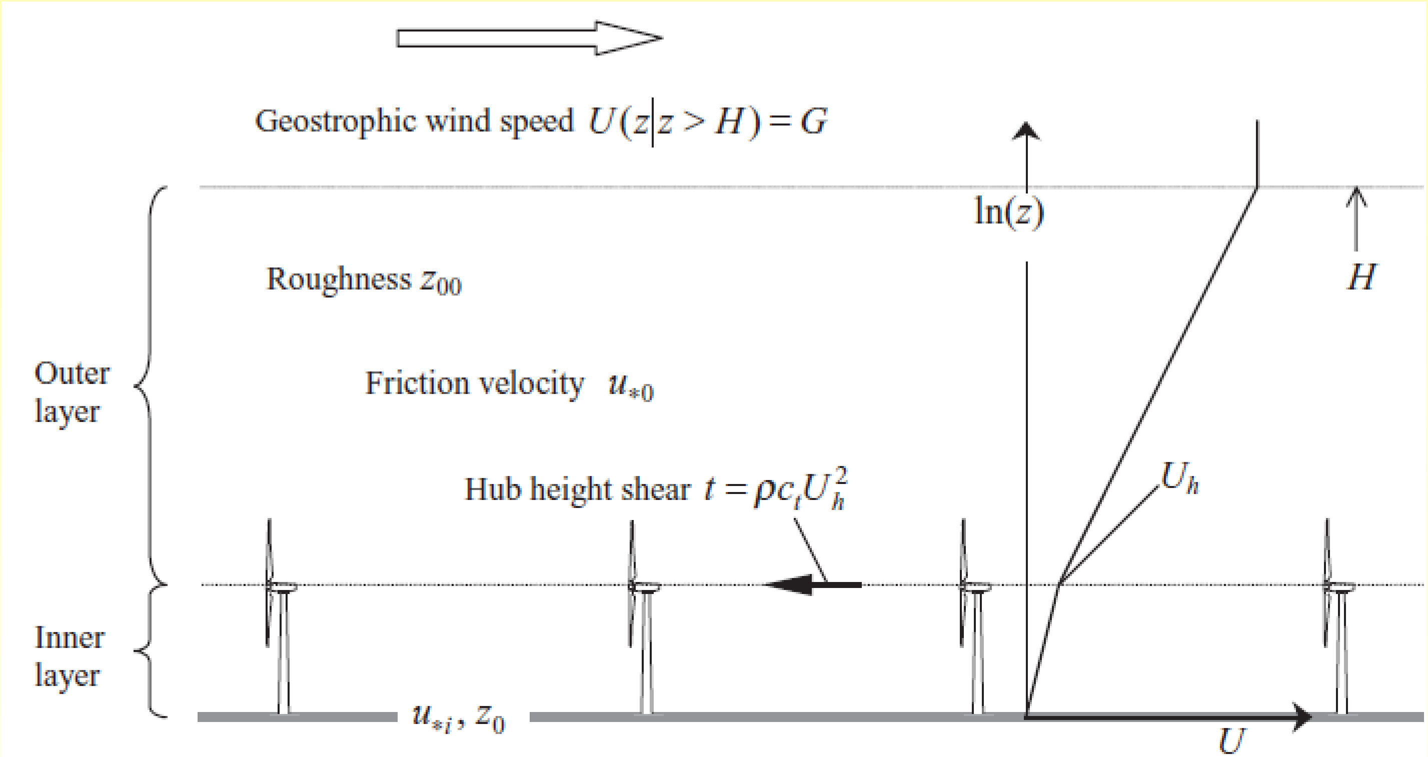
Taken from [1]

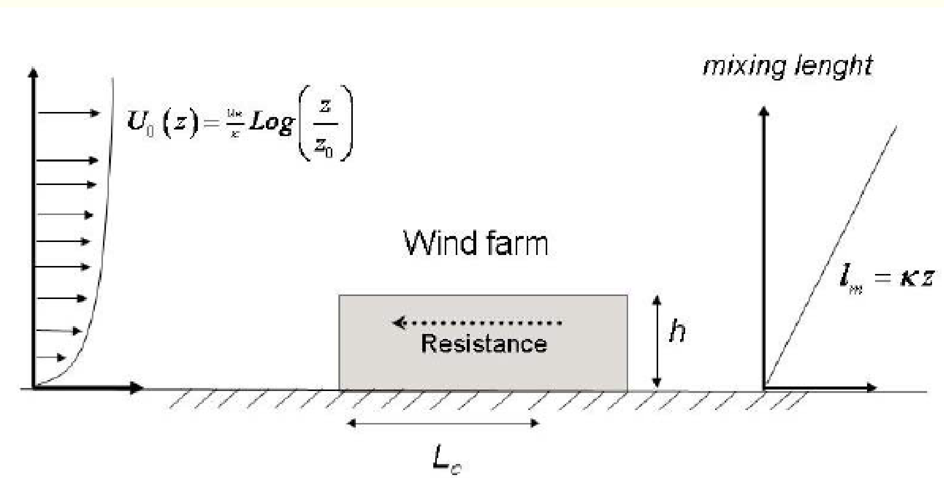
Wind Turbine Farm Interaction with Boundary Layer





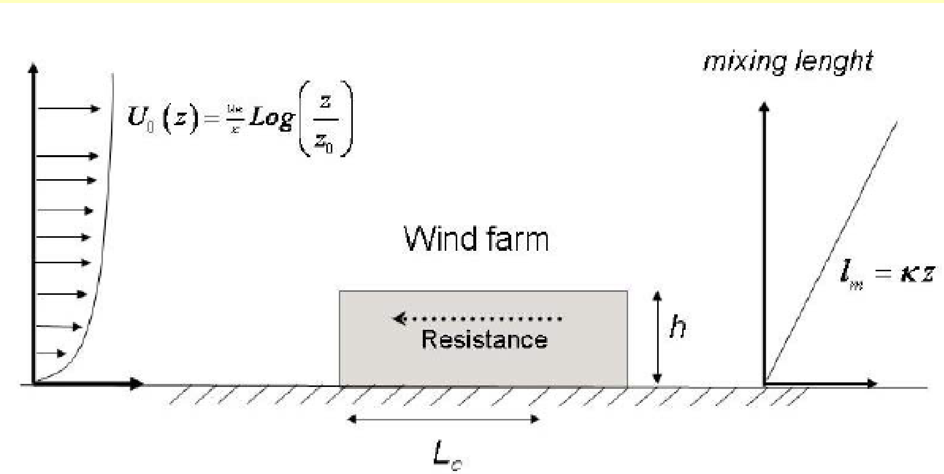
Wind Turbine Farm Interaction with Boundary Layer





Taken from [2]

Wind Turbine Farm Interaction with Boundary Layer

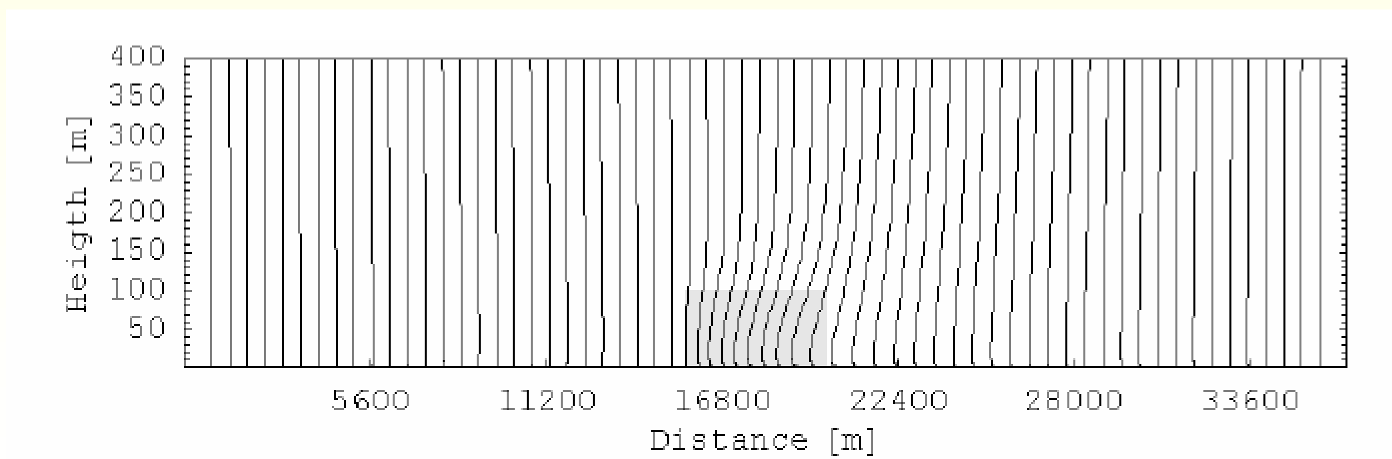


Taken from [2]

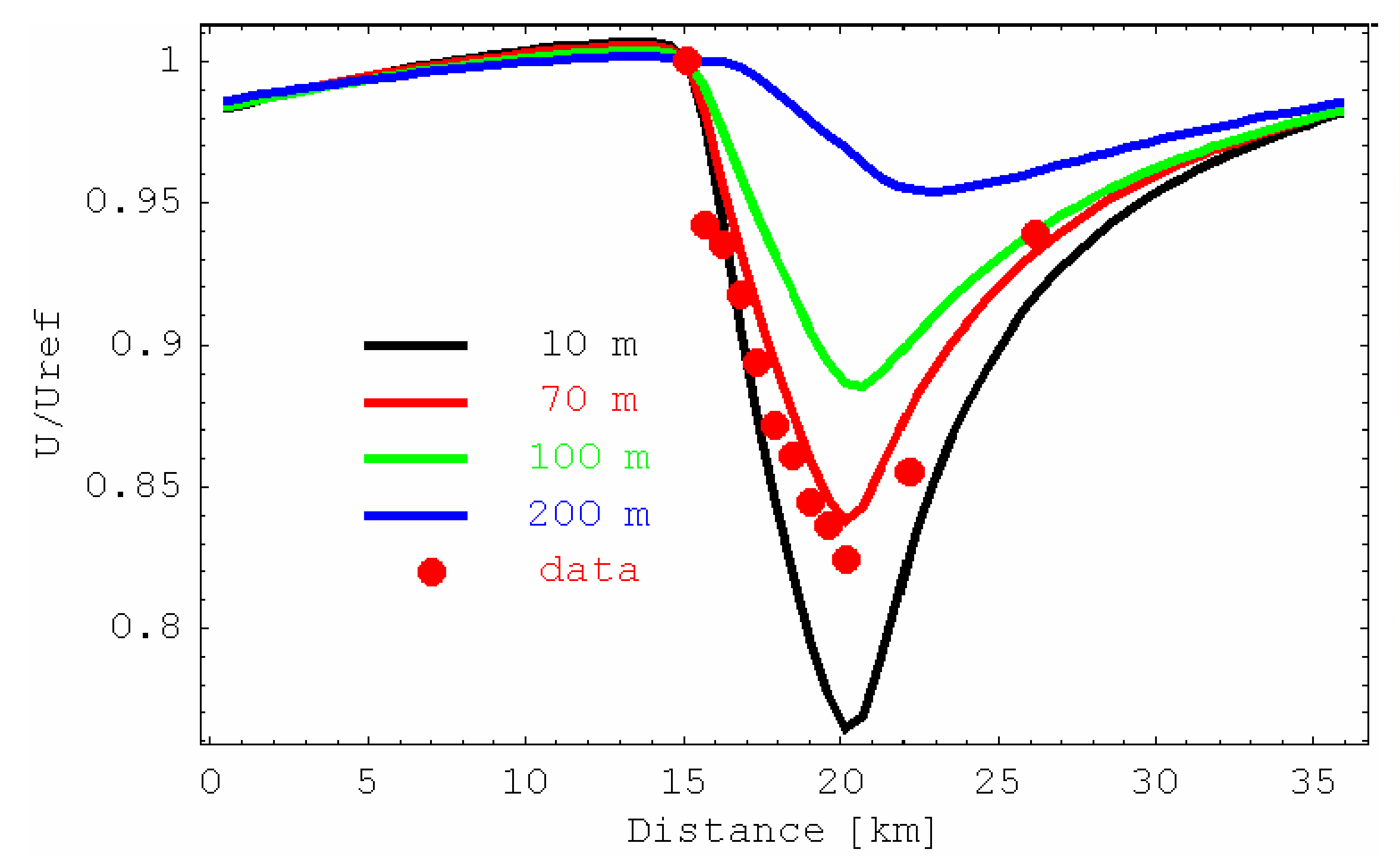
$$U_j \frac{\partial U_i}{\partial x_j} + \frac{\partial P}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j} - f_i$$

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$F_i = \tfrac{1}{2} c_d A_i U_i |U|$$



Wind Turbine Farm Interaction with Wind Field



Data from Horns rev: good agreement

Taken from [3]

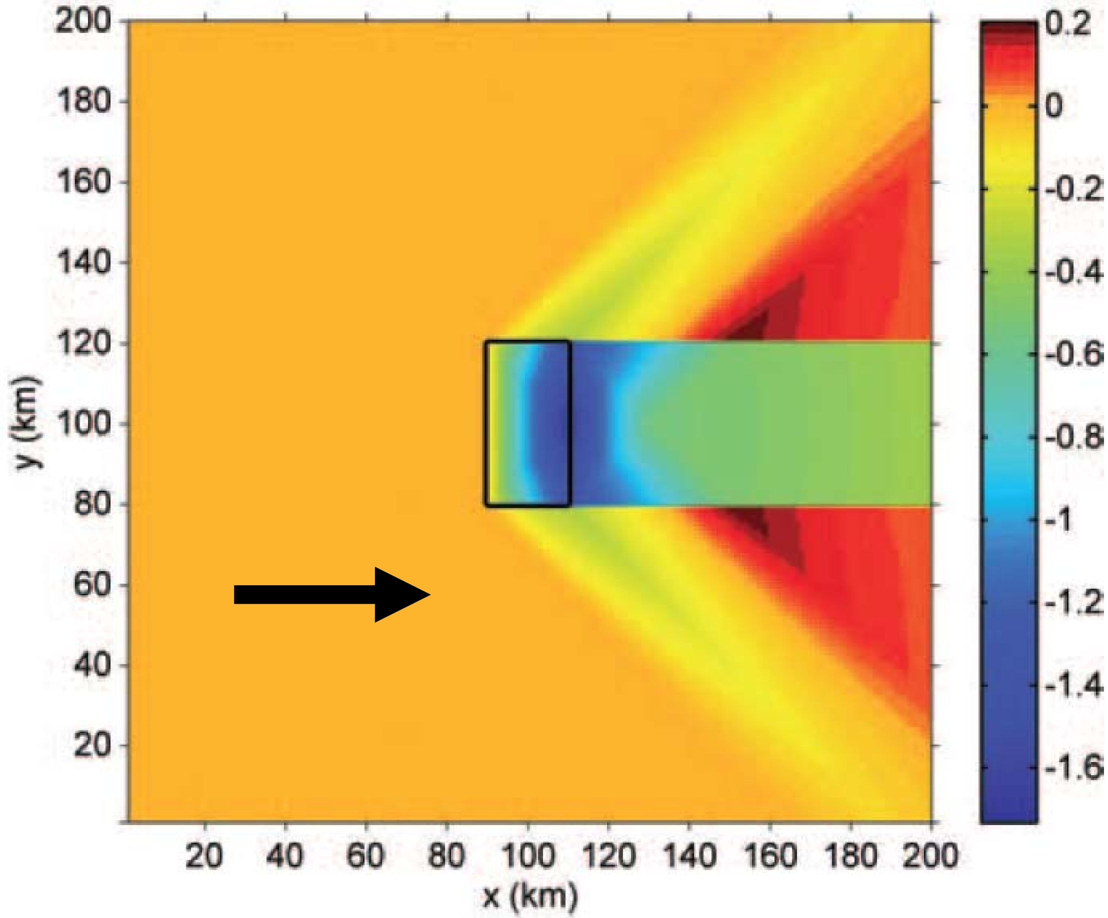
Wind Turbine Farm Interaction with Boundary Layer

$$i\sigma_B\hat{u}_B = -ik\hat{p}_B - C_B\hat{u}_B - C_T\hat{u}_B + \hat{F}_x$$

$$i\sigma_B\hat{v}_B = -il\hat{p}_B - C_B\hat{v}_B - C_T\hat{v}_B + \hat{F}_y$$

$$F_x = -nF_T/\rho H$$

$$F_T = (1/2)\rho C_D U_B^2 A_T.$$



Taken from [4]

Wind Turbine Monopile Interaction with Wave Field

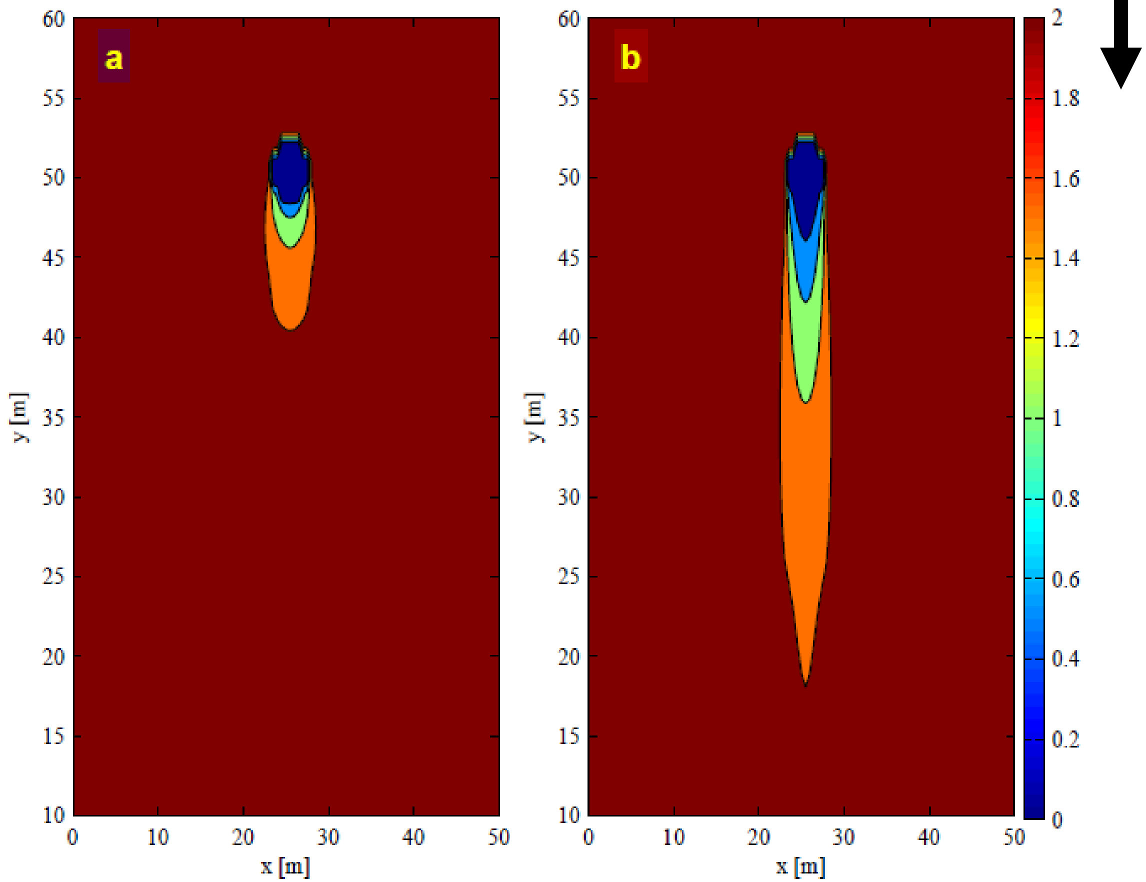
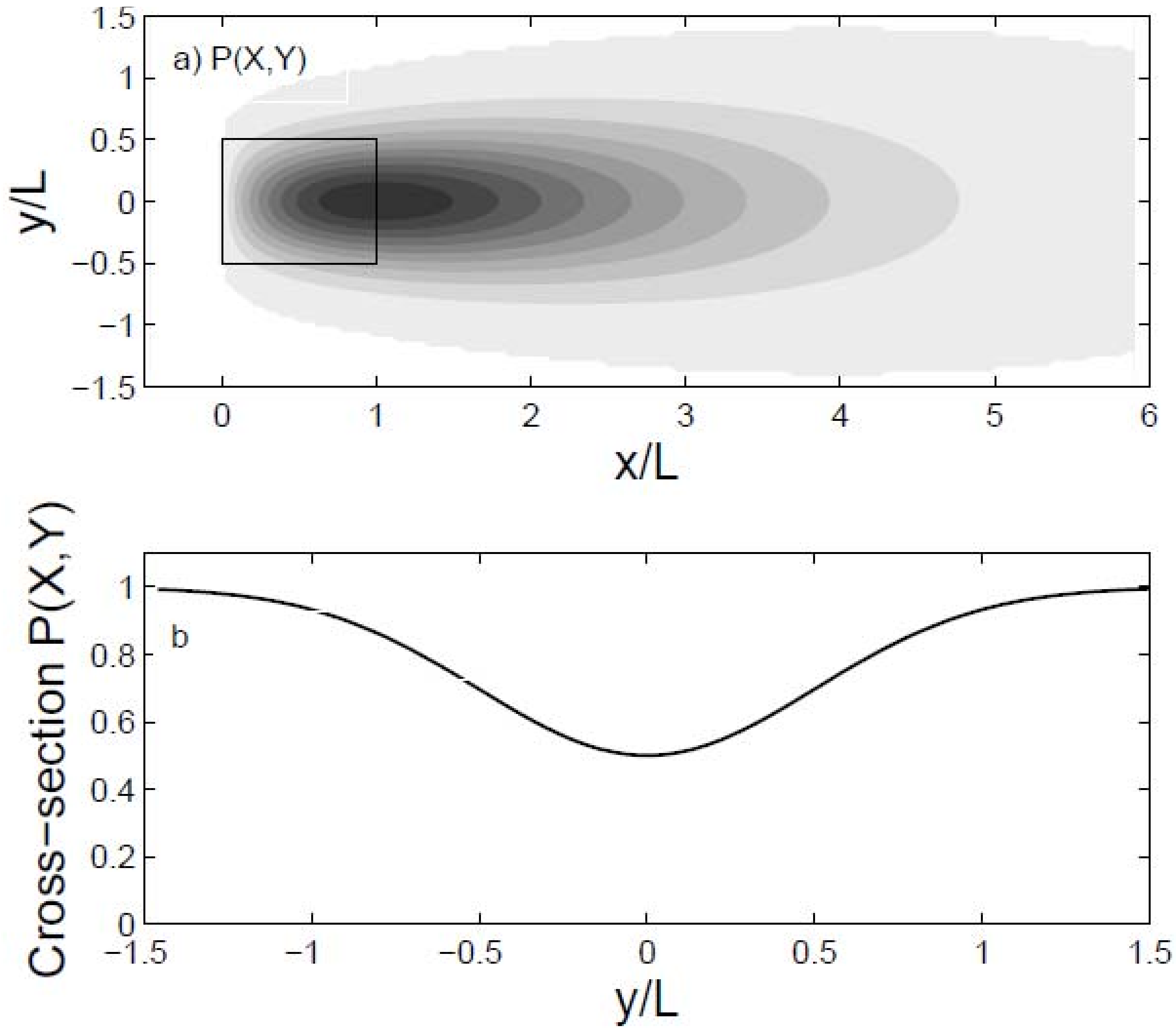


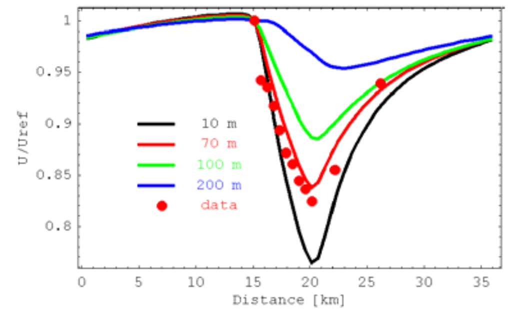
Fig. 2. Computed SWAN stationary significant wave height with reflection effect for narrow spreading angle 2° and broad directional spreading of 28°.

Taken from [5]

Wind Turbine Farm Interaction with Wind and Wave Field

$$P(X,Y) = \exp\left(-\left(\frac{2Y}{\alpha L + \beta X}\right)^2\right)\max\left(\frac{X\exp((1-X)/L)}{L}, 0\right),$$



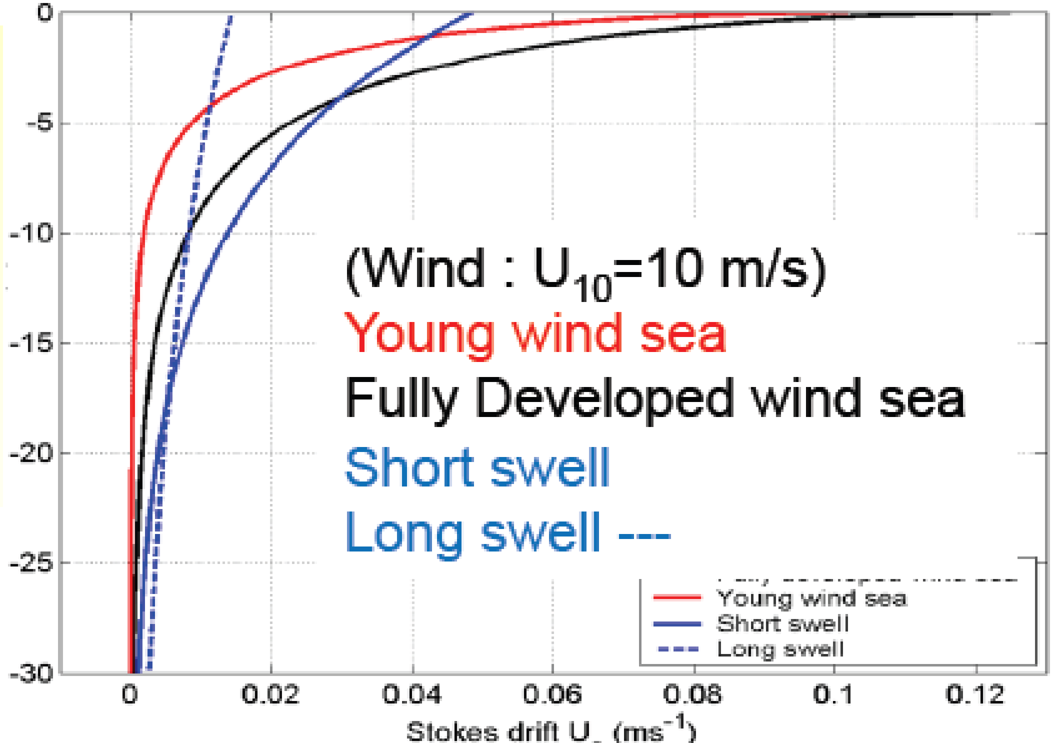


Taken from [5]

Wave parameters

$$\mathbf{U}_s(z) = 4\pi \int_\theta \int_f f\mathbf{k}E(f,\theta)e^{-2k|z|}\, df\, d\theta,$$

$$\mathbf{F}_{ds} = -4\pi \int_f \int_\theta f S_{ds}(f,\theta)\hat{\mathbf{k}} k e^{-2k|z|}\, d\theta\, df,$$



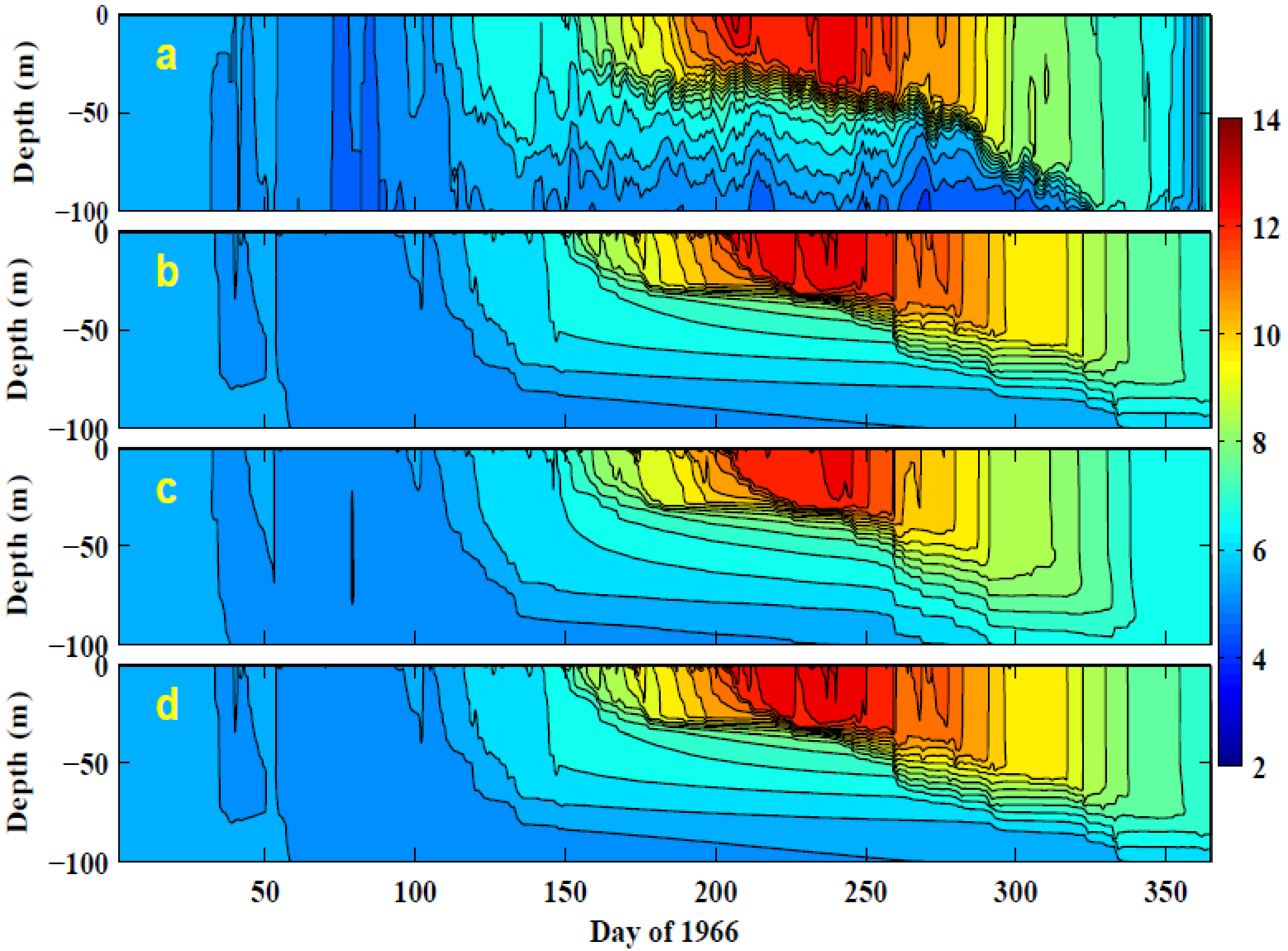
$$\rho_w \nu_t \frac{\partial \mathbf{U}}{\partial z} = \vec{\tau}^{\,surf}_{mod},$$

where

$$\vec{\tau}^{\,surf}_{mod} = \tau_{tot} - 2\pi\rho_w \int_f \int_\theta \widehat{\mathbf{k}} f S_{in}(f,\theta)\, d\theta\, df.$$

Wave Effect On Upper Ocean

OWS Papa. Ocean Weather Station (OWS) Papa long term observations of meteorological parameters and temperature profiles (at 50°N, 145°W) are applied as a final validation test case for the whole of year 1966. Figure 2 (Top) shows the results of the simulated temperature for (a) observations, (b) simulation results based on Ba12, (c) WTI–modified GOTM results, and (c) no-wave effect. Similar to the PROVESS test case, the heat content of the upper 50 m, MLD evolution, and temperature evolution at OWS Papa show that the WTI–based modification captures the observations better than the Ba12-modified GOTM results.



Taken from [6]

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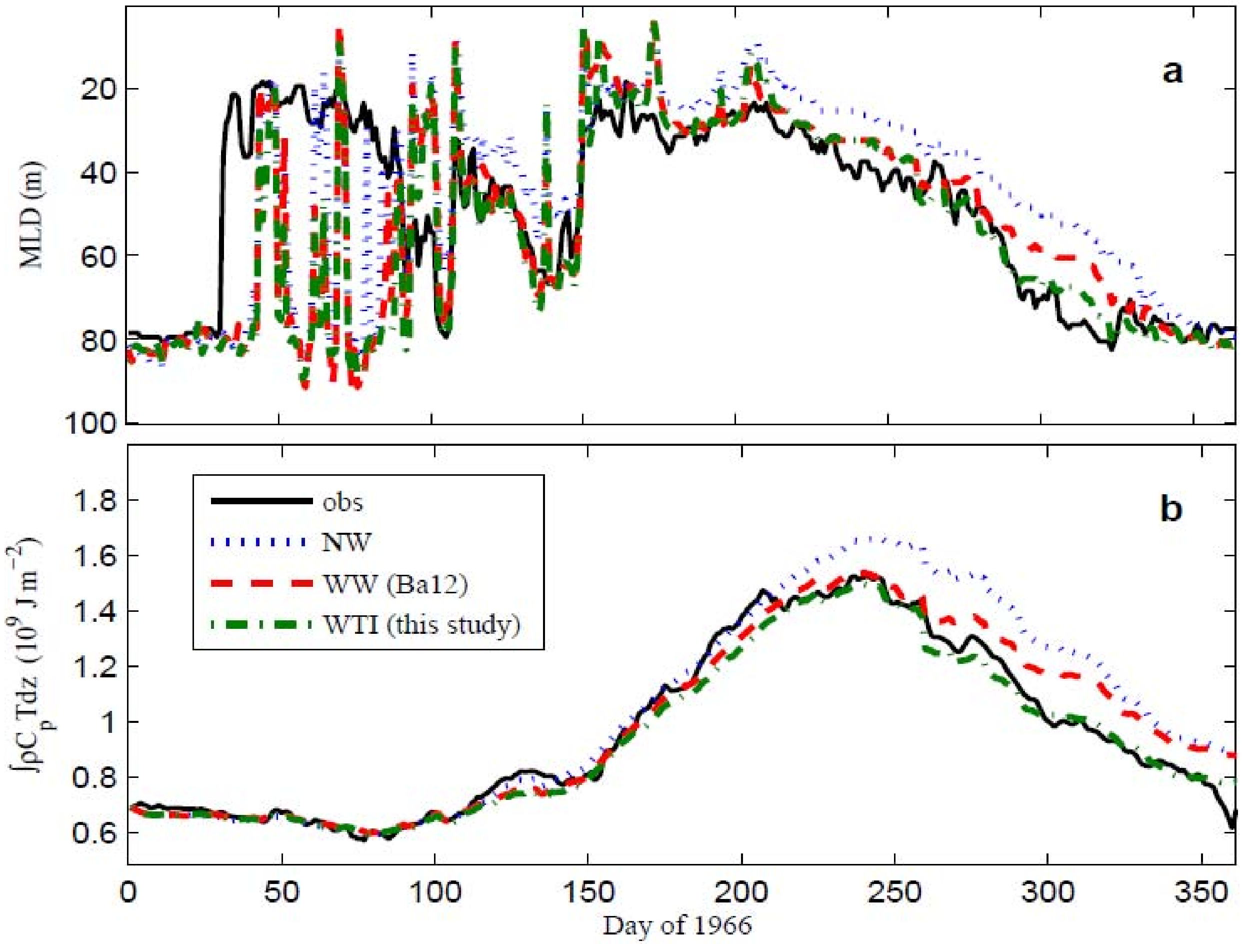


Taken from [6]

Fig. 2. *Top*: Temperature evolution at OWS Papa in the northern Pacific Ocean for year 1966, (a) observations, (b) GOTM run with wave forcing effects based on [13], (c) GOTM with the wave–turbulence interaction modification, (d) GOTM without wave–forcing. *Bottom*: Temporal variability of (a) MLD and (b) heat content in the upper 50 m.

Upper Ocean Response to Large Wind Farm: 2D study

$$\frac{\partial \Theta}{\partial t} + \frac{\partial \mathbf{F}(\Theta)}{\partial x} + \frac{\partial \mathbf{G}(\Theta)}{\partial y} = \mathbf{S}(t),$$

in which

$$\Theta = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix}, \ \mathbf{F}(\Theta) = \begin{bmatrix} uh \\ u^2 h + \frac{1}{2} g h^2 \\ uvh \end{bmatrix}, \ \mathbf{G}(\Theta) = \begin{bmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g h^2 \end{bmatrix},$$

and the wave-modified external source term $\mathbf{S}(t)$ is given as

$$\mathbf{S}(t) = \frac{1}{\rho_w} \begin{bmatrix} 0 \\ \tau_x - \tau_{in}^x - \tau_B^x \\ \tau_y - \tau_{in}^y - \tau_B^y \end{bmatrix} + \begin{bmatrix} 0 \\ f_{cor}(v + v_s) - \mathbf{F}_{ds}^x \\ -f_{cor}(u + u_s) - \mathbf{F}_{ds}^y \end{bmatrix},$$

Part I: Simplified 2D Shallow water wave as theoretical benchmark

Pycnocline depth differential equation

$$\frac{\partial}{\partial t}\left[f_{cor}^2 - g' h_0 \nabla^2\right] h = f_{cor} \nabla . \mathbf{U}_s - \frac{f_{cor}}{\rho_w} \nabla \times \vec{\tau} + \frac{f_{cor}}{\rho_w} \nabla \times \vec{\tau}_{in}.$$

- By non-dimensionalizing above equation by $f_{cor}^{-1},\ L,\ \Delta\tau (f_{cor} \rho L)^{-1}$ for time, length , and active layer depth,

$$\left[1 - \gamma^2 \nabla^2\right](h - h_0) = -t \nabla \times \left(\frac{\vec{\tau}}{\Delta \tau} - \frac{\vec{\tau}_{in}}{\Delta \tau}\right) + t \frac{\rho_w}{\Delta \tau} \nabla . \mathbf{U}_s,$$

Where $\gamma = \sqrt{g' h_0} / (f_{cor} L)$

Part I: Ideal wind and wave parameterizations

- Wind stress, wave-induced stress, and Stokes drift

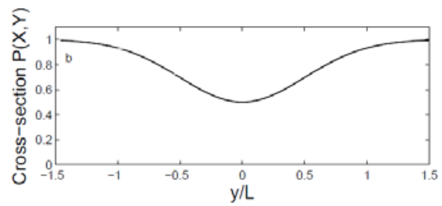
- Large obstacle in the ocean will disturb wind field (wake), wave field and oceanic currents

$$\Lambda = \Lambda_{init} - \Delta\Lambda_* P(X, Y)$$

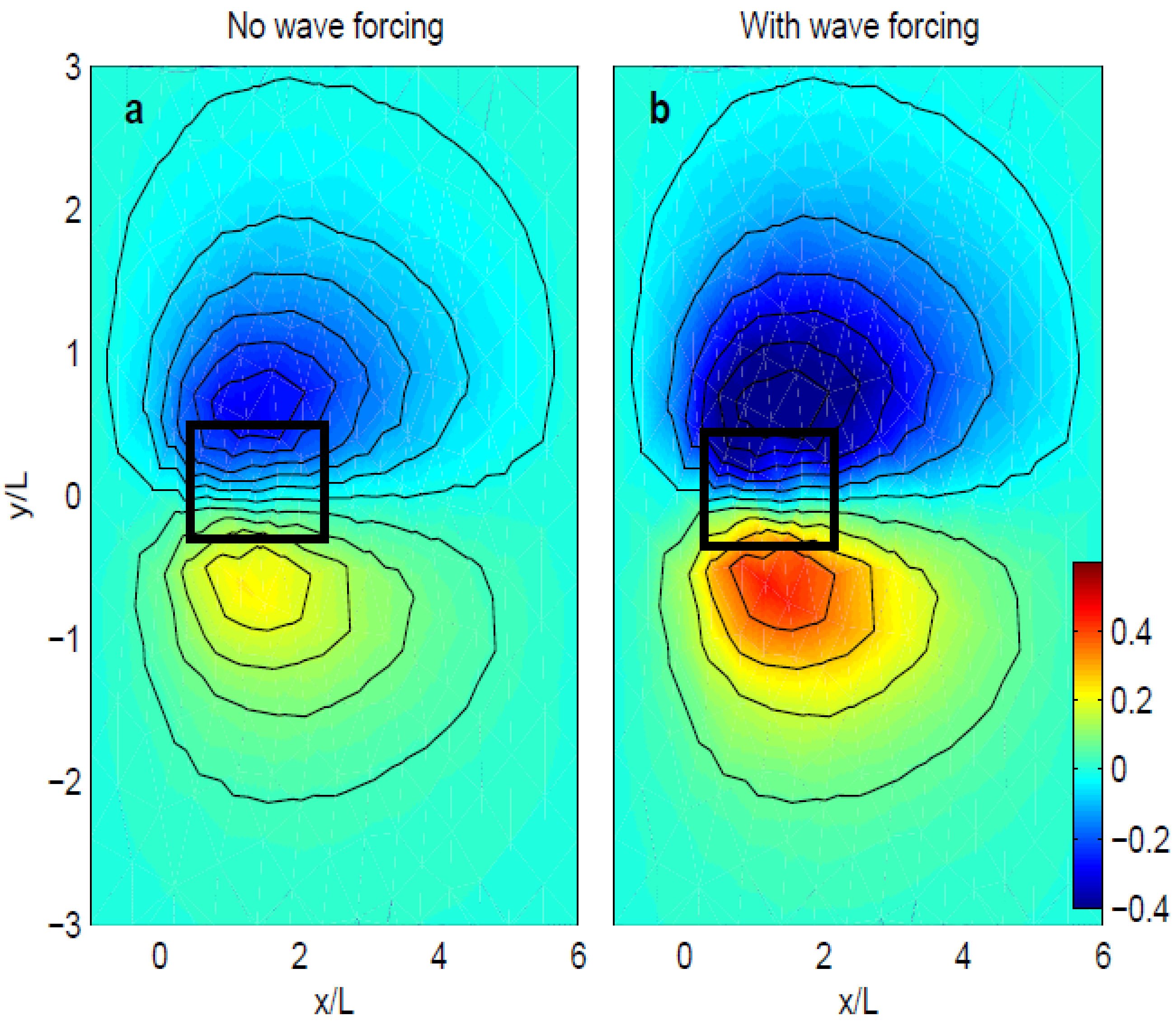
Where $\Lambda = [\vec{\tau}\ \vec{\tau}_{in}\ \mathbf{U}_s]^T$ and $\Delta\Lambda_* = [\Delta\vec{\tau}\ \Delta\vec{\tau}_{in}\ \Delta\mathbf{U}_s]^T$

$$P(X, Y) = \exp\left(-\left(\frac{2Y}{\alpha L + \beta X}\right)^2\right) \max\left(\frac{X \exp((1 - X)/L)}{L}, 0\right),$$

Part I: Solving 2D modified linear shallow water wave



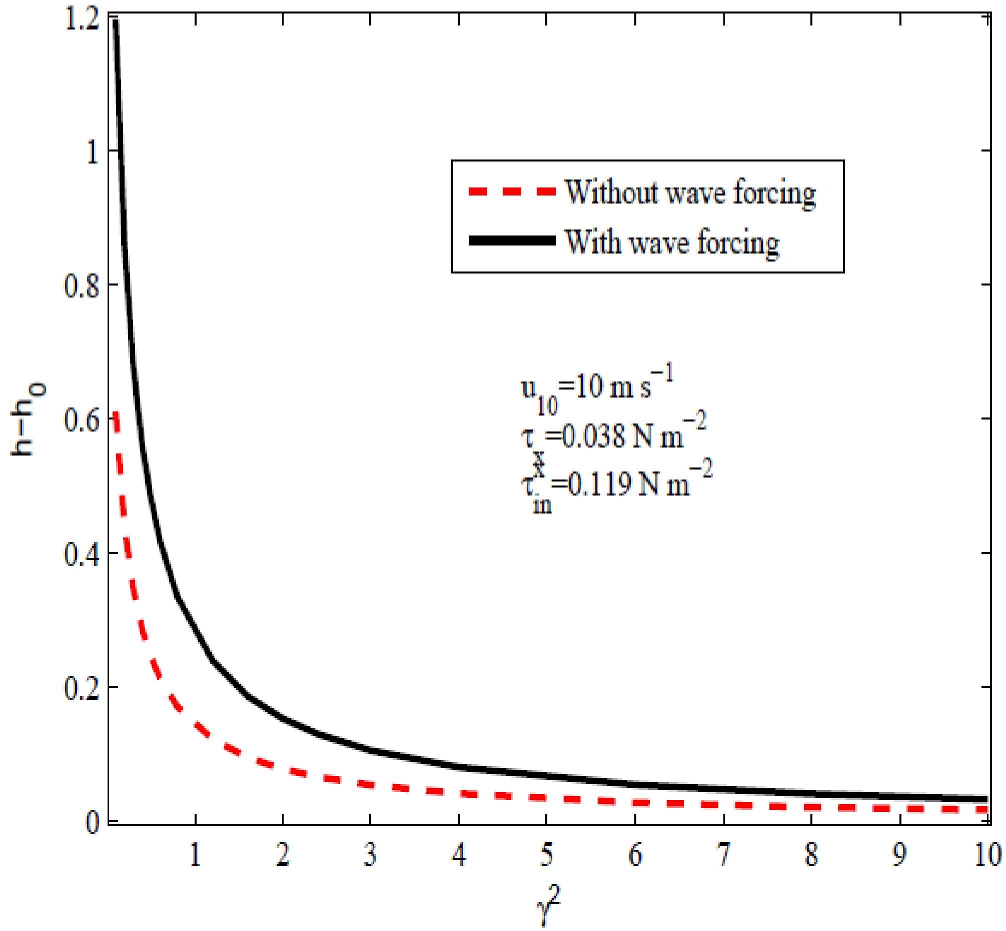
Taken from [7]



$\gamma = \sqrt{g' h_0/(f_{cor} L)}$

Thichness of active upper active layer for $\gamma^2 = 1$. a) No-wave forcing, b) with wave forcing effect.

Part I: Solving 2D modified linear shallow water wave



Taken from [7]

Fig. 3. The maximum amplitude of pycnoclene height as a function of γ^2. Solid line shows with wave forcing effect and dashed line shows no-wave forcing.

Part II: Full nonlinear-Numerical modelling

$$\frac{\partial \Theta}{\partial t} + \frac{\partial \mathbf{F}(\Theta)}{\partial x} + \frac{\partial \mathbf{G}(\Theta)}{\partial y} = \mathbf{S}(t),$$

in which

$$\Theta = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix}, \ \mathbf{F}(\Theta) = \begin{bmatrix} uh \\ u^2 h + \frac{1}{2} g h^2 \\ uvh \end{bmatrix}, \ \mathbf{G}(\Theta) = \begin{bmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g h^2 \end{bmatrix},$$

and the wave-modified external source term $\mathbf{S}(t)$ is given as

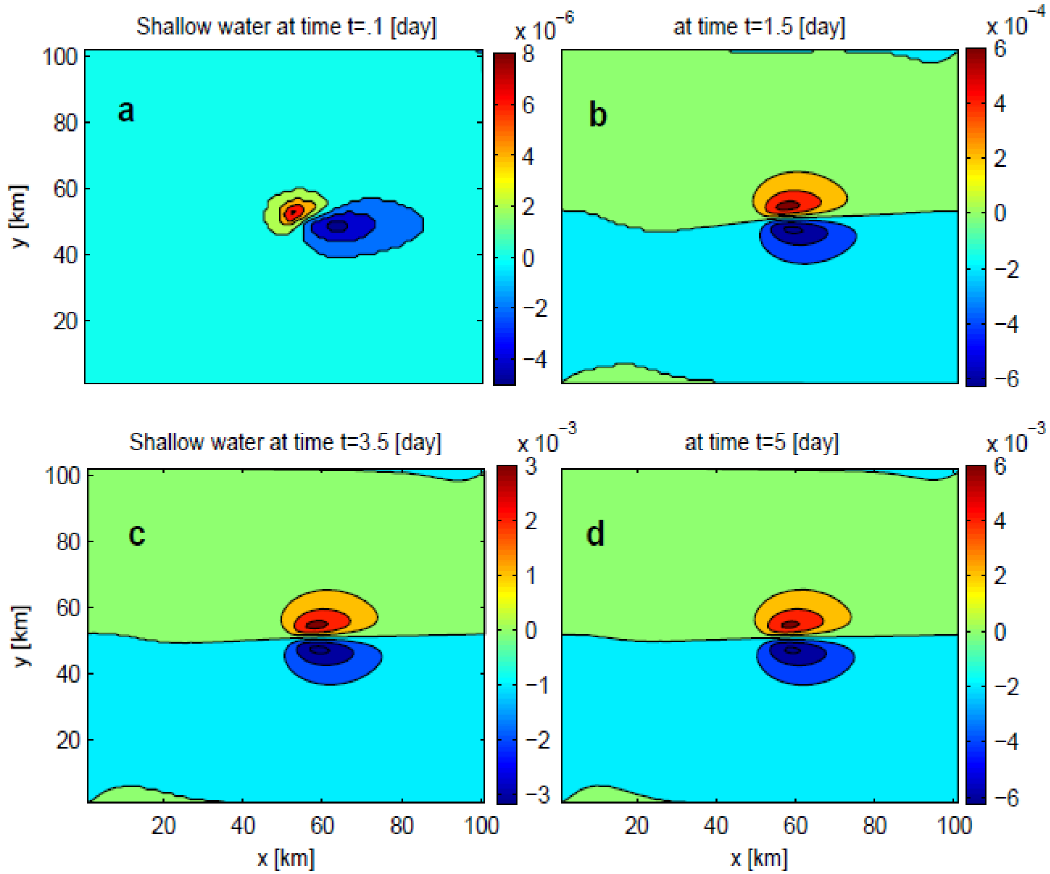
$$\mathbf{S}(t) = \frac{1}{\rho_w} \begin{bmatrix} 0 \\ \tau_x - \tau_{in}^x - \tau_B^x \\ \tau_y - \tau_{in}^y - \tau_B^y \end{bmatrix} + \begin{bmatrix} 0 \\ f_{cor}(v + v_s) - \mathbf{F}_{ds}^x \\ -f_{cor}(u + u_s) - \mathbf{F}_{ds}^y \end{bmatrix},$$

$$\Theta_{i,j}^{n+1} = \Theta_{i,j}^n - \frac{\Delta t}{\Delta x}\left(\mathbf{F}_{i+\frac{1}{2},j}^{n+\frac{1}{2}} - \mathbf{F}_{i-\frac{1}{2},j}^{n+\frac{1}{2}}\right) - \frac{\Delta t}{\Delta x}\left(\mathbf{G}_{i,j+\frac{1}{2}}^{n+\frac{1}{2}} - \mathbf{G}_{i,j-\frac{1}{2}}^{n+\frac{1}{2}}\right),$$

where

$$\mathbf{F}_{i+\frac{1}{2},j}^{n+\frac{1}{2}} = \frac{\mathbf{F}(\Theta_{i,j}^n) + \mathbf{F}(\Theta_{i+1,j}^n)}{2} - \frac{1}{2}\left|\lambda\left(\frac{\Theta_{i,j}^n + \Theta_{i+1,j}^n}{2}\right)\right|(\Theta_{i+1,j}^n - \Theta_{i,j}^n),$$

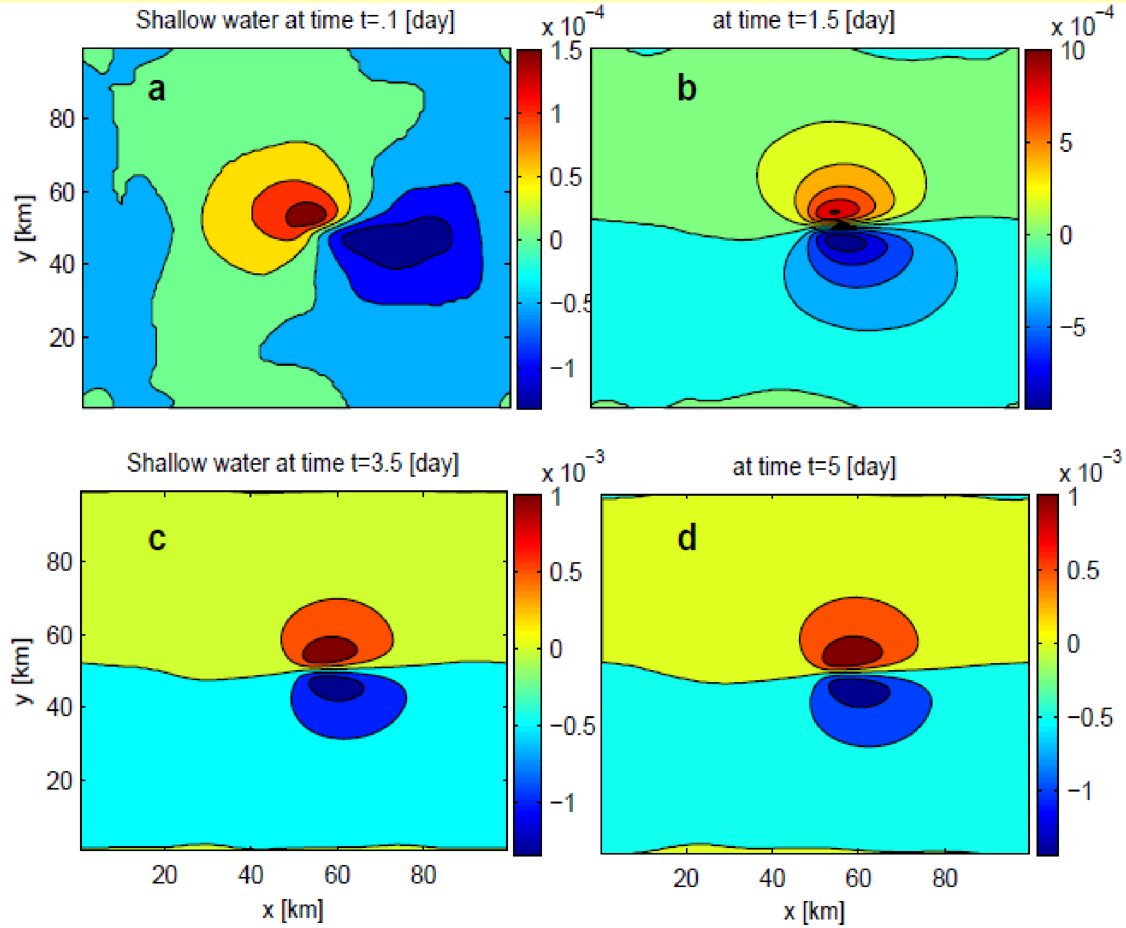
Part II: Full nonlinear-Numerical modelling



Taken from [7]

Fig. 5. Results of the Lax-Friedrichs technique for non-linear shallow water wave by including bottom friction, horizontal diffusion term for different periods: : a) 0.1 day, b) 2.5 days, 3) 3.5 days and d) 5 days. After about 3 days, upper ocean response to the constant forcing becomes weaker and we see a very slow linearly growth in pycnocline height

Part II: Full nonlinear-Numerical modelling



Taken from [7]

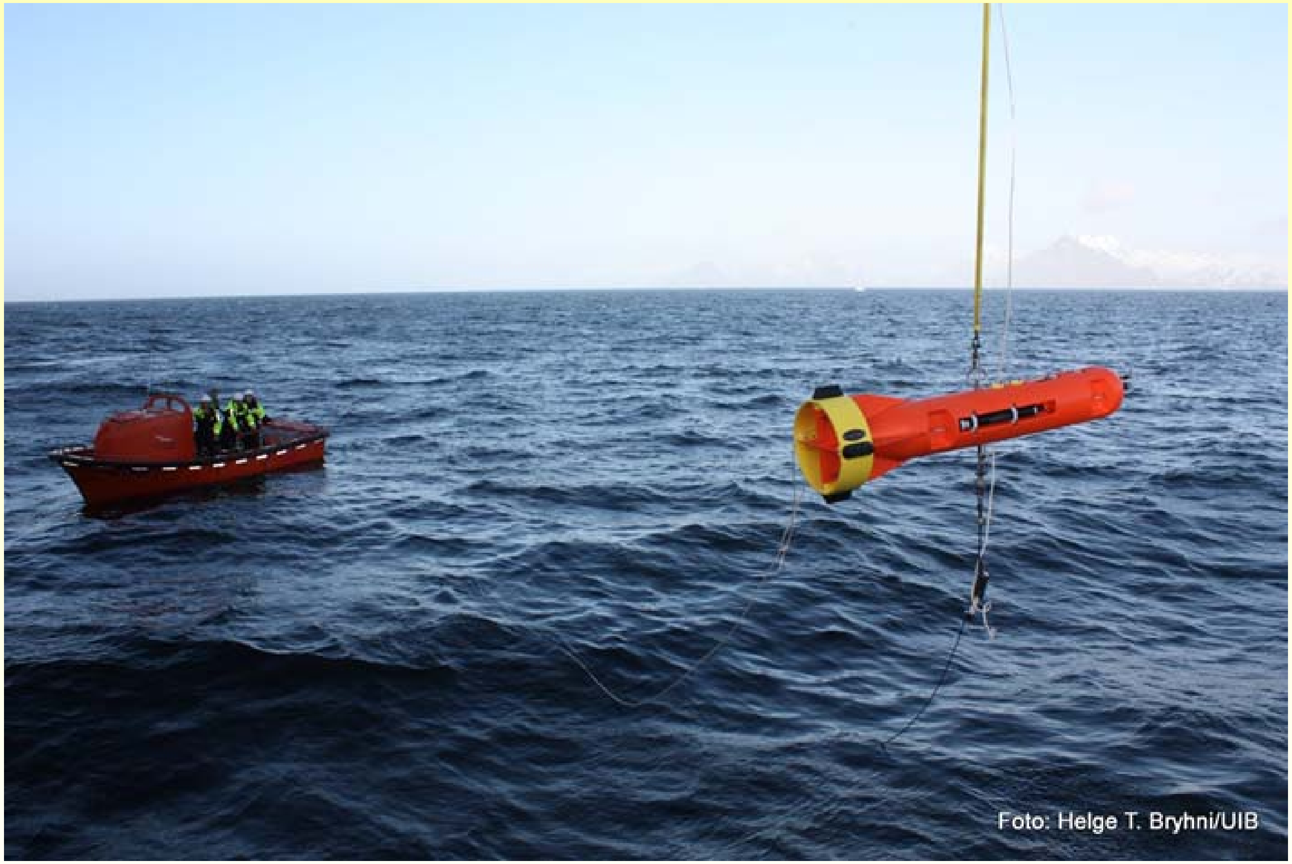
Fig. 6. Spatial disturbances in the pycnocline height by using two-dimensional results of ROMS for different periods: a) 0.1 day, b) 2.5 days, 3) 3.5 days and d) 5 days.

Instrumentation

Site: Vestfjorden

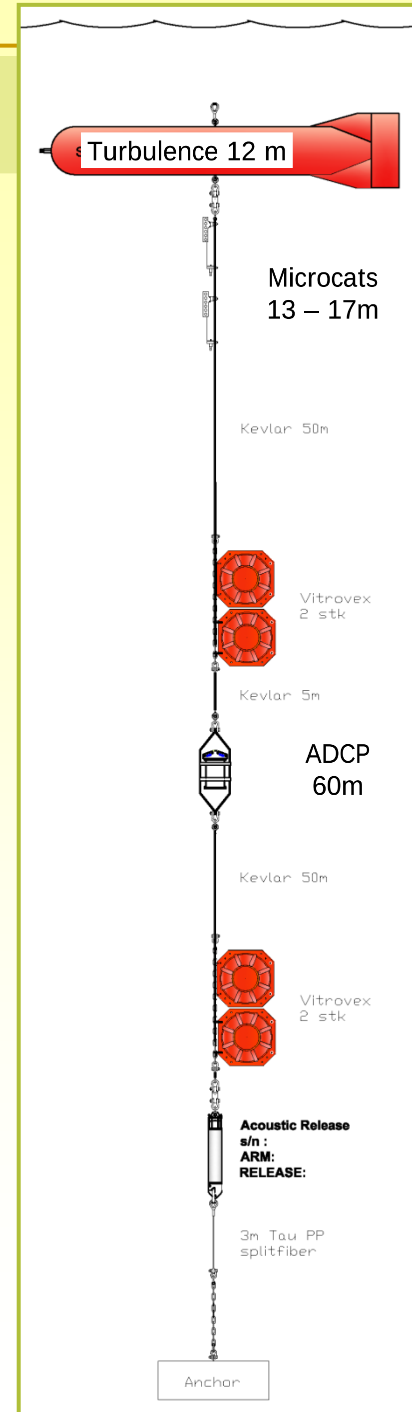
R.V. Johan Hjort

8-13 April 2011.

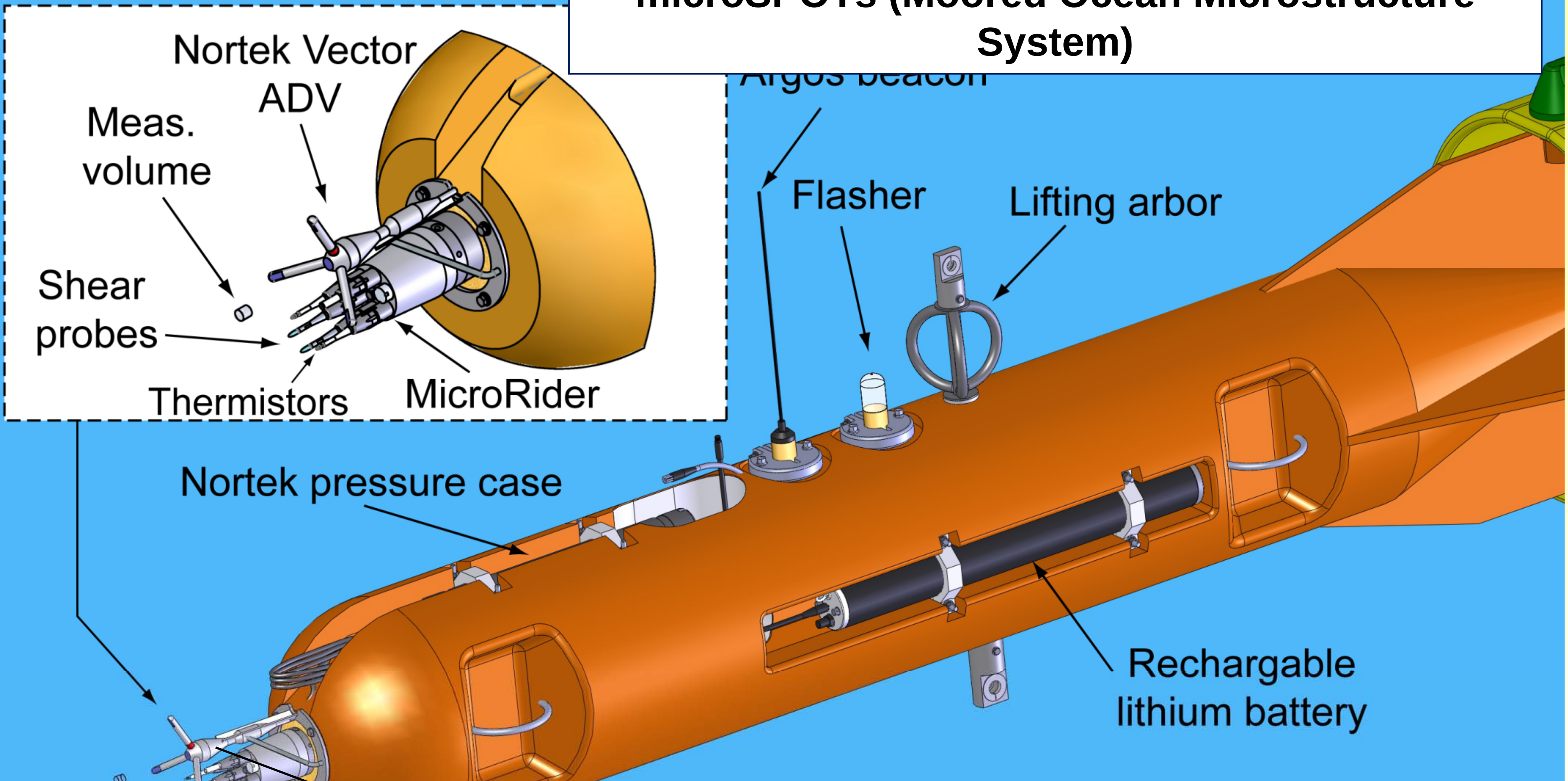


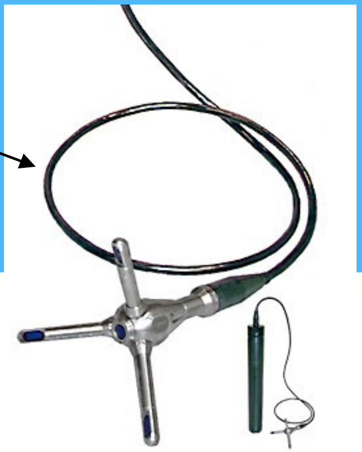
microSPOTS

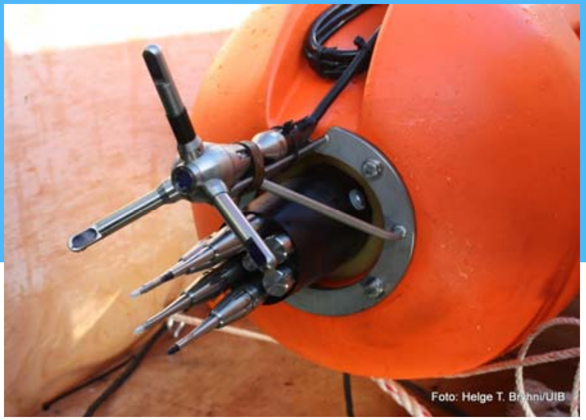
(Microstructure Ocean Turbulence System)



microSPOTs (Moored Ocean Microstructure System)



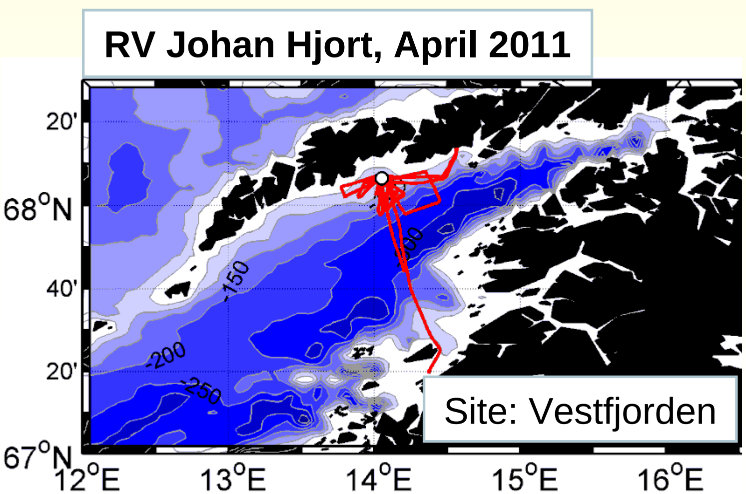


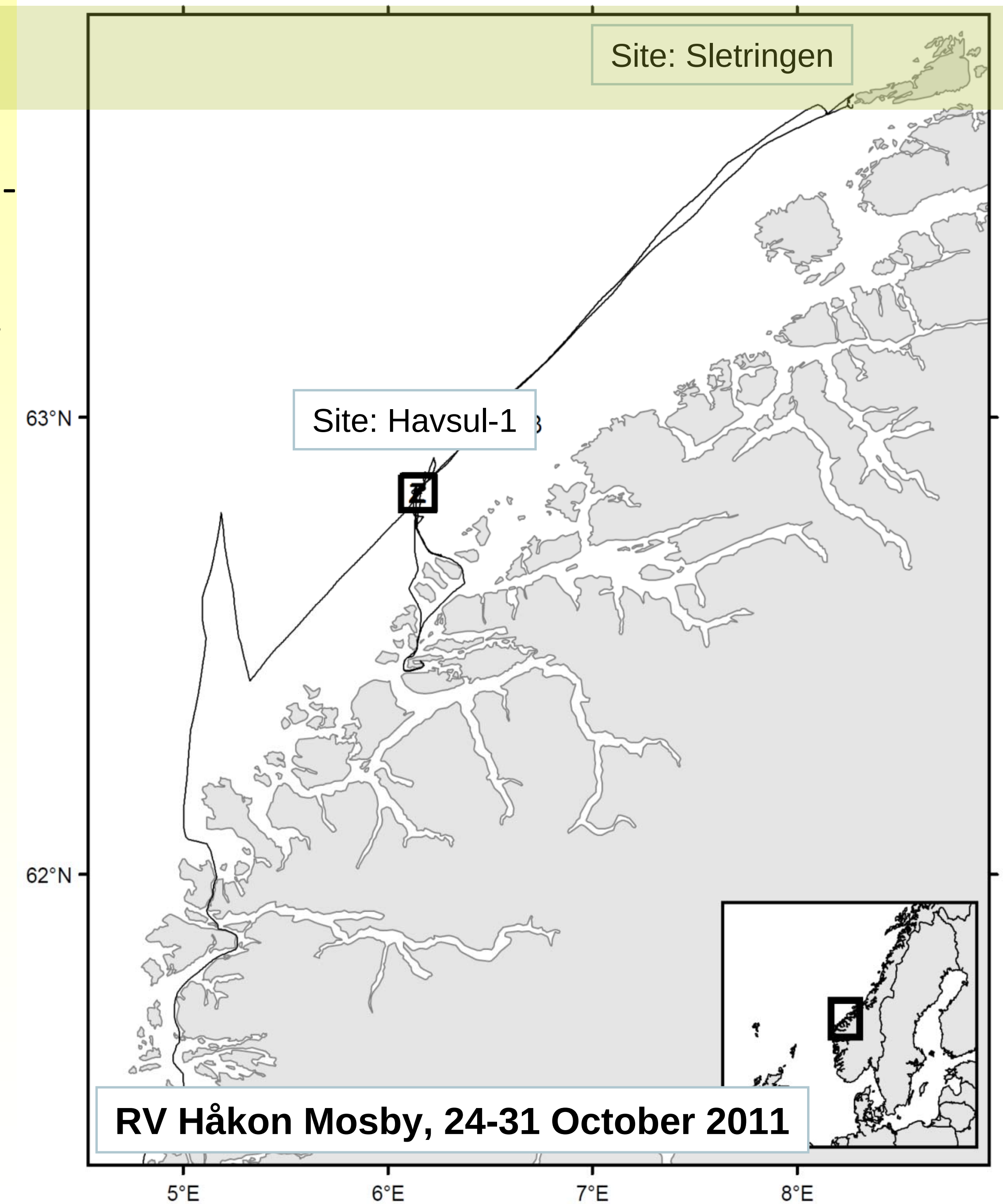


Measurements

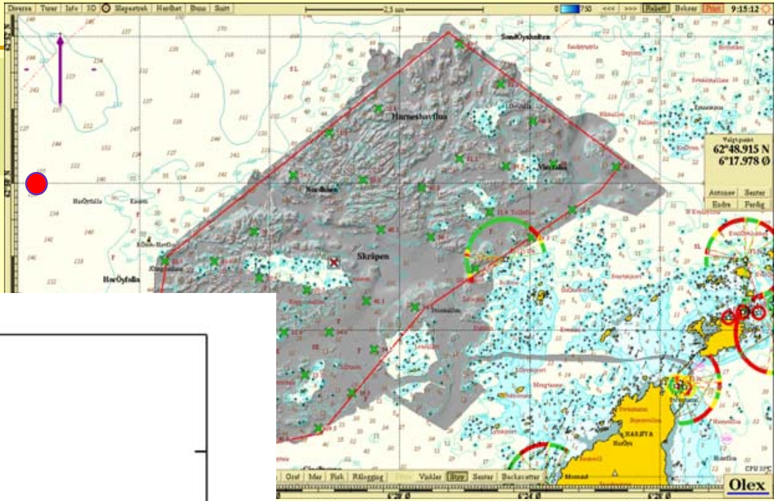
Field Work

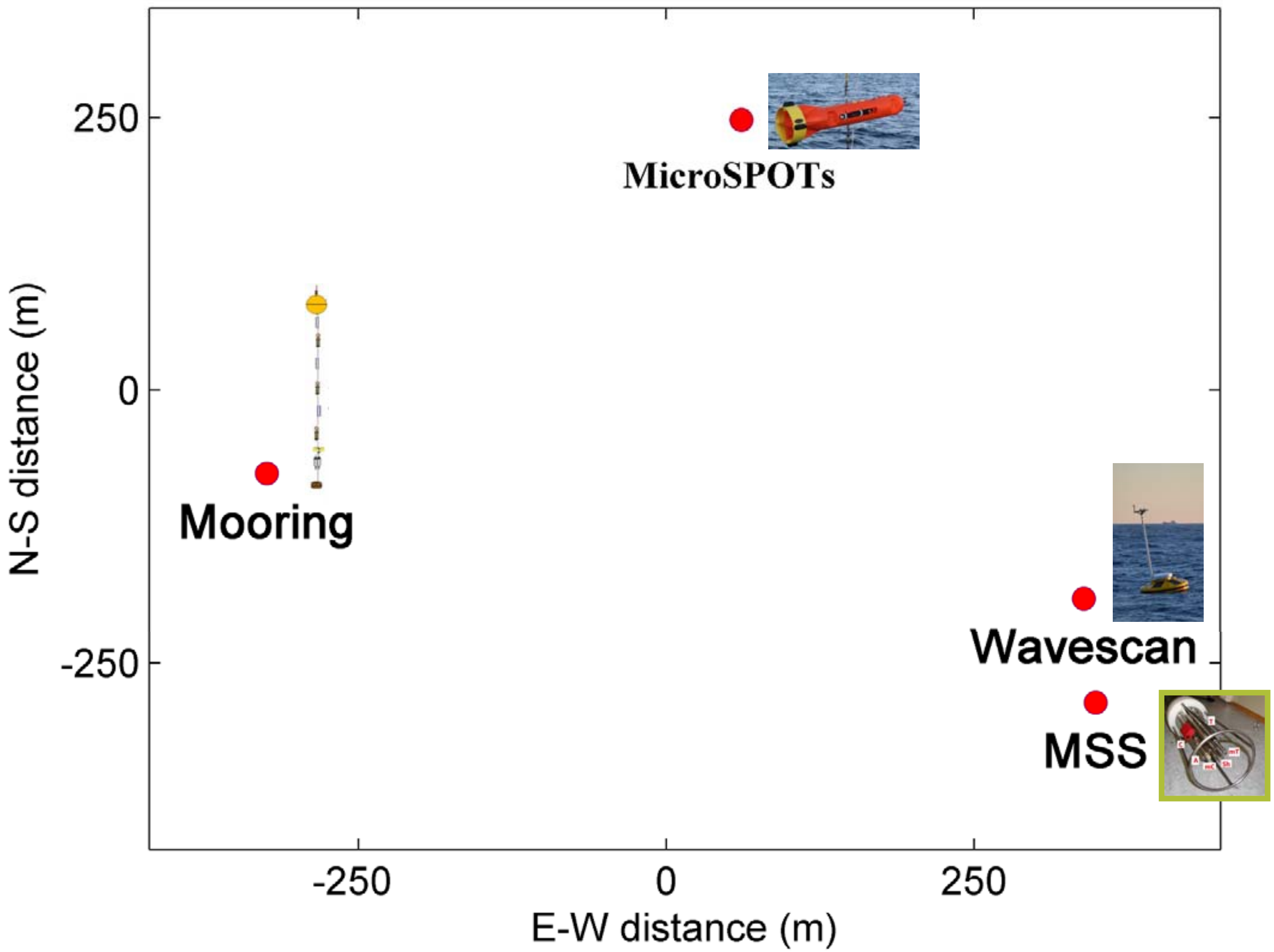
- Sletringen Buoy recovery & re-deployment, May 2011
- Test cruise, RV Johan Hjort, 8-13 April 2011
- Dedicated cruise, RV Håkon Mosby October 2011





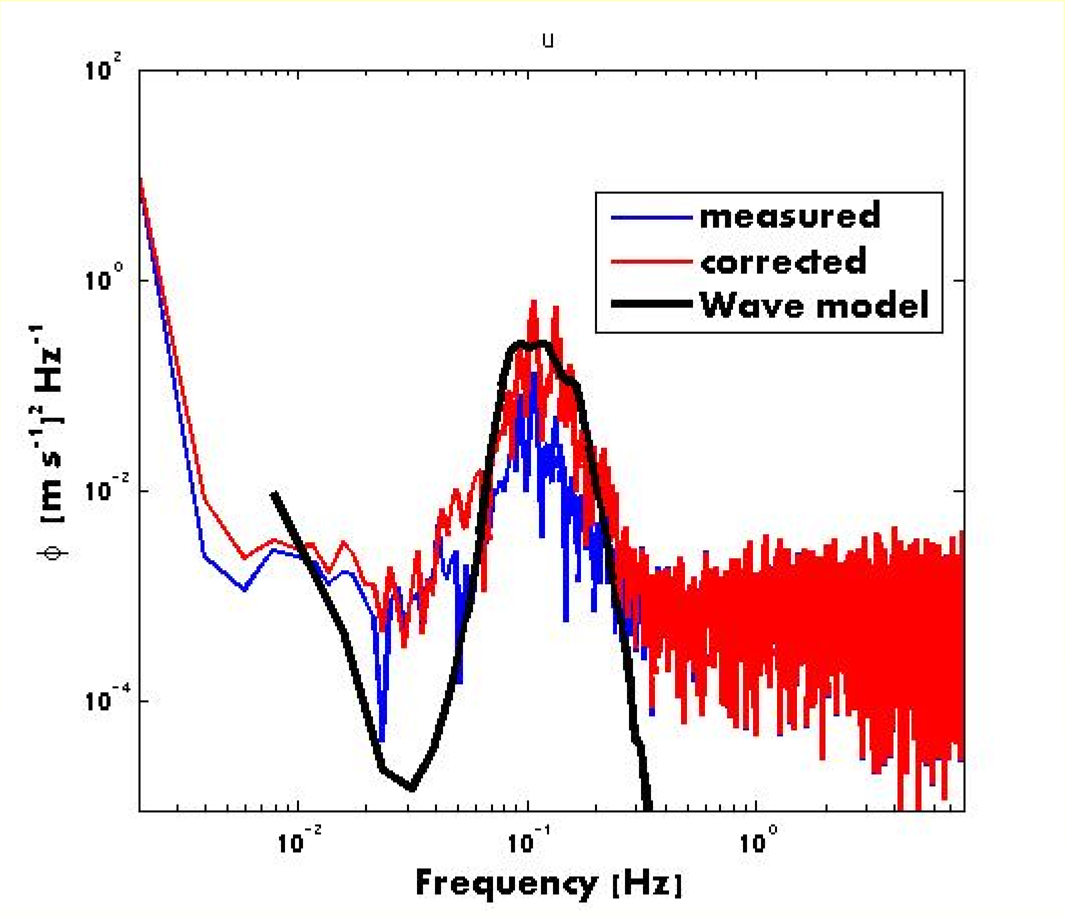
Site: Havsul-1

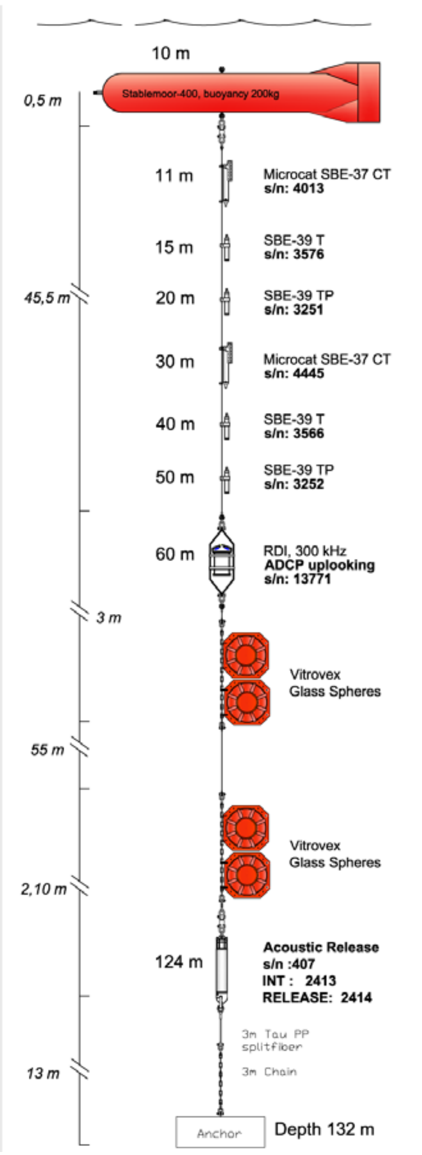




Particle velocity spectrum beneath wind waves (Analytical study)

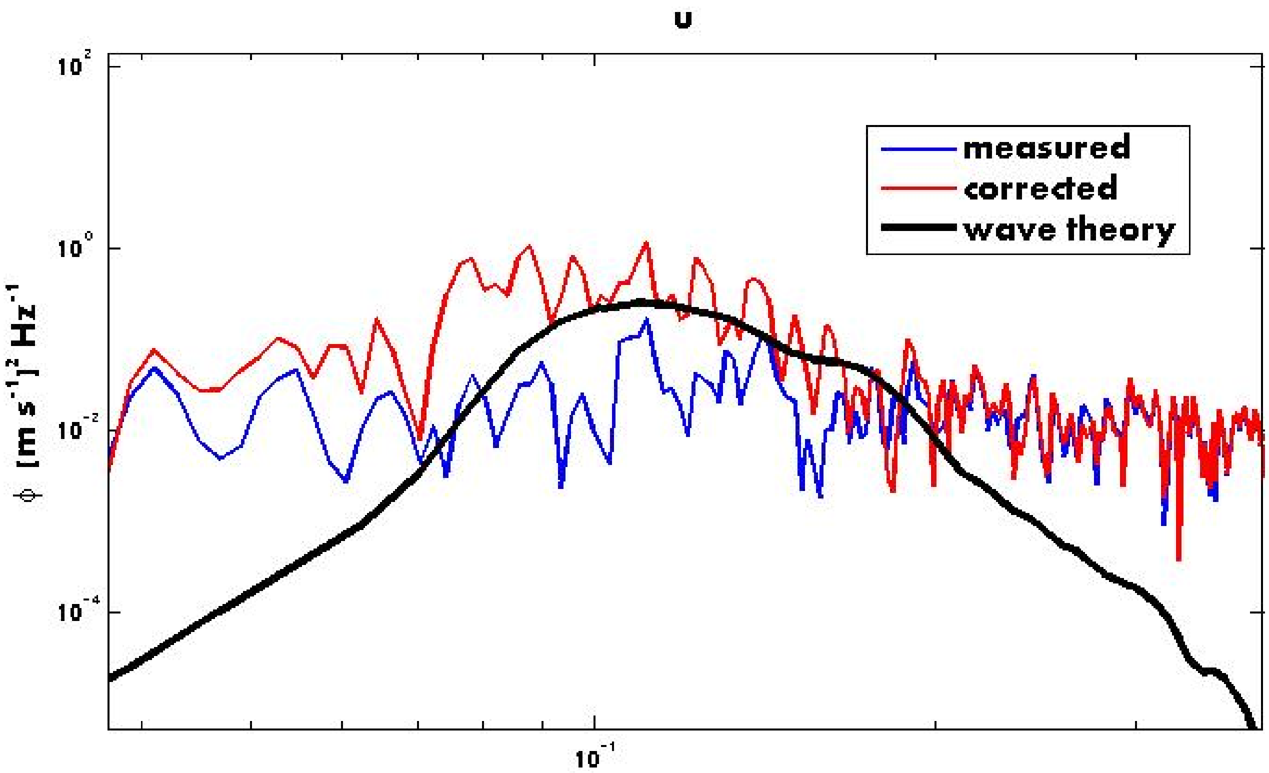
26-Oct-2011 10:00:00

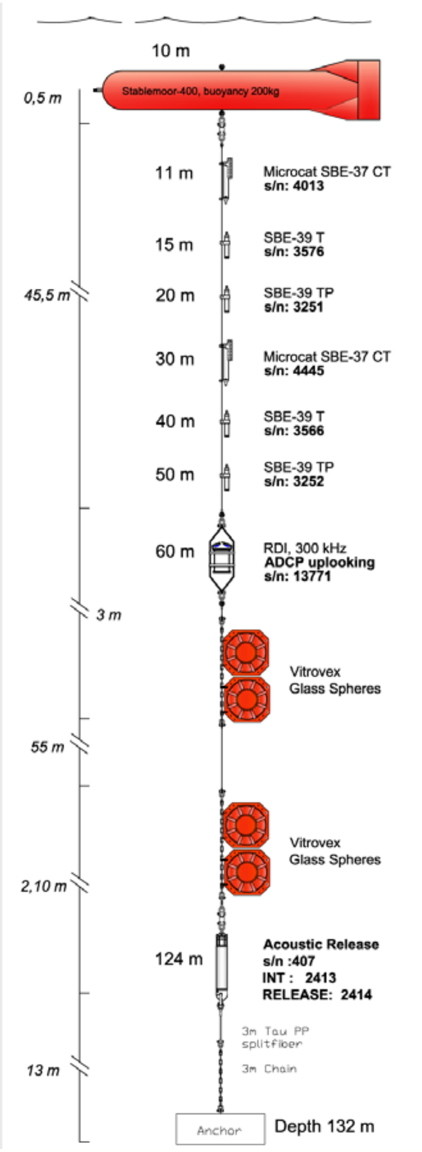




Particle velocity spectrum beneath wind waves (Analytical study)

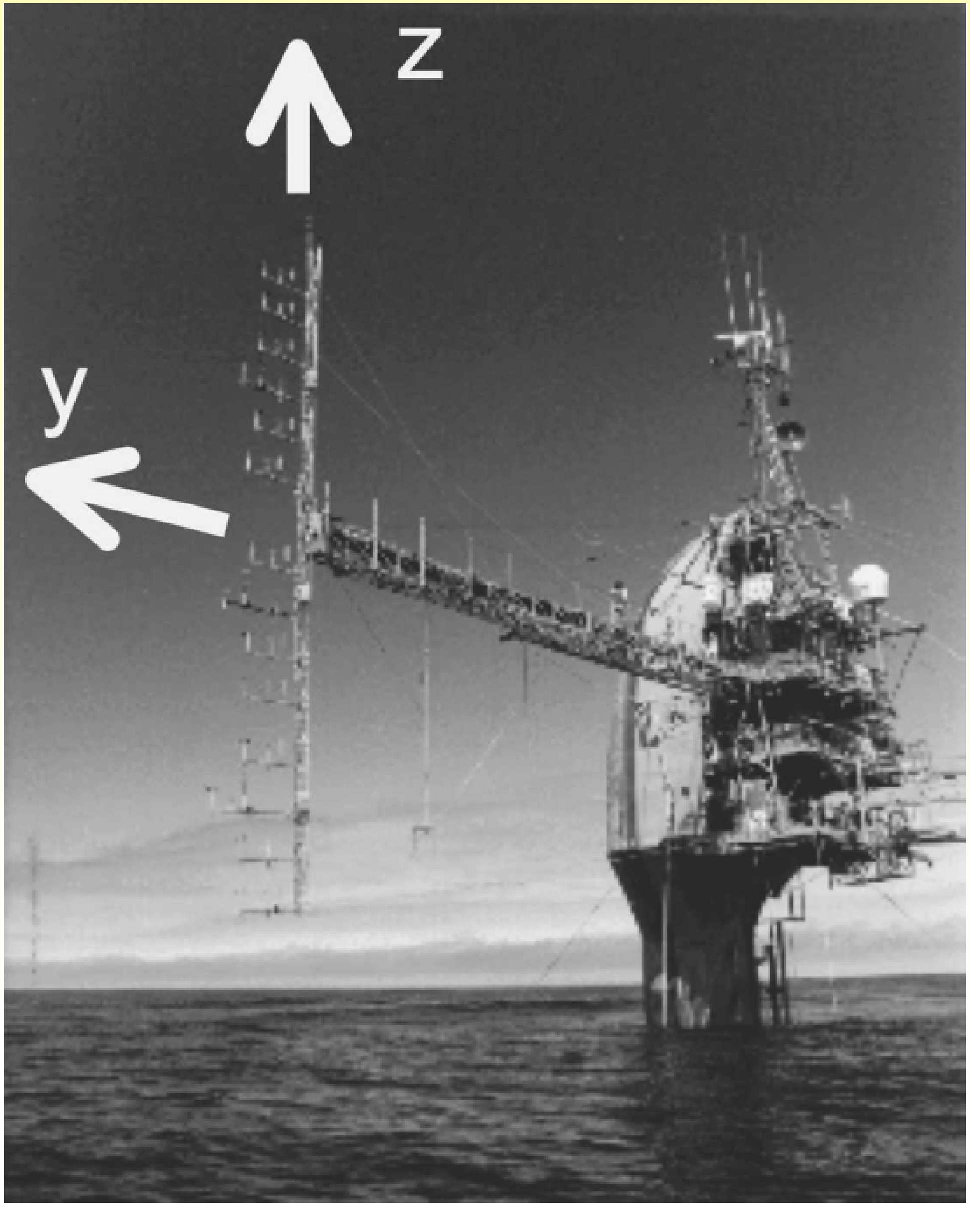
25-Oct-2011 11:00:00



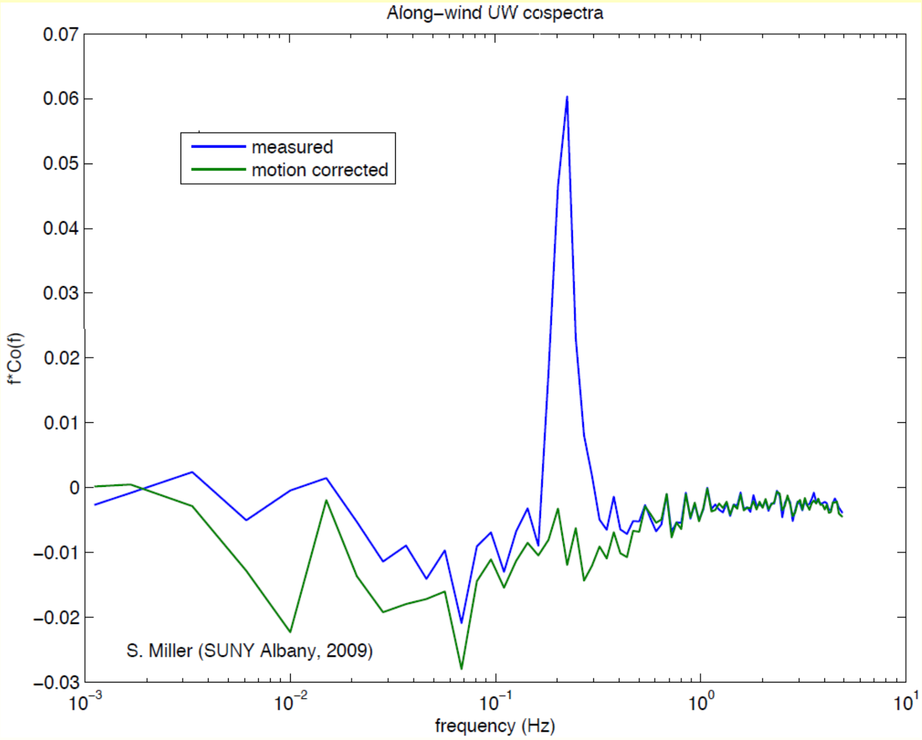


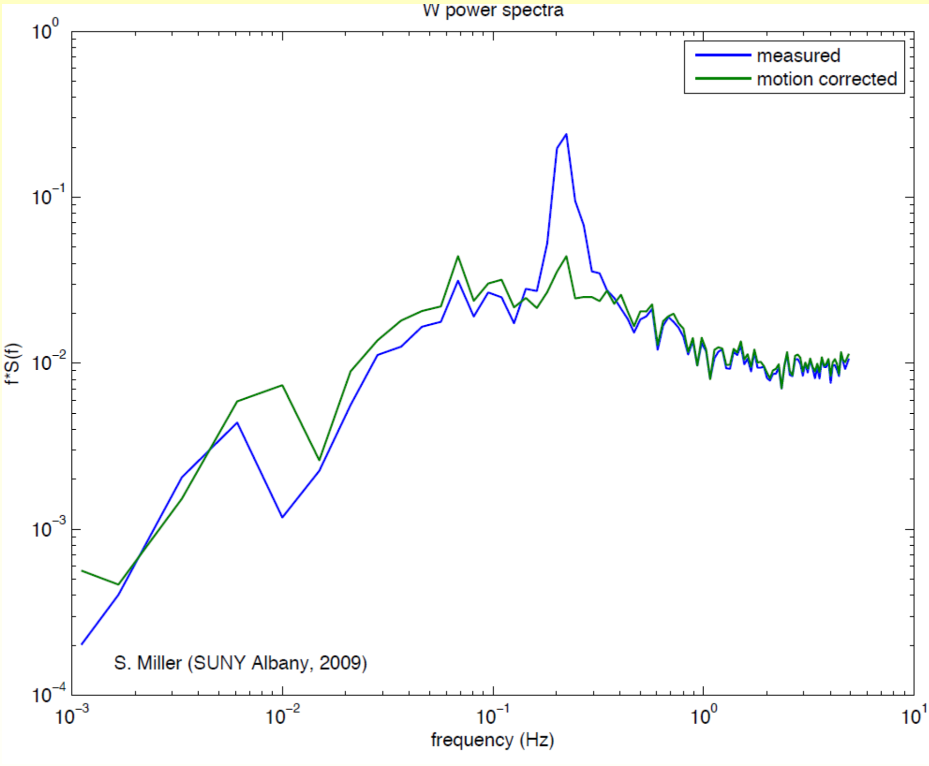
Results: FLIP platform

The method is applied to a high-resolution dataset, including four levels of turbulence within 20 m of the ocean surface, measured over deep ocean waves using the stable research platform R/P *FLIP* [3].



Results: FLIP platform





Conclusions:

References

[1] **Danish Technical University report, 2006,** Assessing wind energy potential In Antarctica

[2] Smith, 2009, Gravity wave effects on wind farmefficiency

[3] **Sten Frandsen et. Al, 2006,** *Analytical Modelling of Wind Speed Deficit in Large Offshore Wind Farms,*

[4] **Sten Frandsen et. Al, 2007**, Summary report: The shadow effect of large wind farms: measurements, data analysis and modelling

[5] **Bakhoday Paskyabi, et. al**, 2012, Surface gravity wave effects on the upper ocea boundary layer: Modification of a one-dimensional vertical mixing model,

[6] **A.D., Jenkins, et. al**, 2012, Modelling the effect of ocean waves on the atmospheric and ocean boundary layers

[7] **Bakhoday Paskyabi, et. al**, 2012, Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves,

Acknowledgements

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