Comparison and characteristics of oceanographic in situ measurements and simulations above submerged sand waves in a tidal inlet

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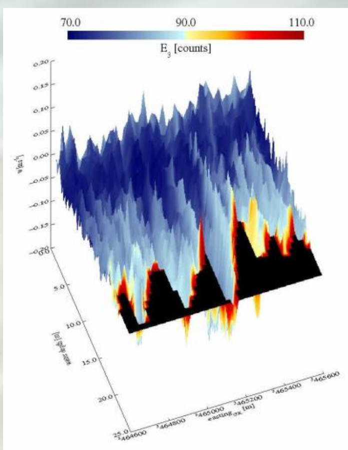

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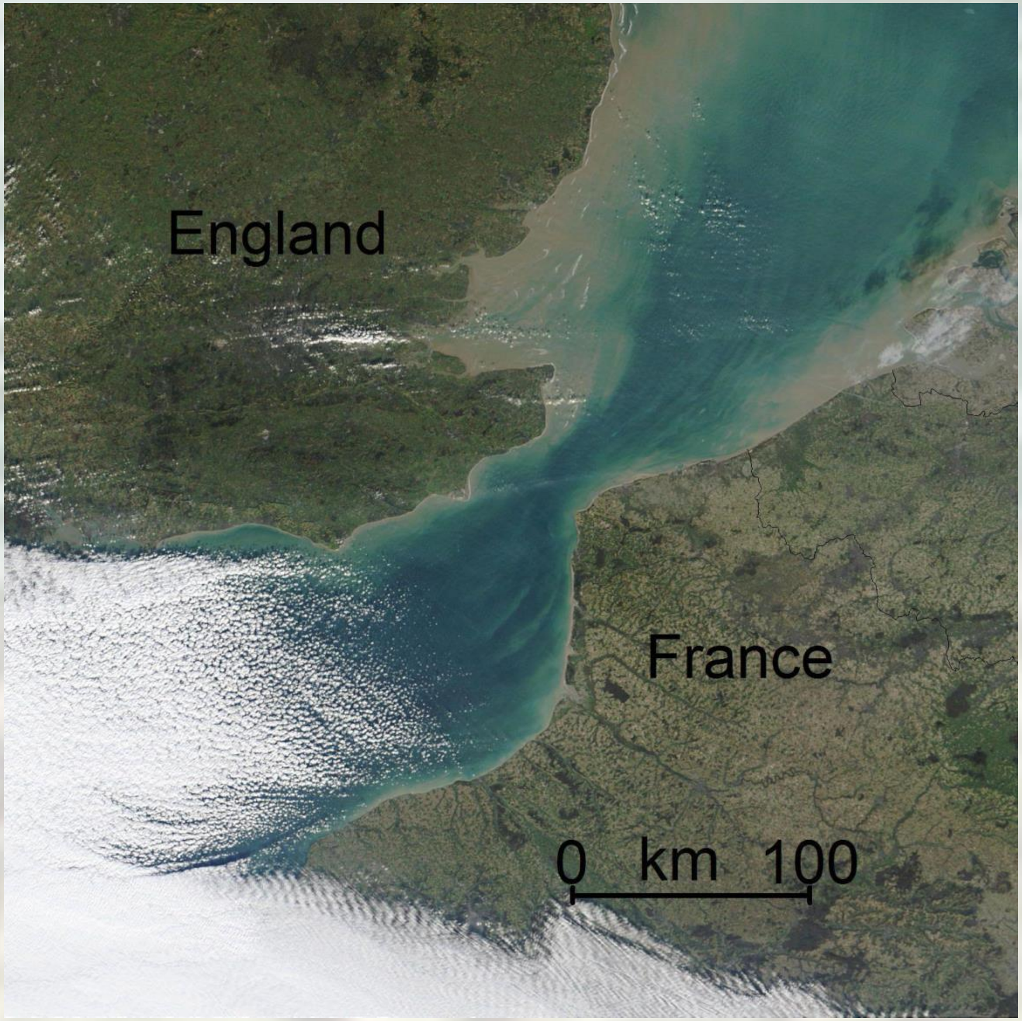
1. Introduction

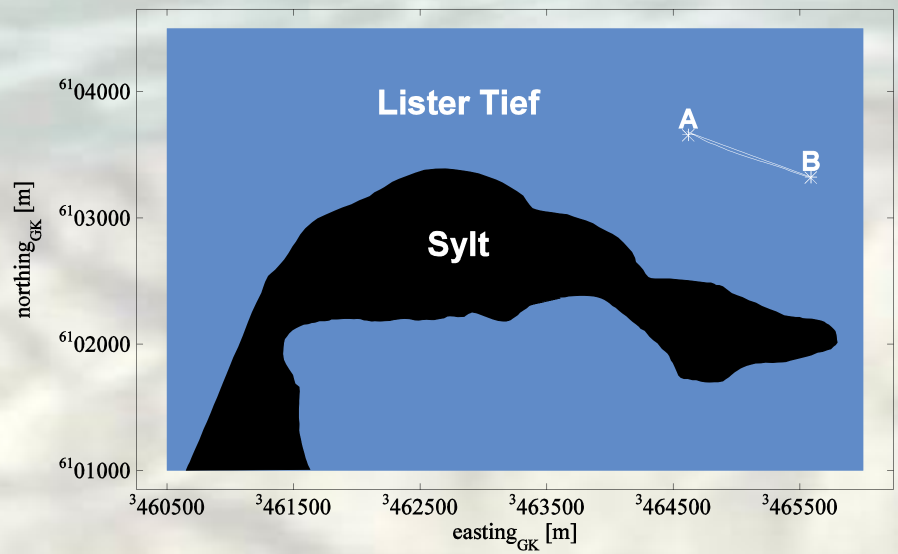
Terra-MODIS satellite image of the Strait of Dover acquired on 9 December 2002; spatial resolution: 250 m (NASA)



Handheld camera image of Hohwacht Bight at the German coast of the Baltic Sea acquired on 8 February 2015

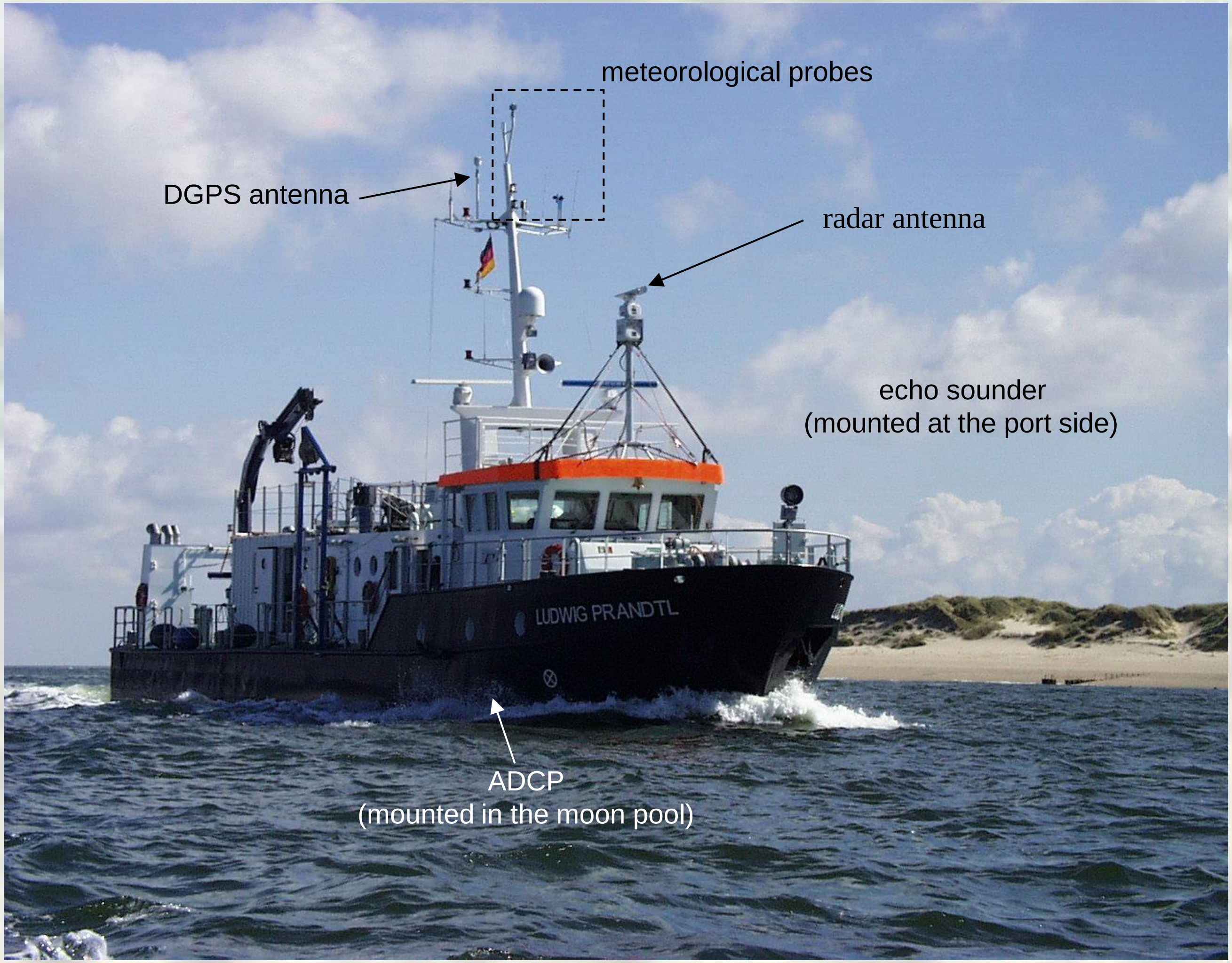
Overview of the North Sea

Positions of runs along transect AB in the study area of the Lister Tief in the German Bight of the North Sea

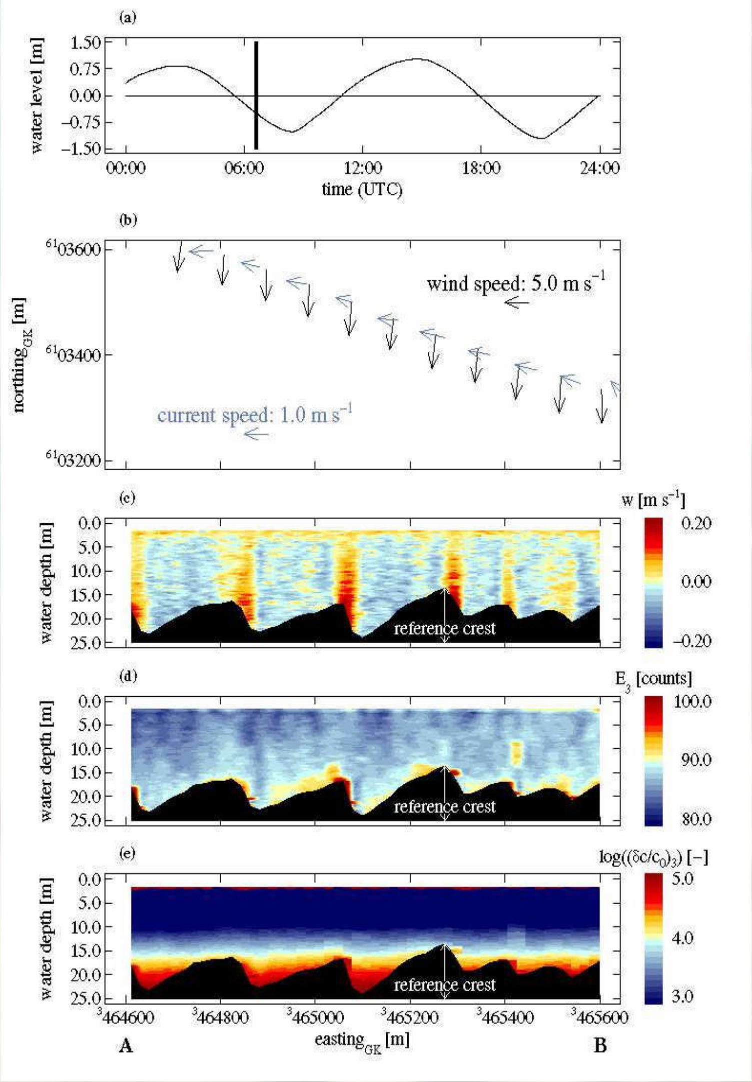


2. Measurements

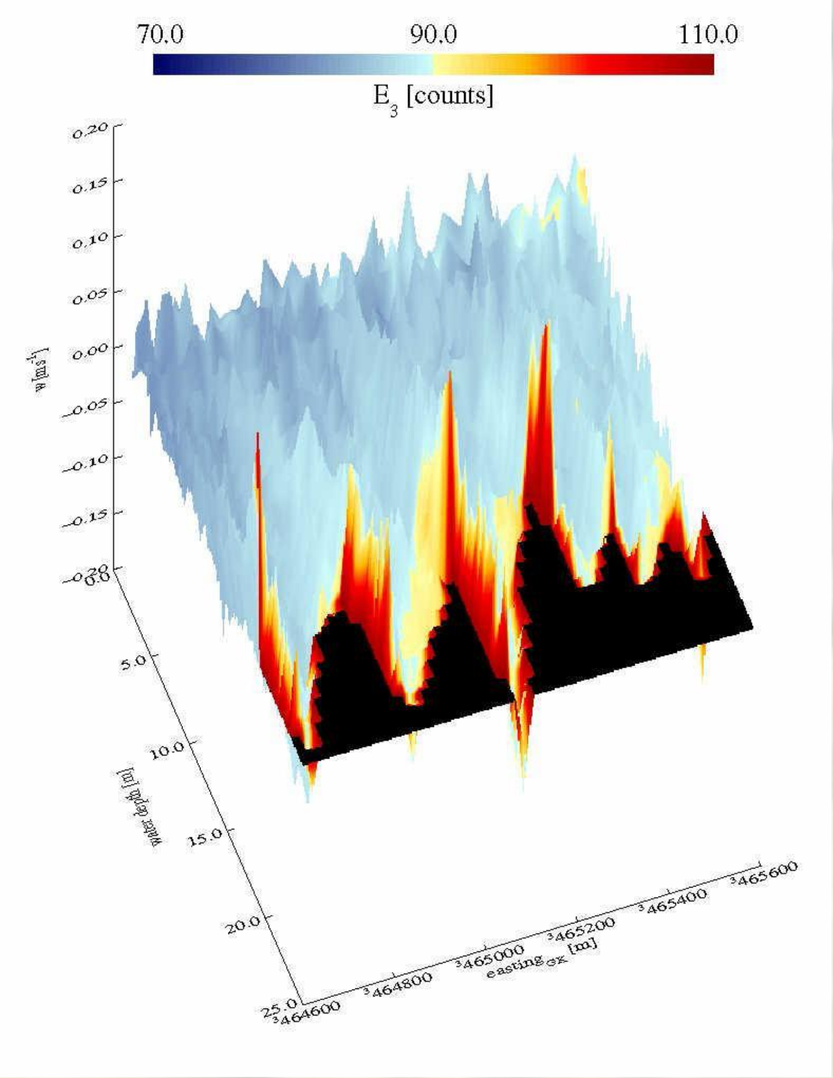
Measurement configuration on board research vessel (R/V) *Ludwig Prandtl* of Helmholtz-Zentrum Geesthacht (HZG) used in the Lister Tief on 05.-16. August 2002



Analyzed ADCP and oceanographic data of run 48 along transect AB during ebb tidal phase at 06:33-06:41 UTC on 10 August 2002

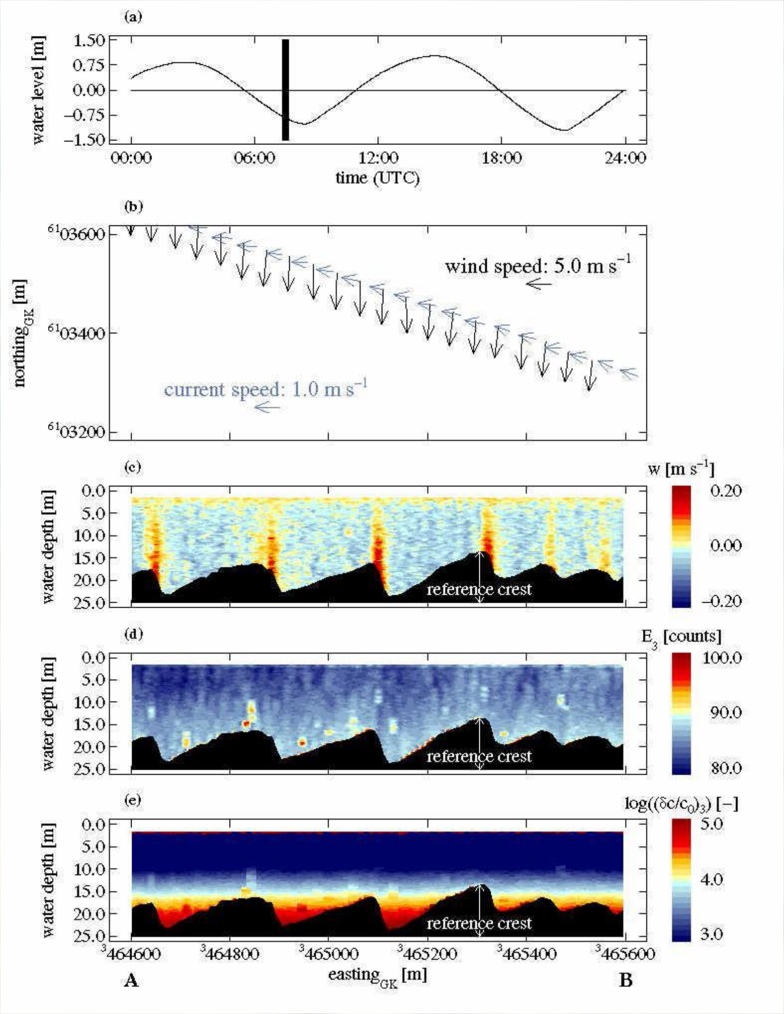


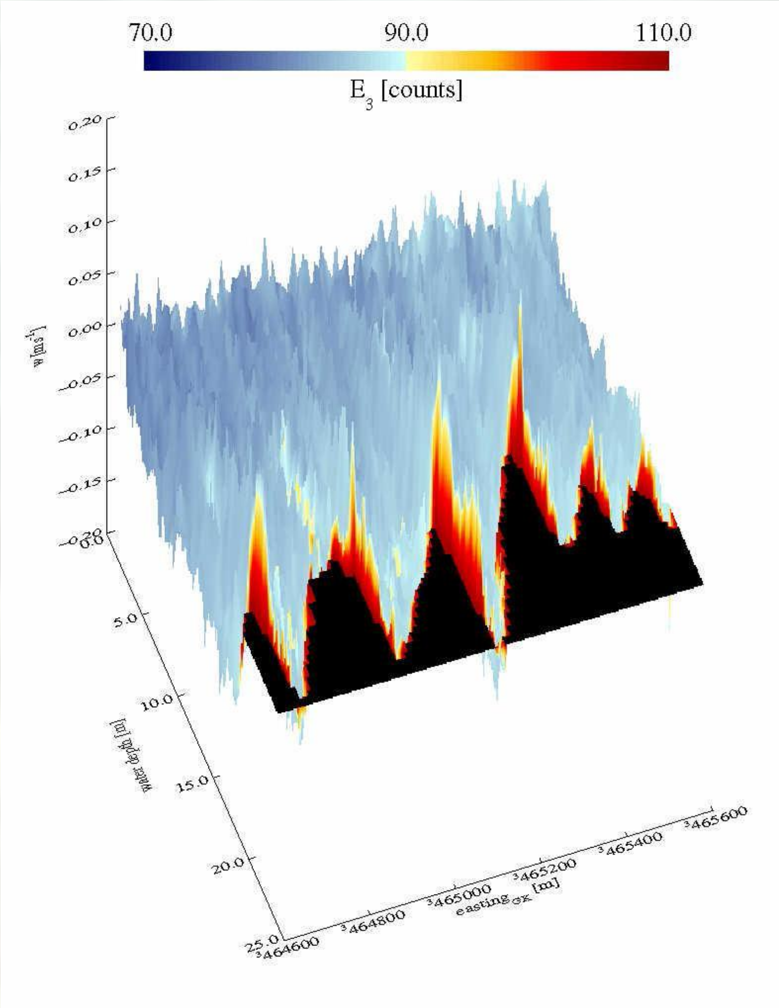
Three dimensional presentation of w and E_3 (color coded) as a function of water depth of run 48 along transect AB as shown on the left side



Analyzed ADCP and oceanographic data of run 51 along transect AB during ebb tidal phase at 07:21-07:40 UTC on 10 August 2002

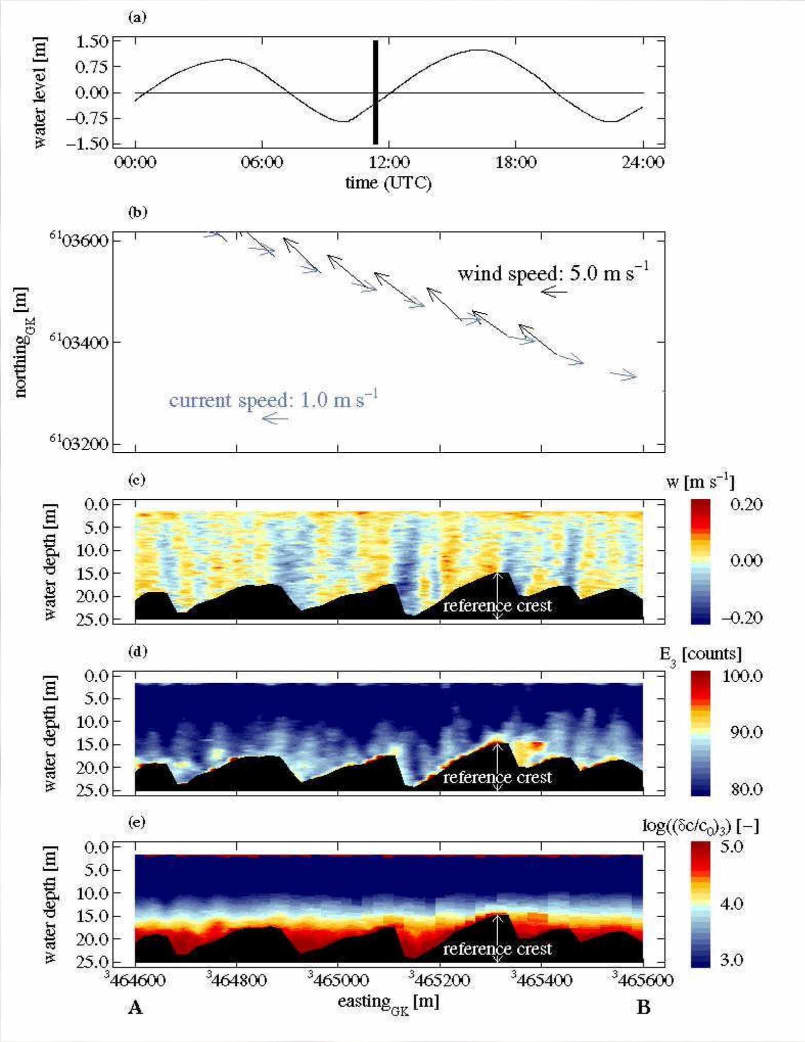
Three dimensional presentation of *w* and E_3(color coded) as a function of water depth of run 51 along transect AB as shown on the left side

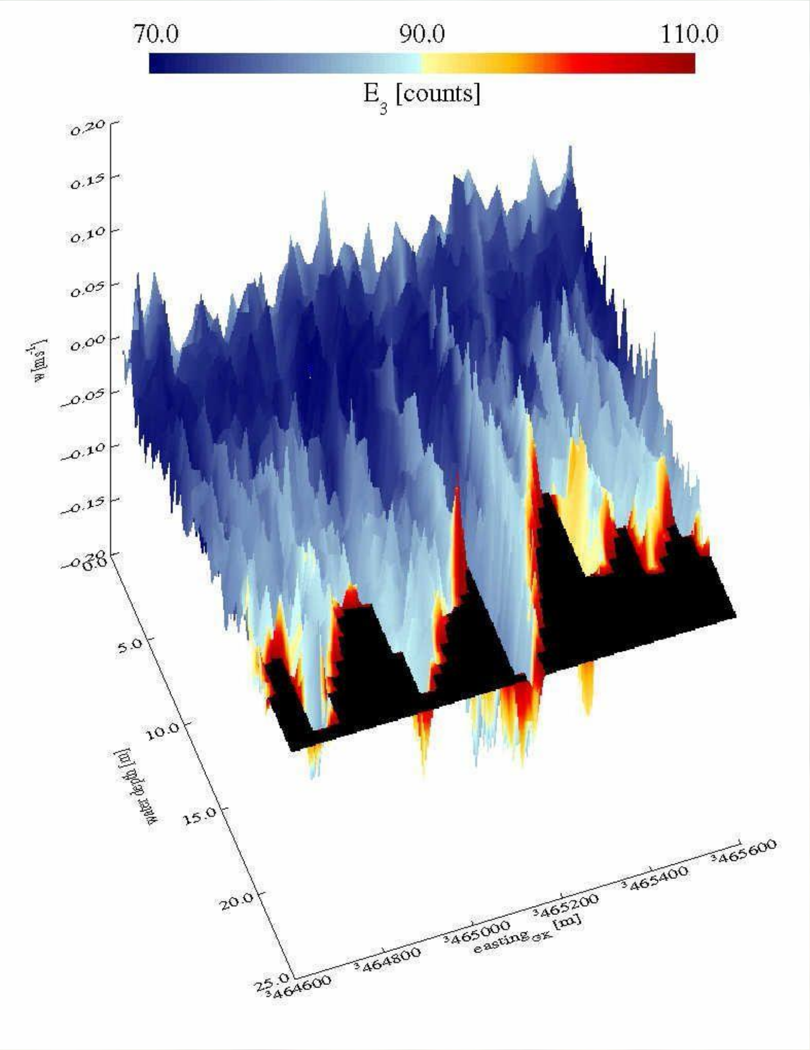




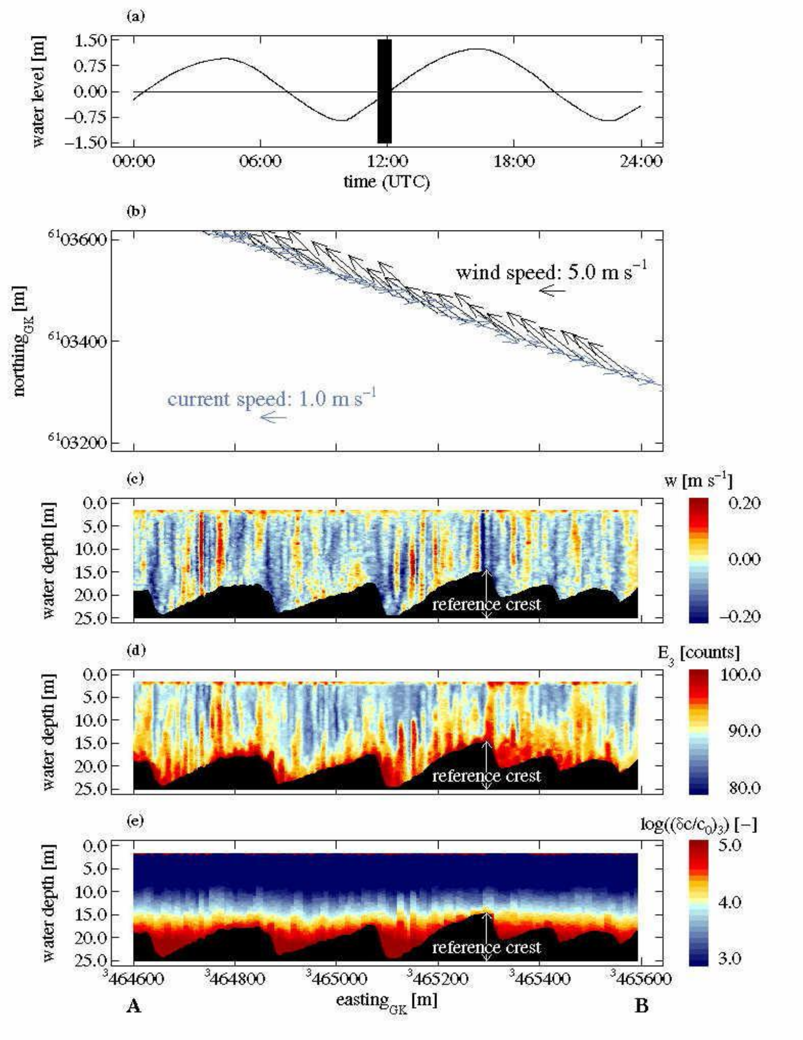
Analyzed ADCP and oceanographic data of run 64 along transect AB during flood tidal phase at 11:16-11:28 UTC on 12 August 2002

Three dimensional presentation of *w* and E_3 (color coded) as a function of water depth of run 64 along transect AB as shown on the left side

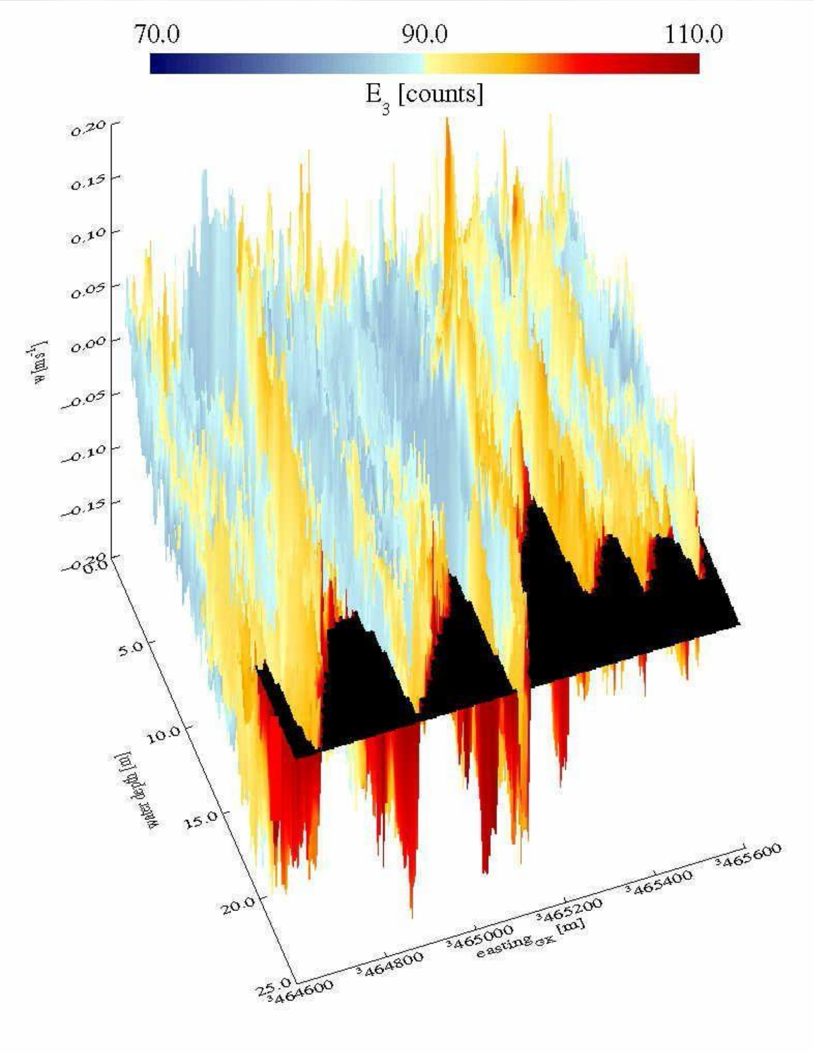




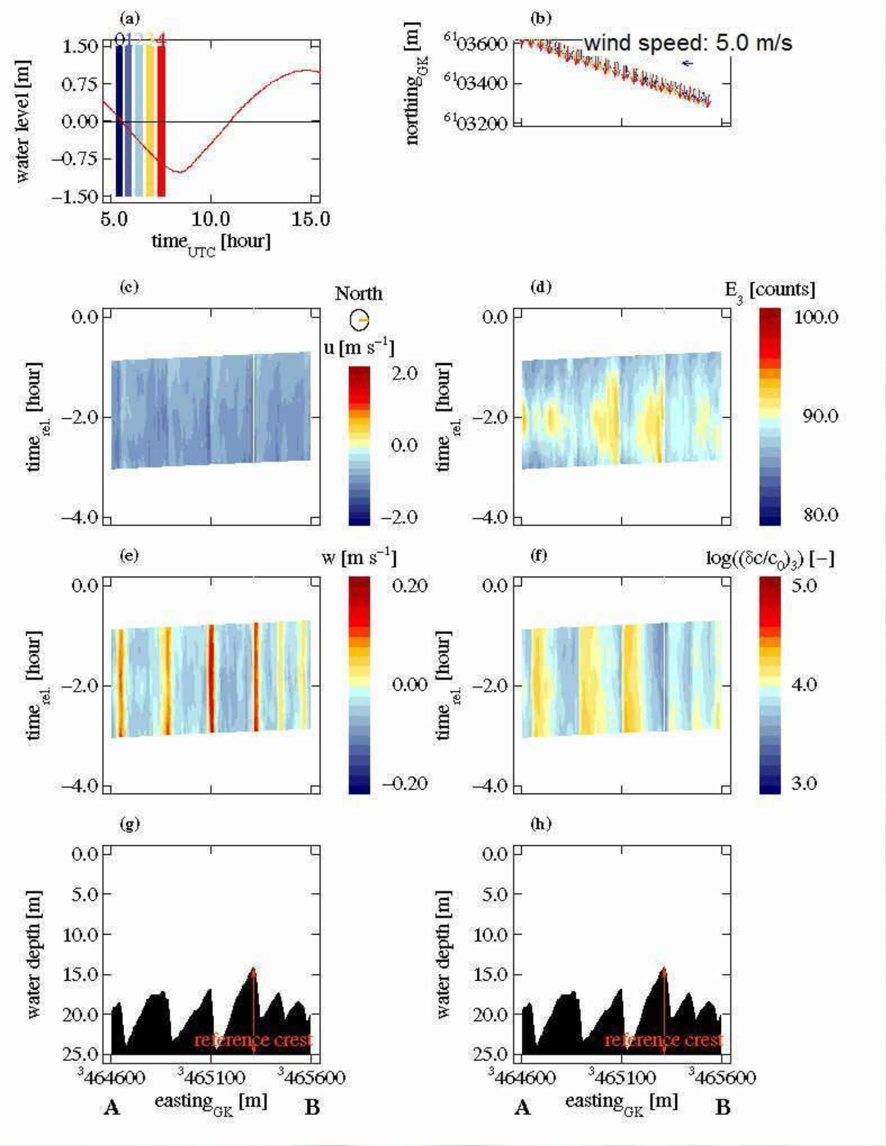
Analyzed ADCP and oceanographic data of run 65 along transect AB during flood tidal phase at 11:33-12:10 UTC on 12 August 2002

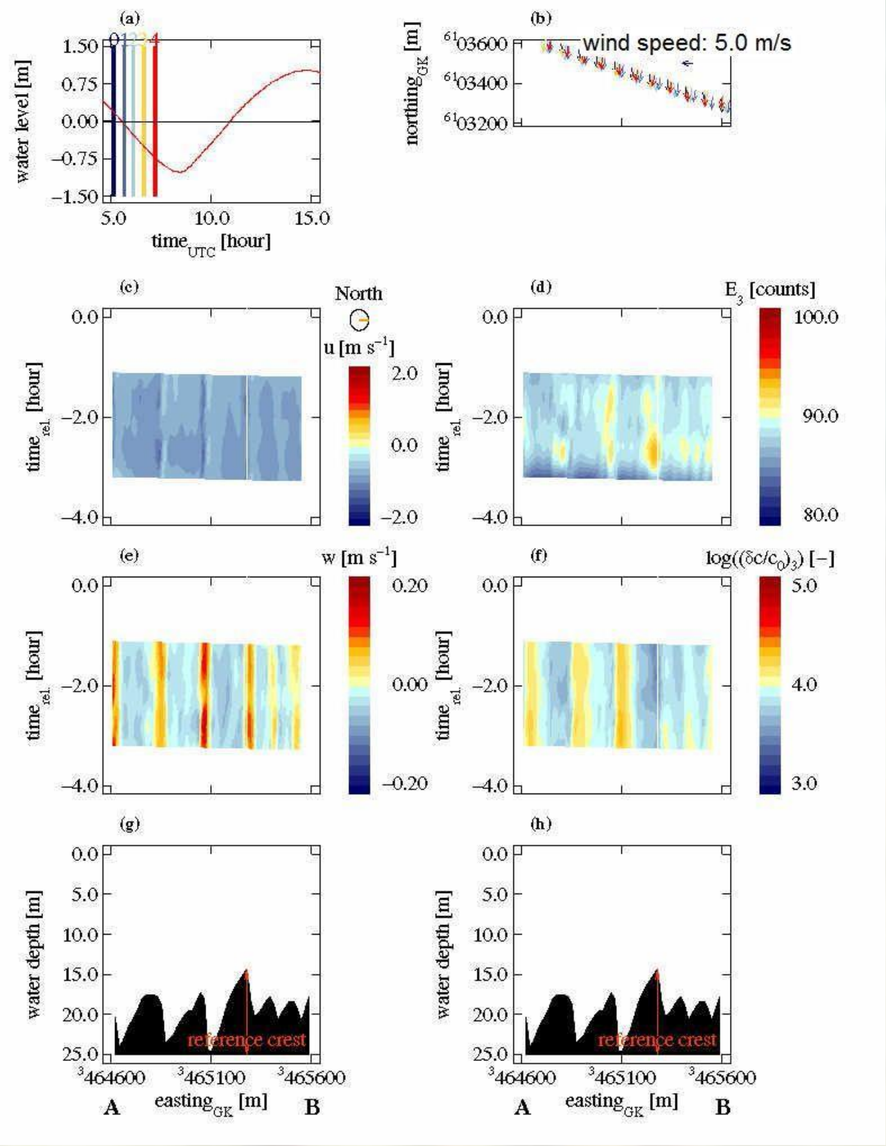


Three dimensional presentation of *w* and E_3 (color coded) as a function of water depth of run 65 along transect AB as shown on the left side



Time series of five selected runs of ADCP data during ebb tidal current phase on 10 August 2002 (current direction is from right to left); research vessel is sailing against the current (left figure) and with the current (right figure)





3. Theory

The dynamic buoyancy density A_d is defined by

$$A_d = \frac{\hat{A}_d}{F \cdot z_b} \approx \frac{1}{2} \cdot \rho \cdot (c_a - 1) \cdot \bar{u}^2 \qquad (1)$$

with the dimensionless lift coefficient c_a

$$c_a = \frac{\pi}{sin(\pi \cdot \beta)} \left(\frac{\beta}{1 - \beta} \right)^{1-2\beta} \qquad (2)$$

and

$$\beta = \frac{\alpha}{\pi} \qquad (3)$$

with α the slope angle of the stoss or lee plane of the sand wave

The gradient of the dynamic buoyancy density perpendicular to the sand wave crest is derived as

$$\frac{\partial A_d}{\partial x} \approx (c_a - 1) \cdot \rho \cdot \bar{u} \cdot \frac{\partial \bar{u}}{\partial x} \qquad (4)$$

Potential energy density E_p and kinetic energy density E_k in the water column in hydrodynamic theory are given by

$$E_p = \frac{\widehat{E}_p}{F \cdot z_b} = \rho \cdot g \cdot \left(z_R - \frac{1}{2} z_b \right) \qquad (5)$$

$$E_k = \frac{\widehat{E}_k}{F \cdot z_b} \approx \frac{1}{2} \cdot \rho \cdot \bar{u}^2 \qquad (6)$$

The total energy density E is the sum of equations (5) and (6)

$$E = E_p + E_k = \rho \cdot g \cdot \left(z_R - \frac{1}{2} z_b\right) + \frac{A_d}{(c_a - 1)} \quad (7)$$

and the action density N is defined by

$$N = \frac{E}{\omega'} \quad (8)$$

where ω' is the radial frequency of the semi-diurnal lunar M_2 tidal wave with

$$\omega' = \frac{2\pi}{T} \quad (9)$$

The gradient of the action density N perpendicular to the sand wave crest is derived as

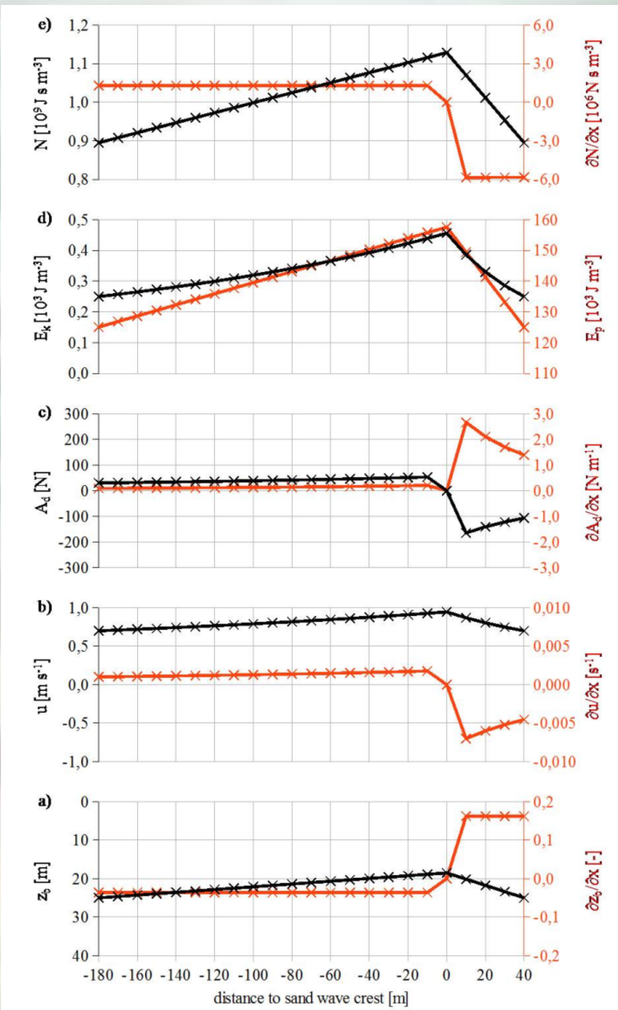
$$\frac{\partial N}{\partial x} = \frac{\rho}{\omega'}\left(-\frac{1}{2}g\frac{\partial z_b}{\partial x} + \bar{u}\frac{\partial \bar{u}}{\partial x}\right) \quad (10)$$

Assuming $\bar{u} \cdot z_b = const = c,$ the following expression is derived

$$\frac{\partial N}{\partial x} = -\frac{\rho}{\omega'}\frac{\partial z_b}{\partial x}\left(\frac{g}{2} + \frac{\bar{u}^2}{z_b}\right) \quad (11)$$

4. Simulations

Simulations of oceanographic parameters for flood (left) and ebb (right) tidal current phases



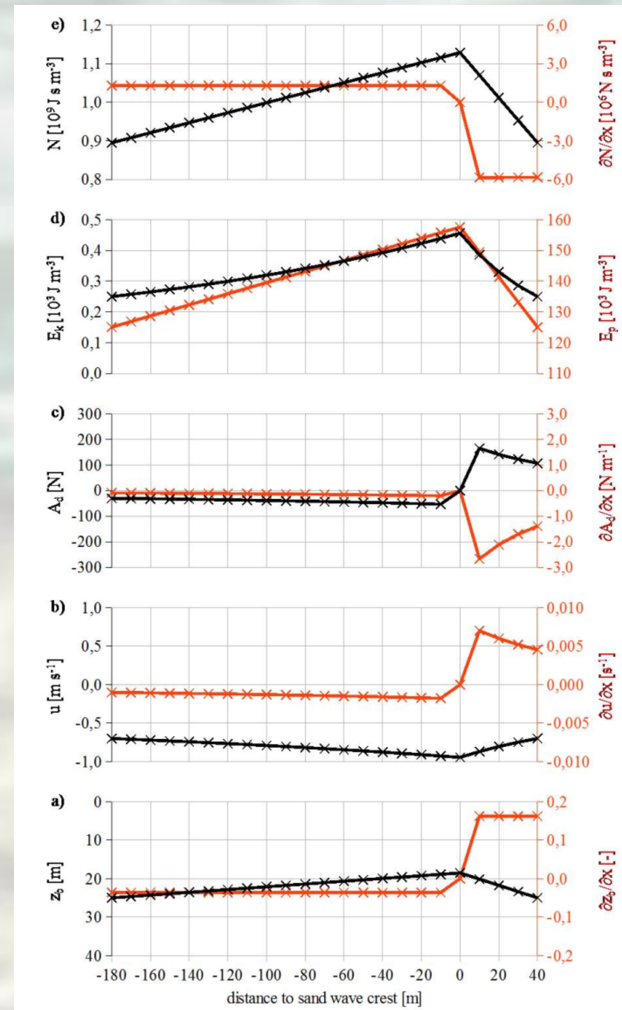
e) action density N (black) and gradient of action density $\partial N/\partial x$ (red)

d) kinetic energy density E_k (black) and potential energy density E_p (red)

c) dynamic buoyancy density A_d (black) and $\partial A_d/\partial x$ (red)

b) tidal current velocity u (black) and $\partial u/\partial x$ (red)

a) water depth z_b (black) and $\partial z_b/\partial x$ (red)



5. Conclusions

1.) Magnitudes of echo intensity E_3 and calculated *SSC* modulation *log* $\left((\delta c/c_0)_3\right)$ depend on wind and current velocities.

2.) Bursts of *w* and E_3 may be triggered at disturbances like megaripples superimposed on sand waves by current wave interaction at high current and wind speeds observed of opposite directions.

3.) ADCP data of *u*, *w*, and E_3 show a definite phase relationship with the crest and upper gentle slope regions of sand waves during ebb tidal current phase.

4.) Enhanced *log* $\left((\delta c/c_0)_3\right)$ shows a phase relationship with trough regions of sand waves during ebb tidal current phase.

5.) During well developing flood and ebb tidal currents the intensities of *u*, *w*, and *log* $\left((\delta c/c_0)_3\right)$ are weakly time dependent.

6.) The ADCP in situ measurements are to be consistent with simulations based on the applied theory.

7.) The action density N and its gradient $\frac{\partial N}{\partial x}$ due to semi-diurnal tide motion are the most important hydrodynamic parameters which characterize comprehensively the dynamics of suspended sediment concentration (SSC) above submerged asymmetric sand waves.