Impact of wind waves on the air-sea momentum fluxes for different wind and sea state conditions and oceanic response

Joanna Staneva, Heinz Günther, A. Behrens, O. Krüger, Corinna Schrum, (HZG, Germany)

Victor Alari (MSI, Estonia),

Oyvind Breivik (Norwegian Met. Institute, Norway)

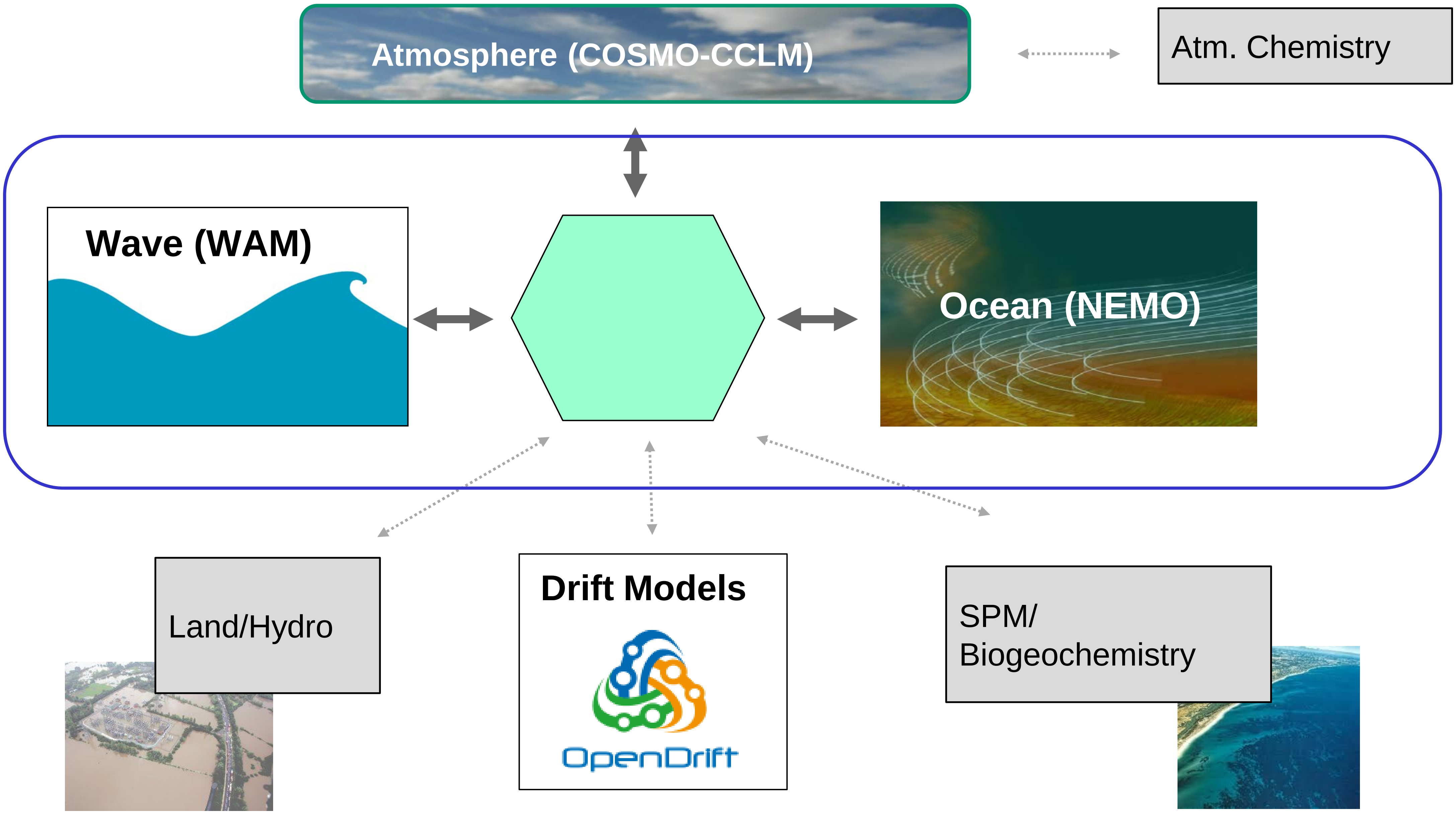
Jean-Raymond Bidlot, Kristian Mogensen (ECMWF, UK)

1ST INTERNATIONAL WORKSHOP ON WAVES, STORM SURGES AND COASTAL HAZARDS

Liverpool, UK, 10-15 September 2017

GCOAST
Geestacht COAstal model SysTem

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research



Outline

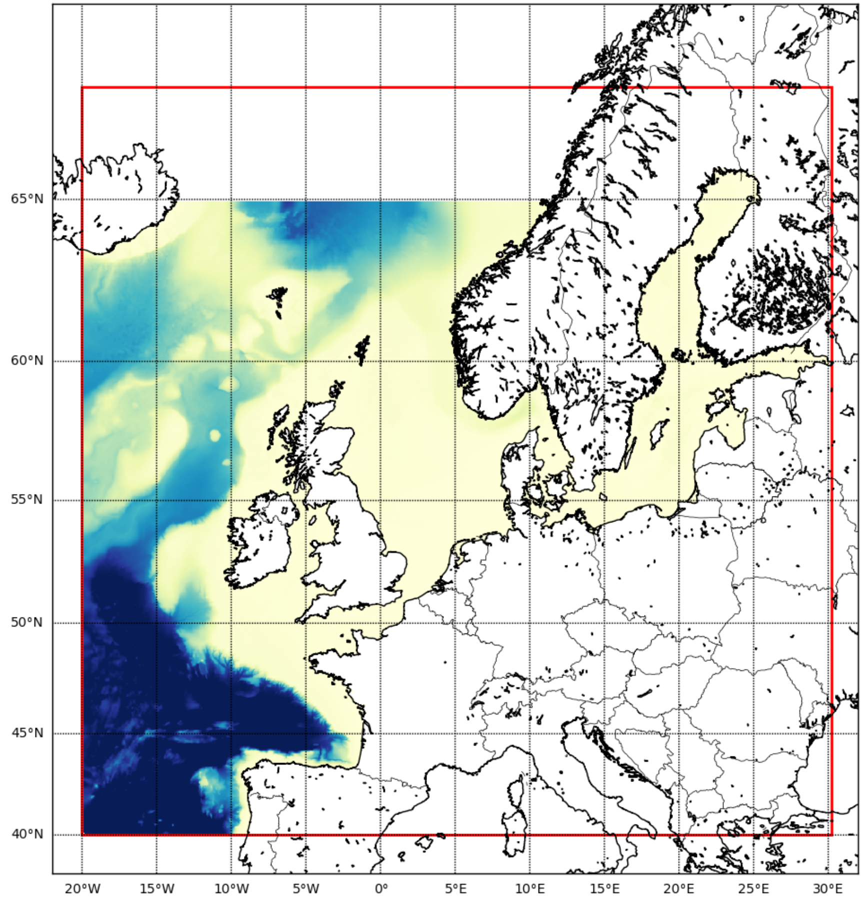
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

- Models and validation
- Physical processes forming wave-circulation interaction
- Wave-induced momentum fluxes during extreme events
- Effects of wave-dependent forcing on circulation and surge predictions
- Sensitivity runs to non-linear term (Snl) in the ocean-side stress
- Applications: transport model sensitivity to wave parameters
- Discussion

Model setup

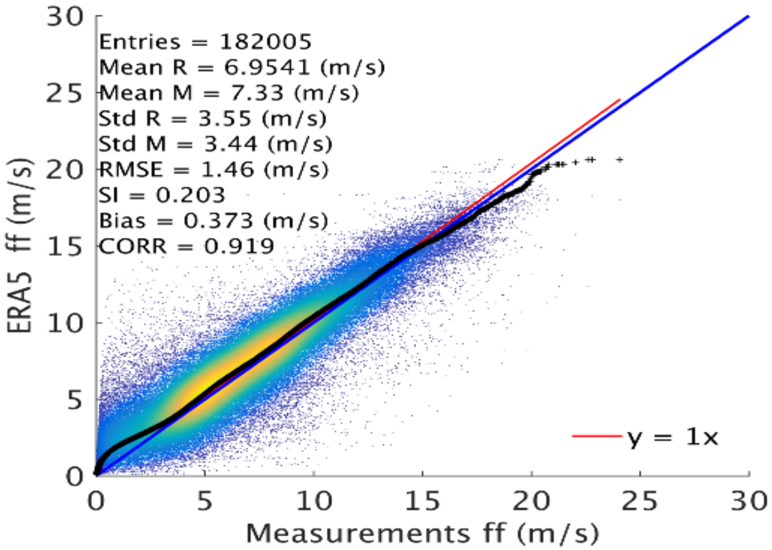
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

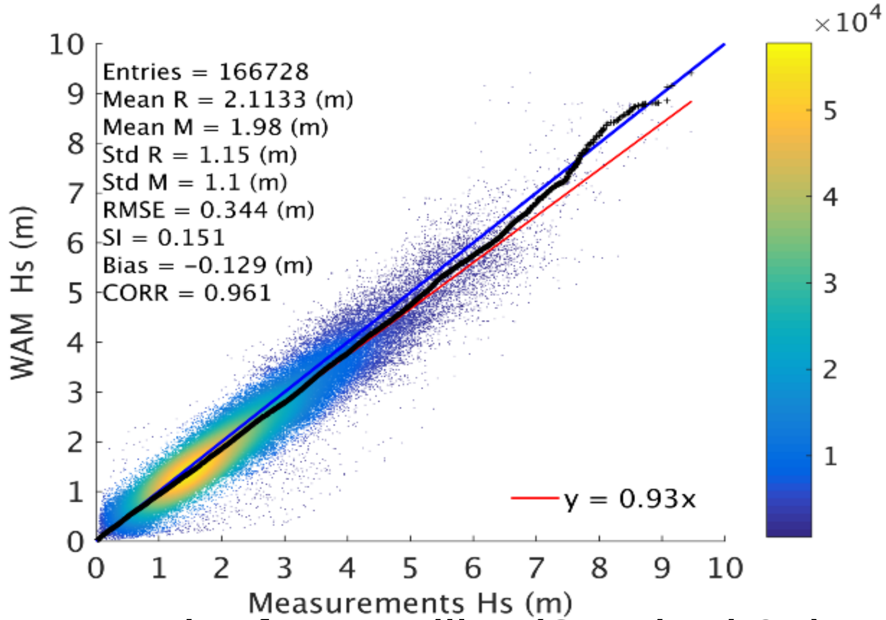
	NEMO 3.6	WAM 4.6.2
Horizontal grid	3.5 km	Same
Vertical grid	56 s layers, emphasis on surface	N/A
Initial field	CMEMS NWS Data	Atlantiic WAM wave data
Boundary condition	OSU tides, CMEMS NWS Data for T,S, u,v, SLH	Atlantic WAM wave data
Forcing	ERA-Interim, ERA-5, DWD COSMO-EU	Same
Vertical diffusion scheme	GLS (*k-eps*)	N/A
Ice	LIM-3	Yes



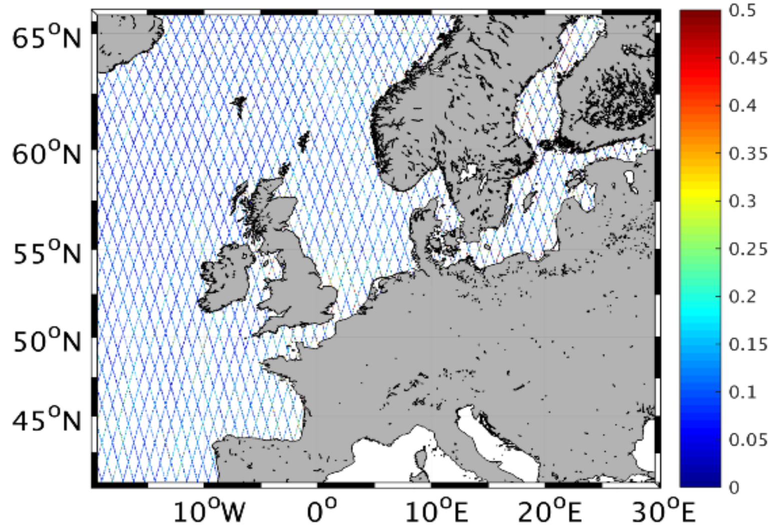
Wave Model validations

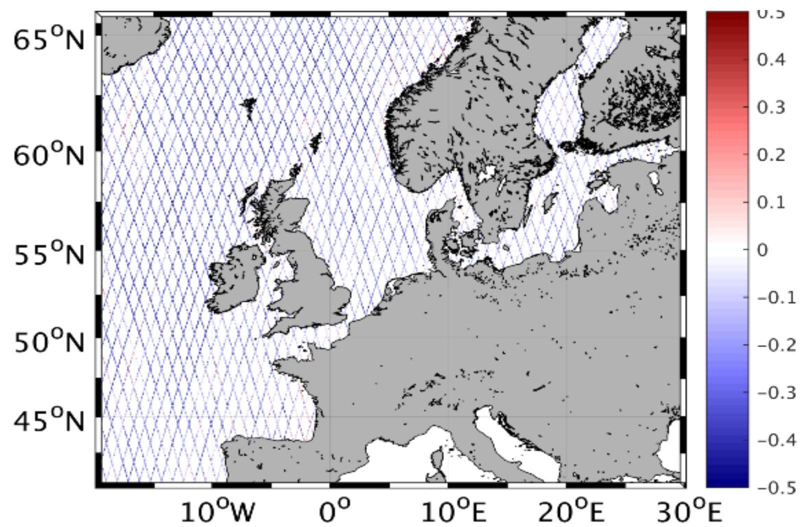
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research





QQ-Scatter plot for satellite (Sentinel 3a)-and wind (top) and significant wave height (bottom)





Scatter Index and Bias of significant wave height for Sentinel-3 altimeter data and WAM

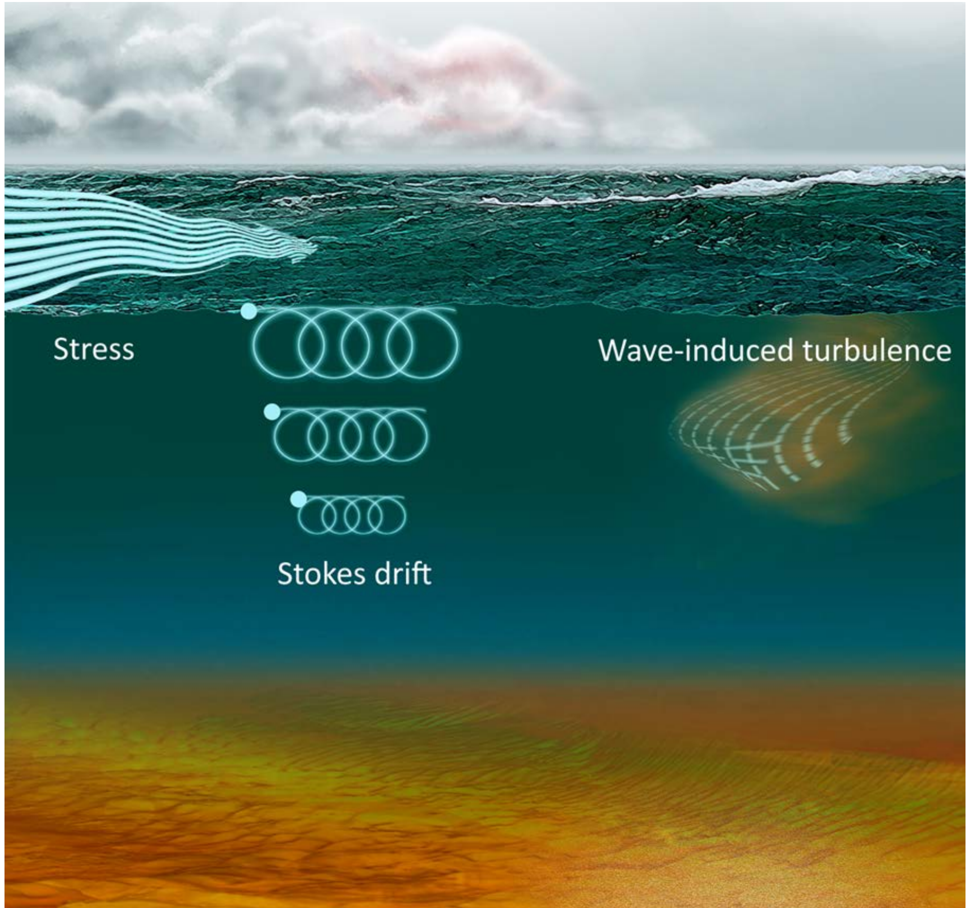
Wave-induced forcing:

The ocean model takes into account the following wave effects:

(1) The Stokes-Coriolis forcing (Hasselmann, 1970; Breyvik, 2015, 2016)

(2) Sea state dependent momentum flux (Janssen, 1989; Janssen, 2012);

(3) Sea state dependent energy flux (Craig and Banner, 1994)



	NEMO	Stokes-Coriolis Force	Ocean Side Momentum Stress	Wave Breaking
CTRL	√			
STCOR	√	√		
TAUOC	√		√	
TKE	√			√
TAUST	√	√	√	
ALLWAVE	√	√	√	√

Physical processes forming wave-circulation interaction: **Stokes-Coriolis forcing**

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Wave forcing variables (WAM 4.6.2)

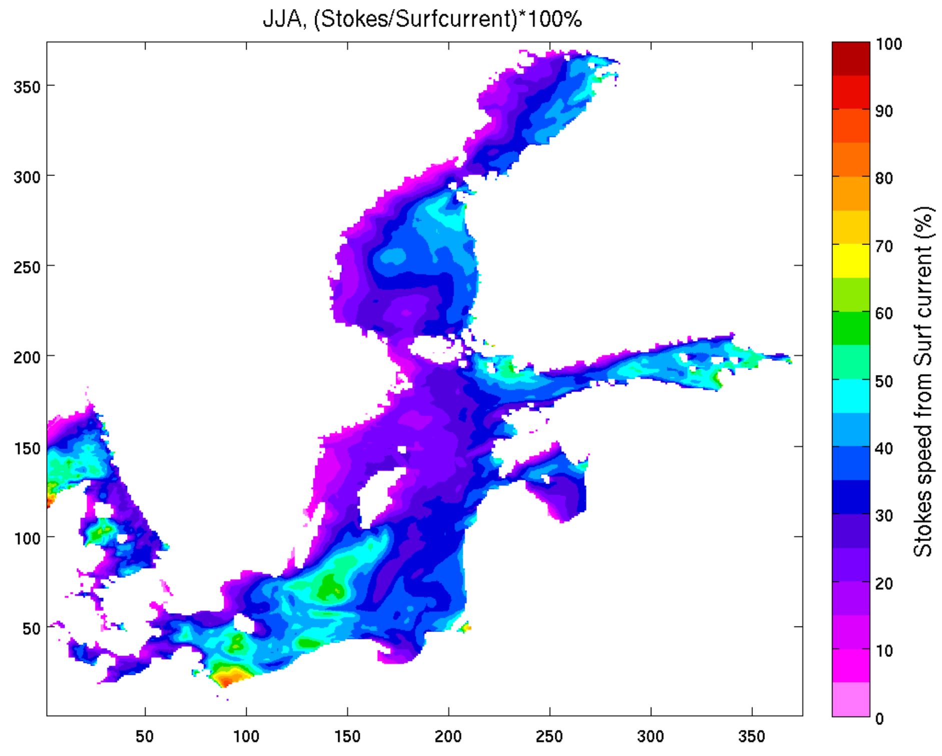
From a directional wave spectrum F(f,θ), where f is the frequency and θ the wave direction, the Stokes drift vector $\mathbf{u_s}$ = (u, v**)** is defined as:

$$\mathbf{u}_s = \frac{4\pi}{g} \int_0^{2\pi} \int_0^{\infty} f\mathbf{k}F(f,\theta)\,df\,d\theta$$

Implementation in momentum equations in NEMO 3.6

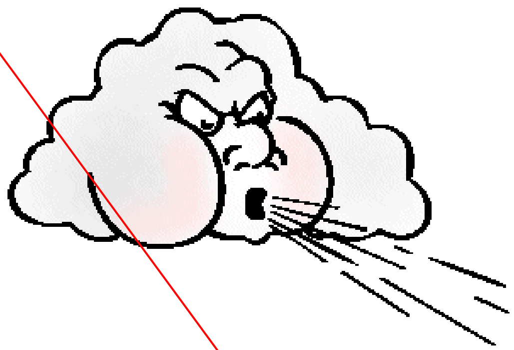
$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + (\mathbf{u} + \mathbf{v}_s) \times f\hat{\mathbf{z}} + \frac{1}{\rho}\frac{\partial \tau}{\partial z}.$$

The Stokes drift profile (Breyvik et al, 2016, JPO)



Physical processes forming wave-circulation interaction: **sea state dependent momentum flux**

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

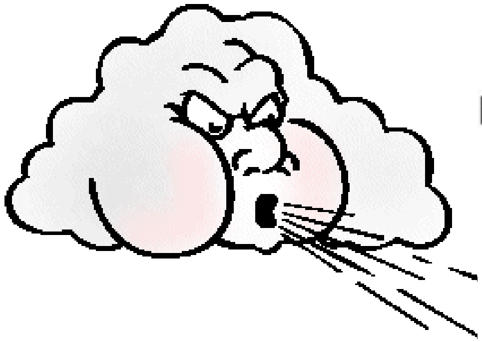


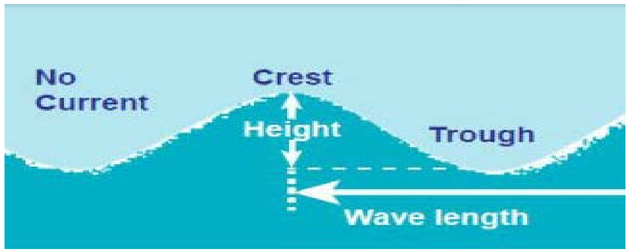
$$\vec{\tau} = c_{aw}^{d}\;\rho_a \left|\vec{U}_{10}\right| \vec{U}_{10}$$

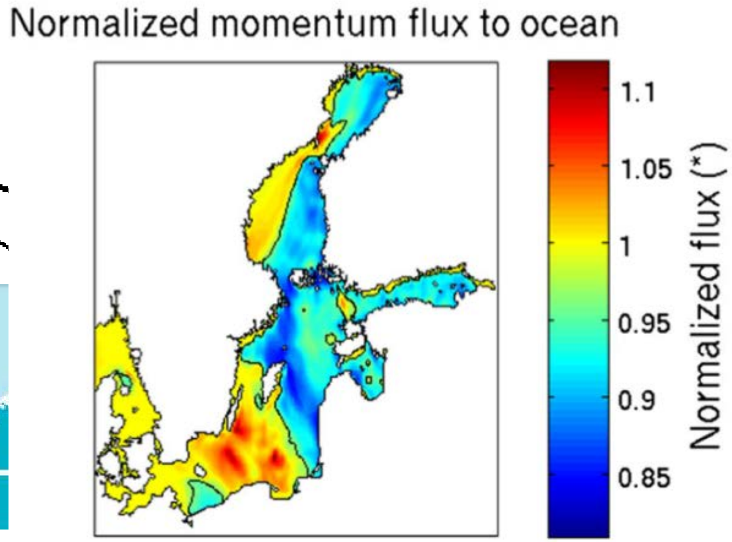
$$c_{aw}^{d} \times 10^{3} = \begin{cases} 1.2 & : 0 < \left|\vec{U}_{10}\right| \le 11\, m/s \\ 0.49 + 0.065\left|\vec{U}_{10}\right| & : 11 < \left|\vec{U}_{10}\right| \le 22\, m/s \end{cases}$$

$$\frac{\partial U}{\partial t} - fV = -gH\frac{\partial \xi}{\partial x} + \tau_x - \tau_{xb}$$

$$\frac{\partial V}{\partial t} + fU = -gH\frac{\partial \xi}{\partial y} + \tau_y - \tau_{yb}$$







$$\frac{\partial U}{\partial t} - fV = -gH\frac{\partial \xi}{\partial x} + \tau_{ocx} - \tau_{xb}$$

$$\frac{\partial V}{\partial t} + fU = -gH\frac{\partial \xi}{\partial y} + \tau_{ocy} - \tau_{yb}$$

Impact of waves to sea surface stress:

Helmholtz-Zentrum
Geesthacht
Centre for Materials and Coastal Research

The common practice in ocean modelling is to compute the wind surface stress based on bulk formulas:

$$\tau_s = \rho_a C_d U_{10}^2,$$

In NEMO, the drag coefficient for neutral stability conditions is by Large and Yeager (2008)

$$C_d = 10^{-3}\left(\frac{2.7}{U_{10}} + 0.142 + \frac{U_{10}}{13.09}\right)$$

TWO wave dependent mechanisms are considered, in order to account for the impact of waves to sea surface stress.

Momentum flux going into the sea from the waves model depends on:

(1**)** **wave-modified drag coefficient**, which changes the air-side stress and
(2) **ocean side stress**, which depends on the balance between wave growth and dissipation

Wave modified drag coefficient

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

The atmospheric stress and air-side friction velocity are related as:

$$\tau_a = \rho_{air} u_*^{\,2}$$

The roughness of the sea surface:

$$z_0 = \alpha_{CH} \frac{u_*^2}{g}$$

α_{CH} is not a constant, but varies with the sea state (Janssen, 1986):

$$\alpha_{CH} = \frac{\hat{\alpha}_{CH}}{\sqrt{1 - \tau_{in} / \tau_a}},$$

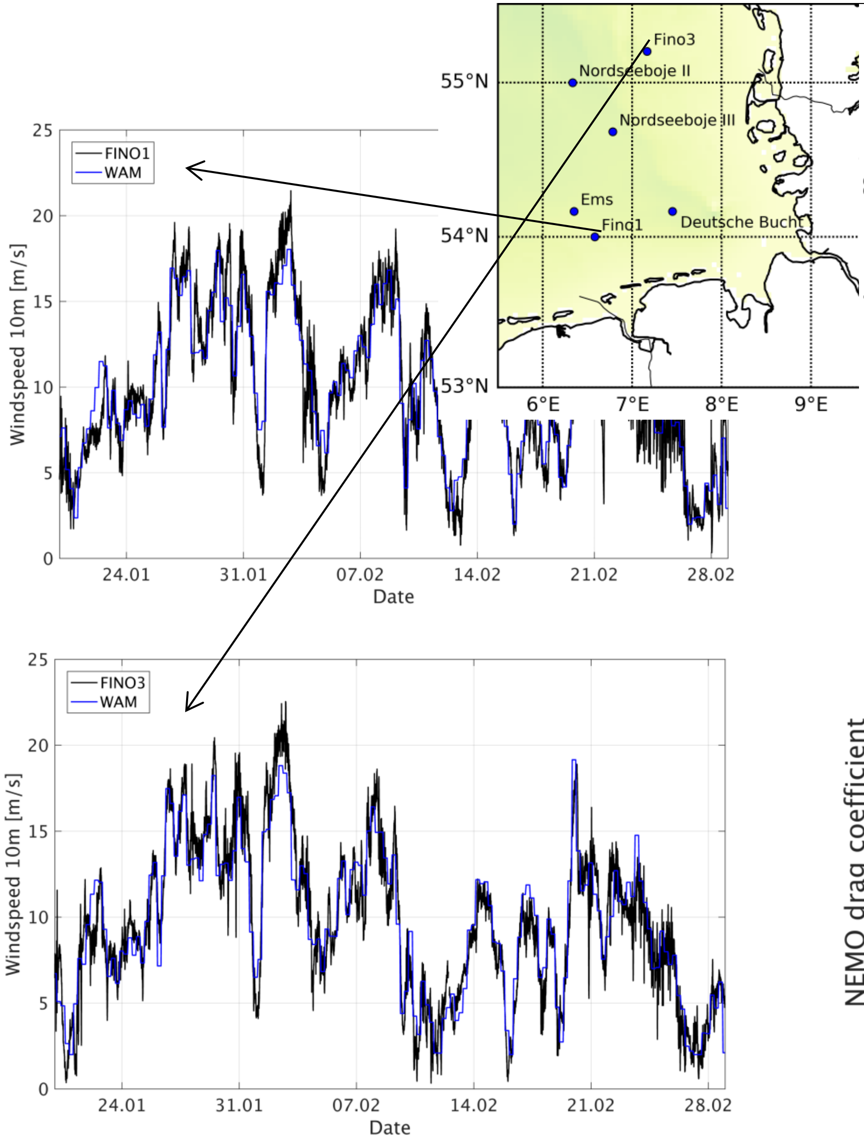
The wave modified drag coefficient: (computed from WAM),

$$C_D = \frac{\kappa^2}{\log^2(10 / z_0)}$$

where *k* is the von Karman constant

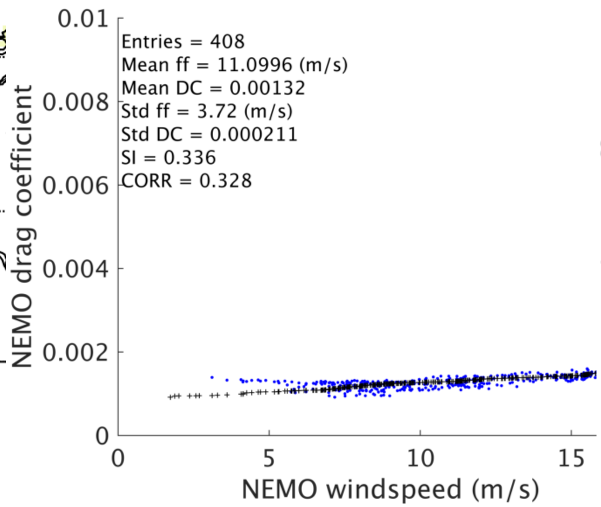
Variation of drag coefficient CD with forcing wind speed FINO1 and FINO3

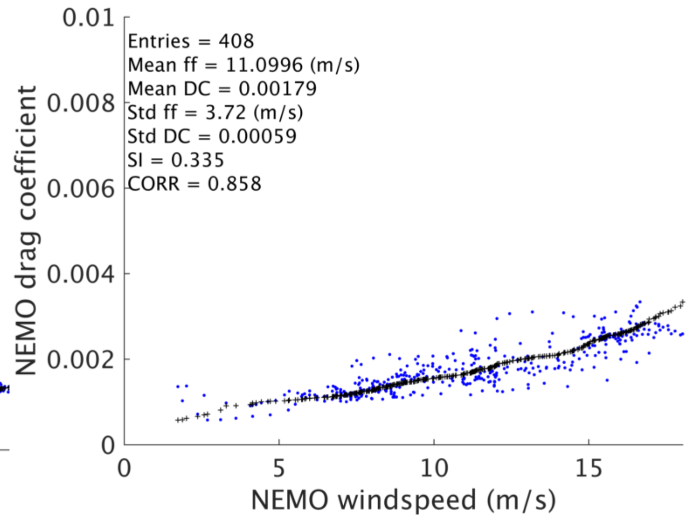
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

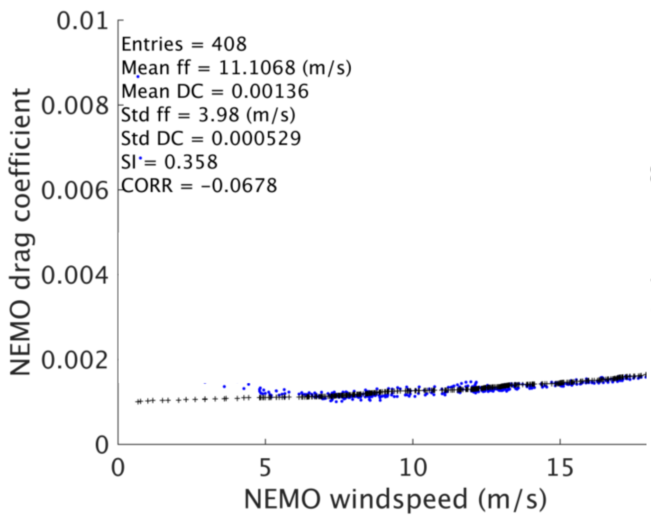


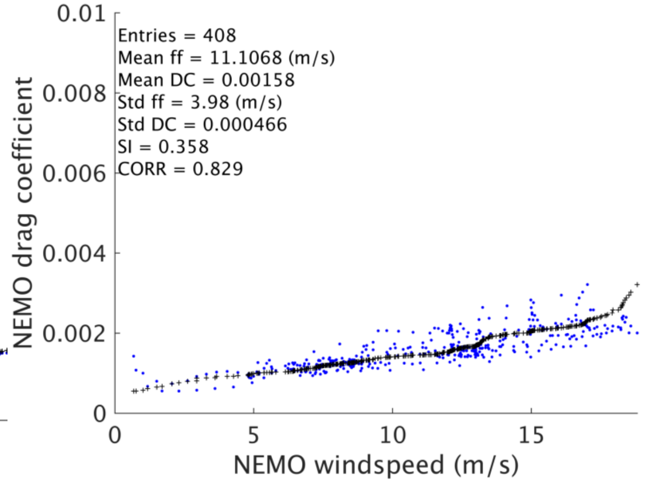
CD_NEMO

CD_WAM









Physical processes forming wave-circulation interaction: ocean side stress

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

The wave-induced stress is related to the wind input to the wave:

$$\tau_{in} = \rho_w g \int_0^{2\pi} \int_0^{\infty} \frac{k}{\omega} S_{in} \, d\omega d\theta$$

The dissipation stress is given by:

$$\overrightarrow{\tau_{diss}} = \rho_w g \int_0^{2\pi} \int_0^{\infty} d\omega d\theta \frac{\vec{k}}{\omega} S_{diss}(\omega, \theta)$$

Waves release momentum to the ocean when they break and therefore the **ocean side stress becomes**:

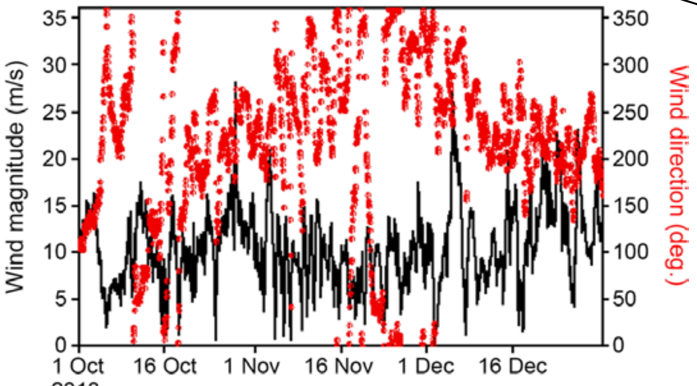
$$\overrightarrow{\tau_{oc}} = \overrightarrow{\tau_a} - \rho_w g \int_0^{2\pi} \int_0^{\omega_c} d\omega d\theta \frac{\vec{k}}{\omega} (S_{in} + S_{diss} + S_{NL})$$

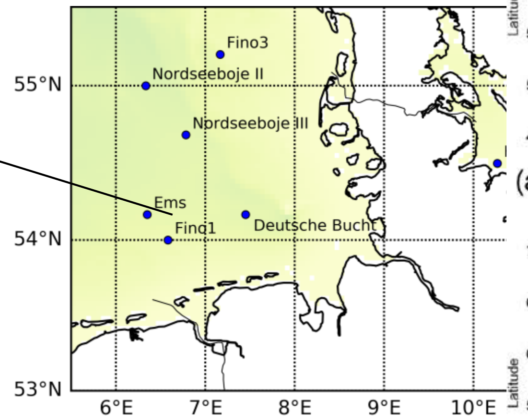
The stress from waves is archived as a normalized quantity (normalized momentum flux) and is applied as a factor to the air-side stress in NEMO as in Breivik et al (2015):

$$\tilde{\tau} = \frac{\tau_{oc}}{\tau_a}$$

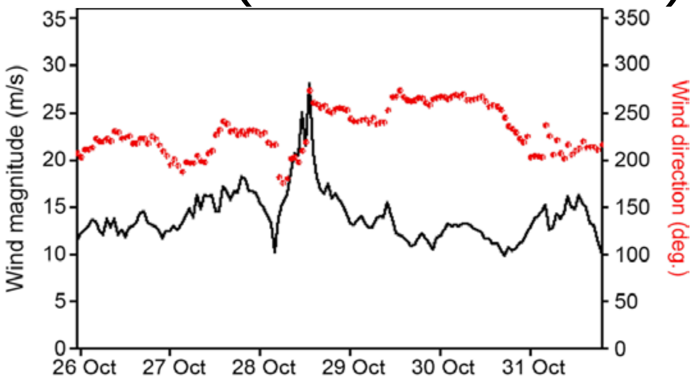
North Sea: Meteo conditions extreme storms Christian and Xavier

at Fino 1 Station

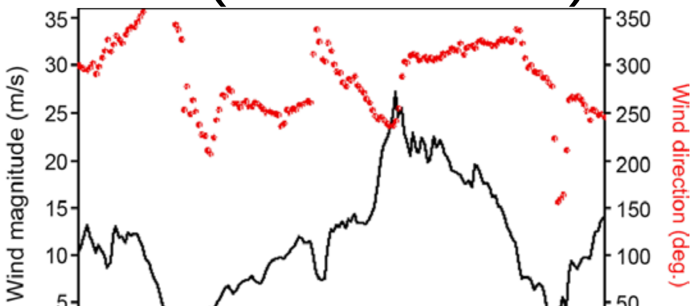




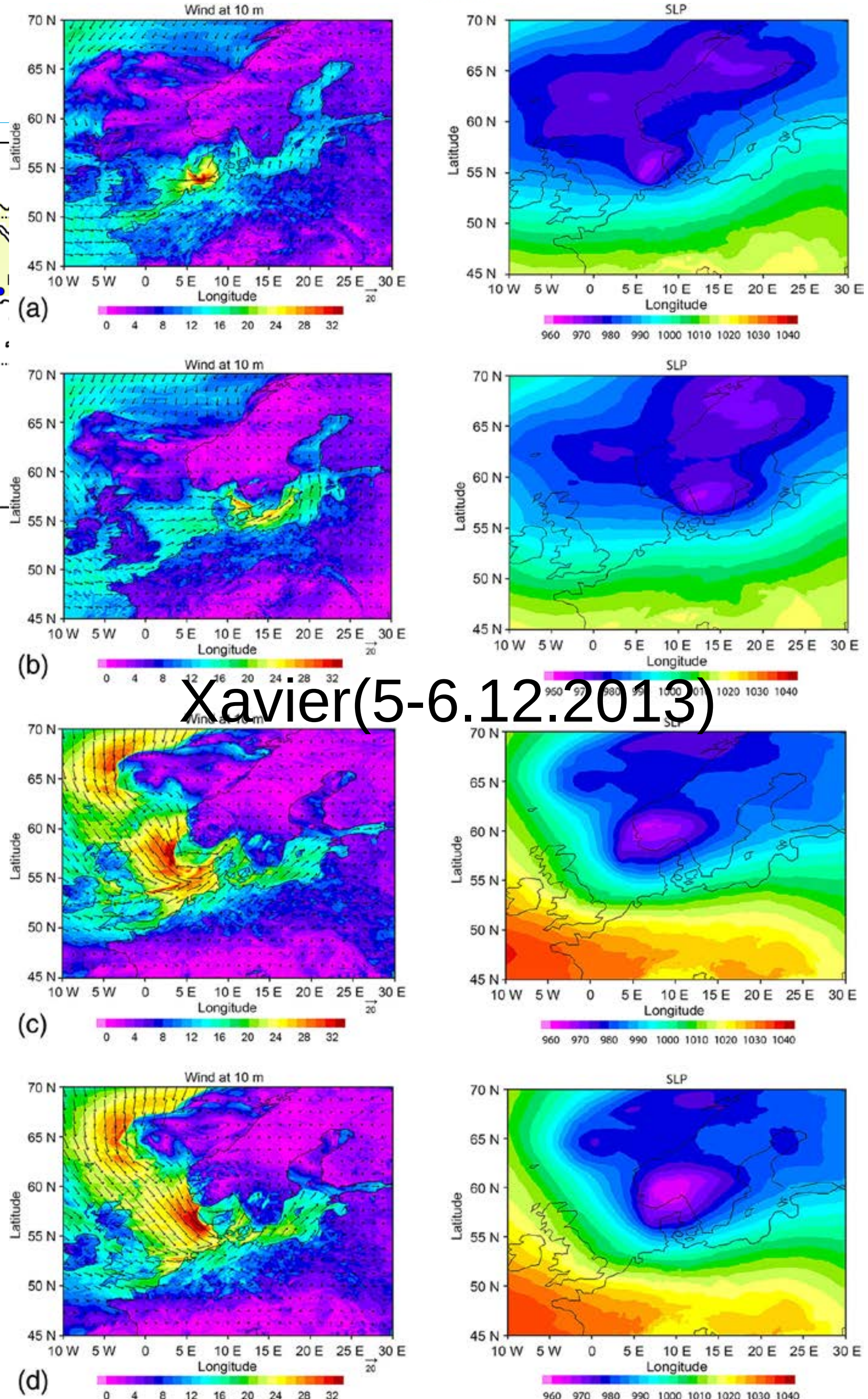
Christian (28-29.10.2013)



Xavier(5-6.12.2013)



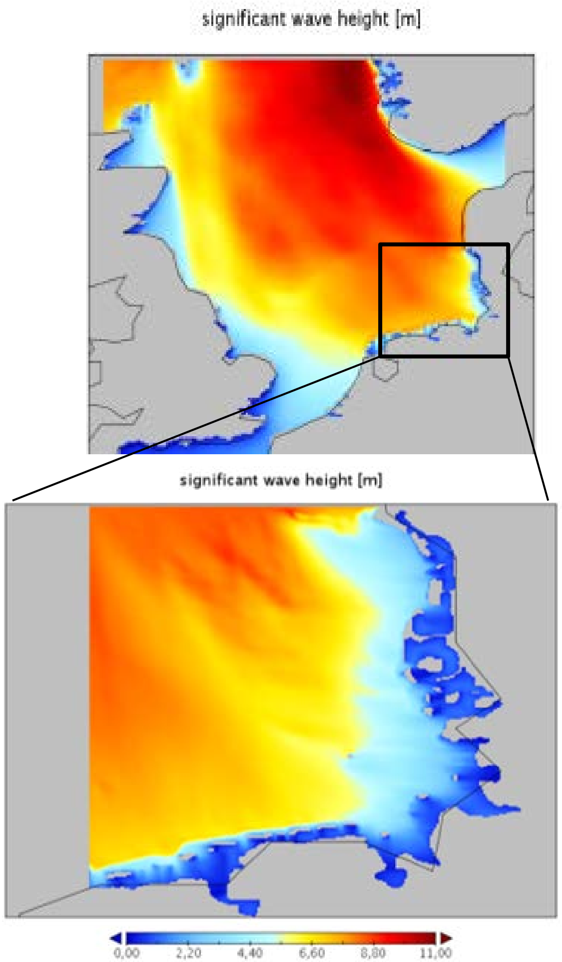
Christian (28-29.10.2013)



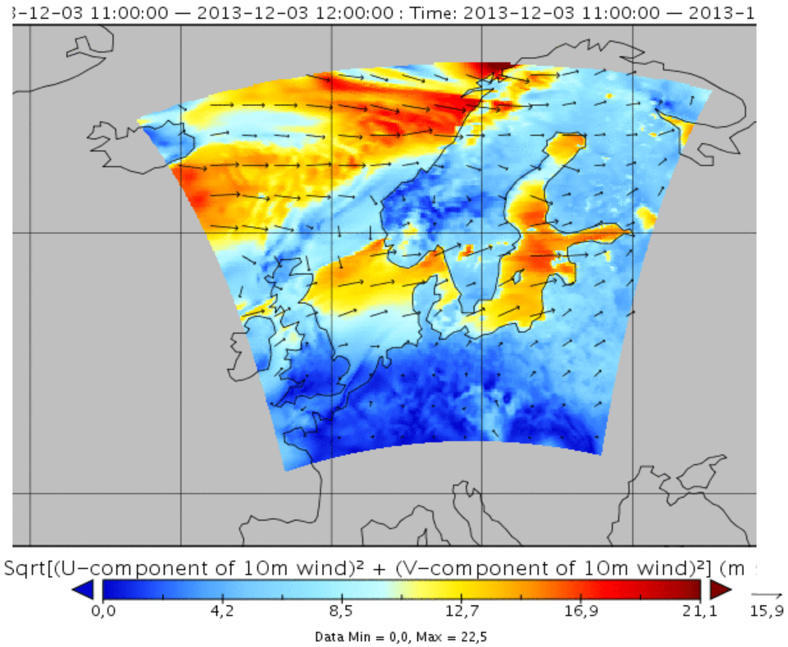
Xavier(5-6.12.2013)

Storm Xaver on 06.12.2013

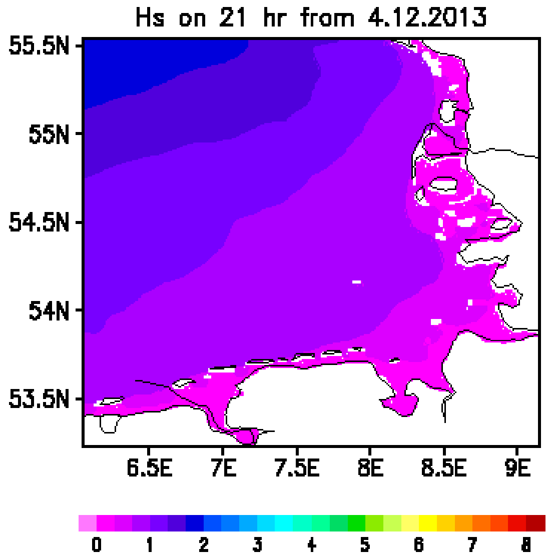
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

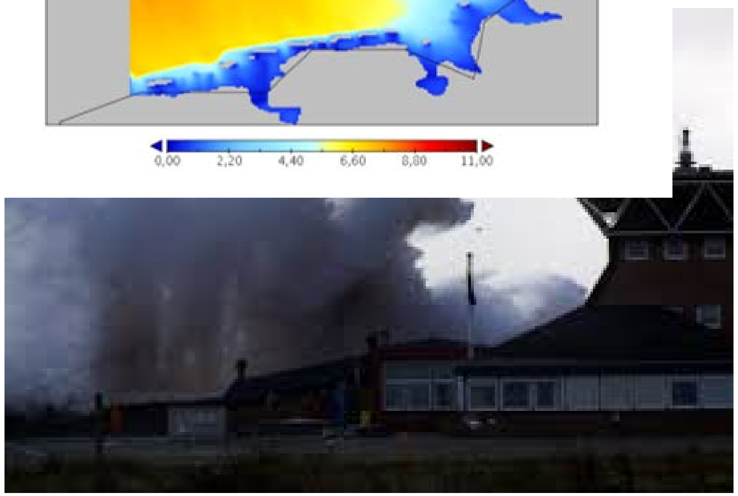


Wind speed at 10m (m/s)



Hs (m)

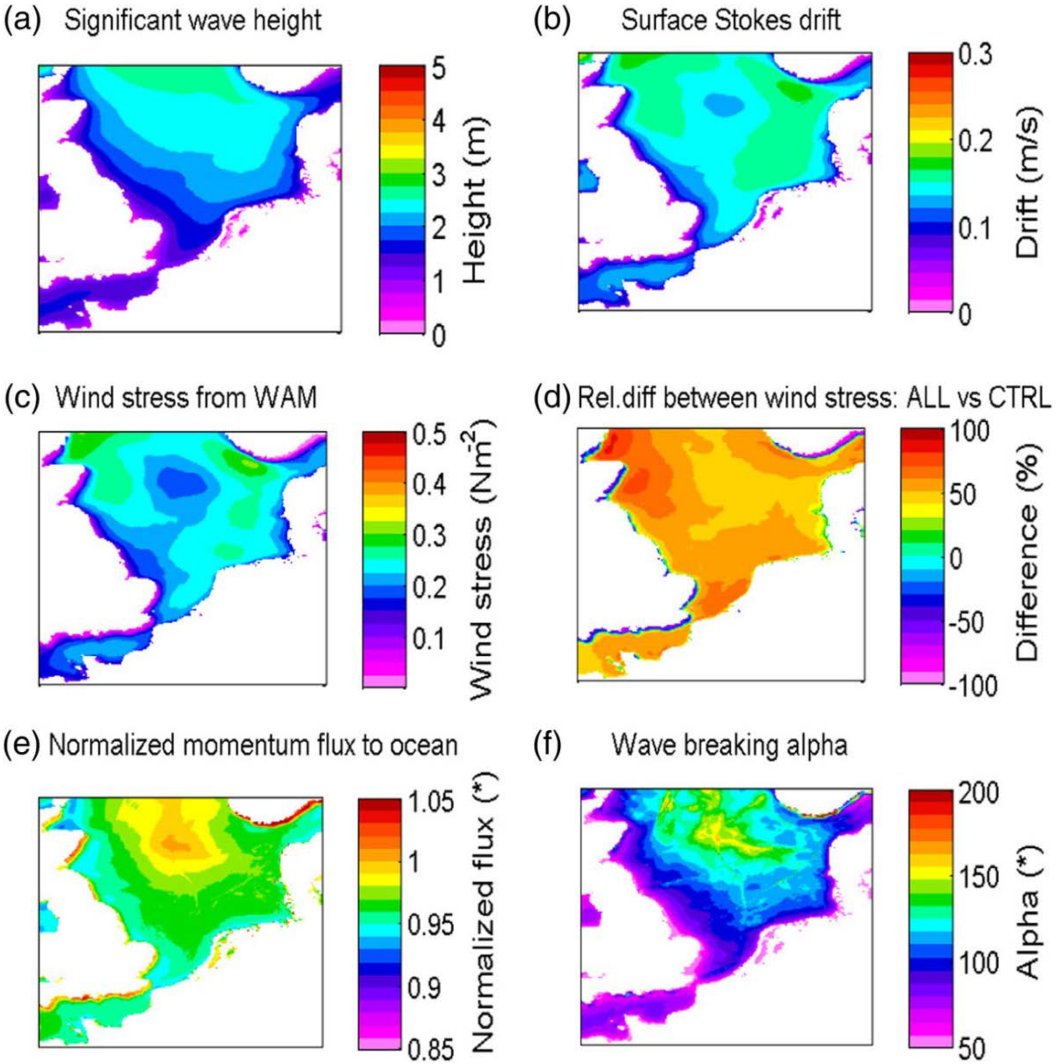




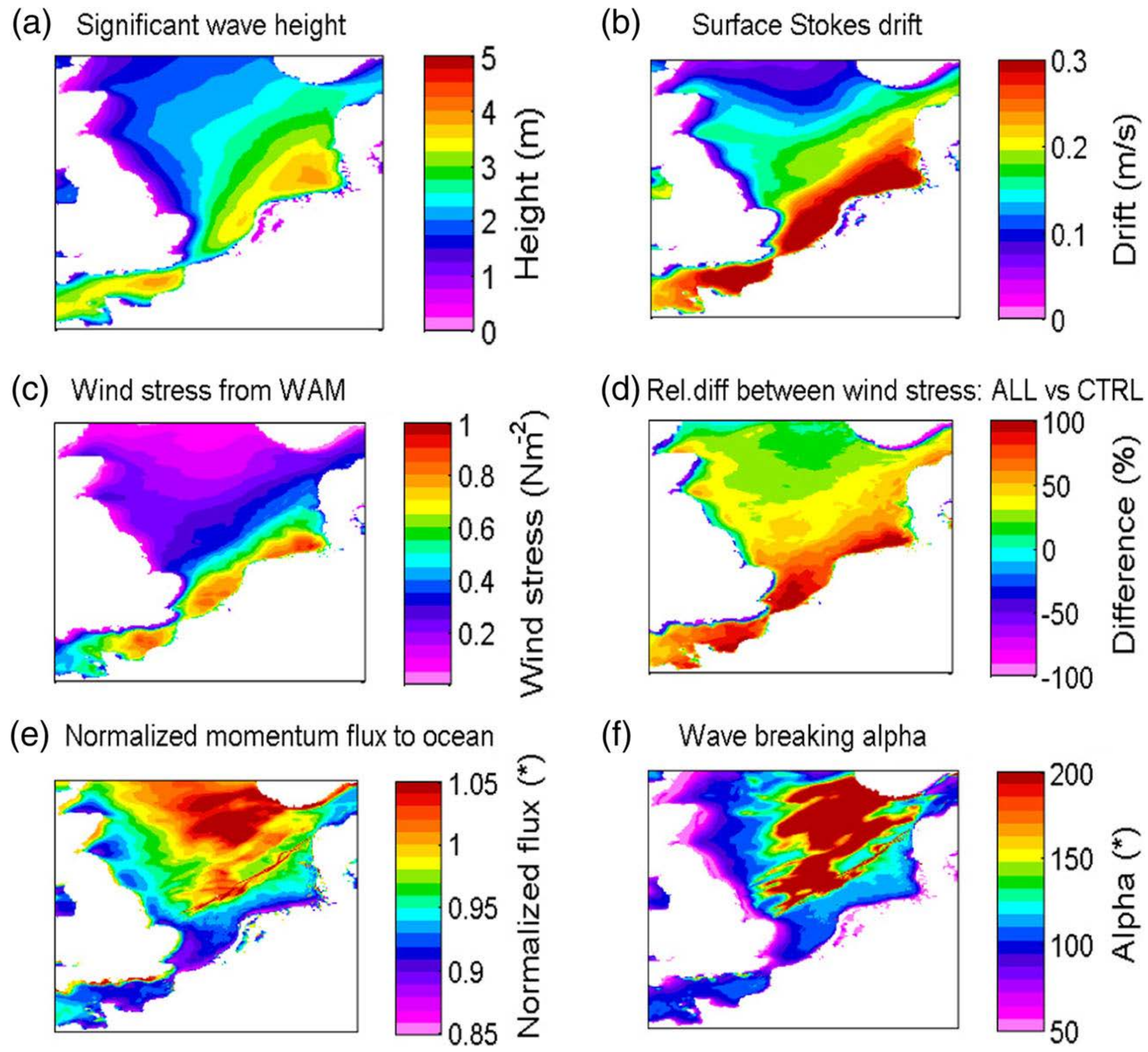
North Sea: wave-induced processes

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Oct-Dec, 2013

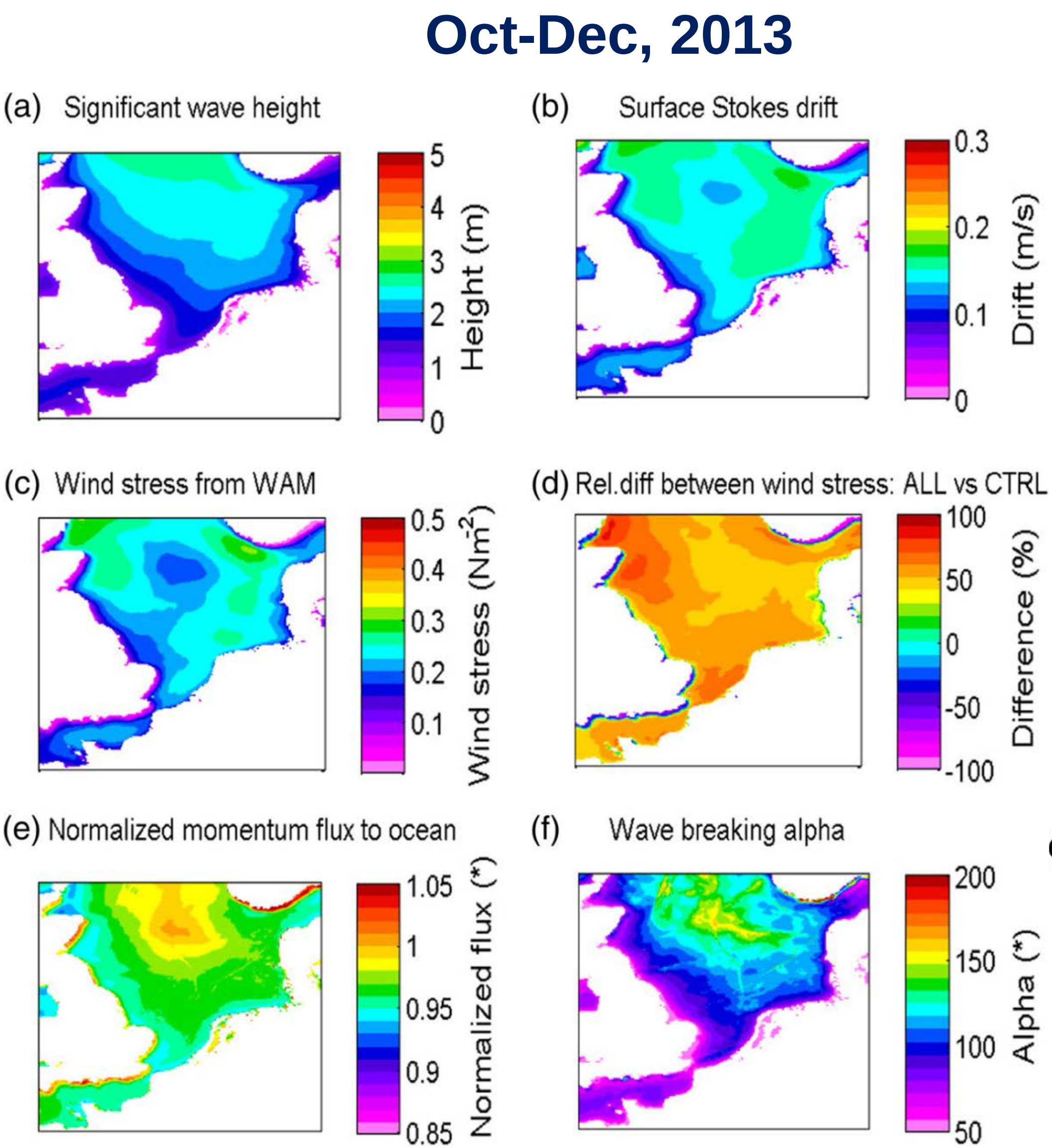


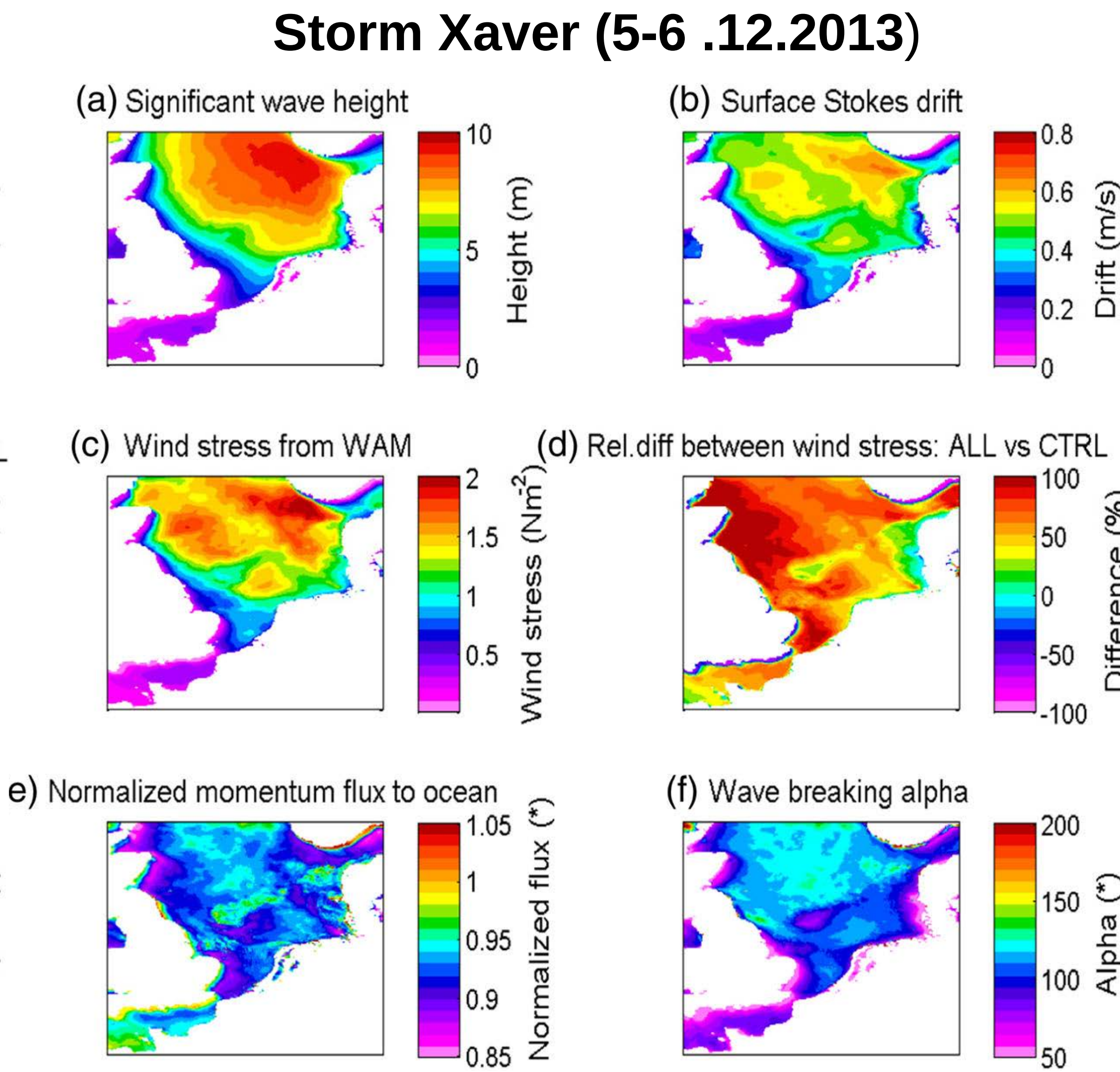
Storm Christian (29.10.2013)



North Sea: Wave-induced processes

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

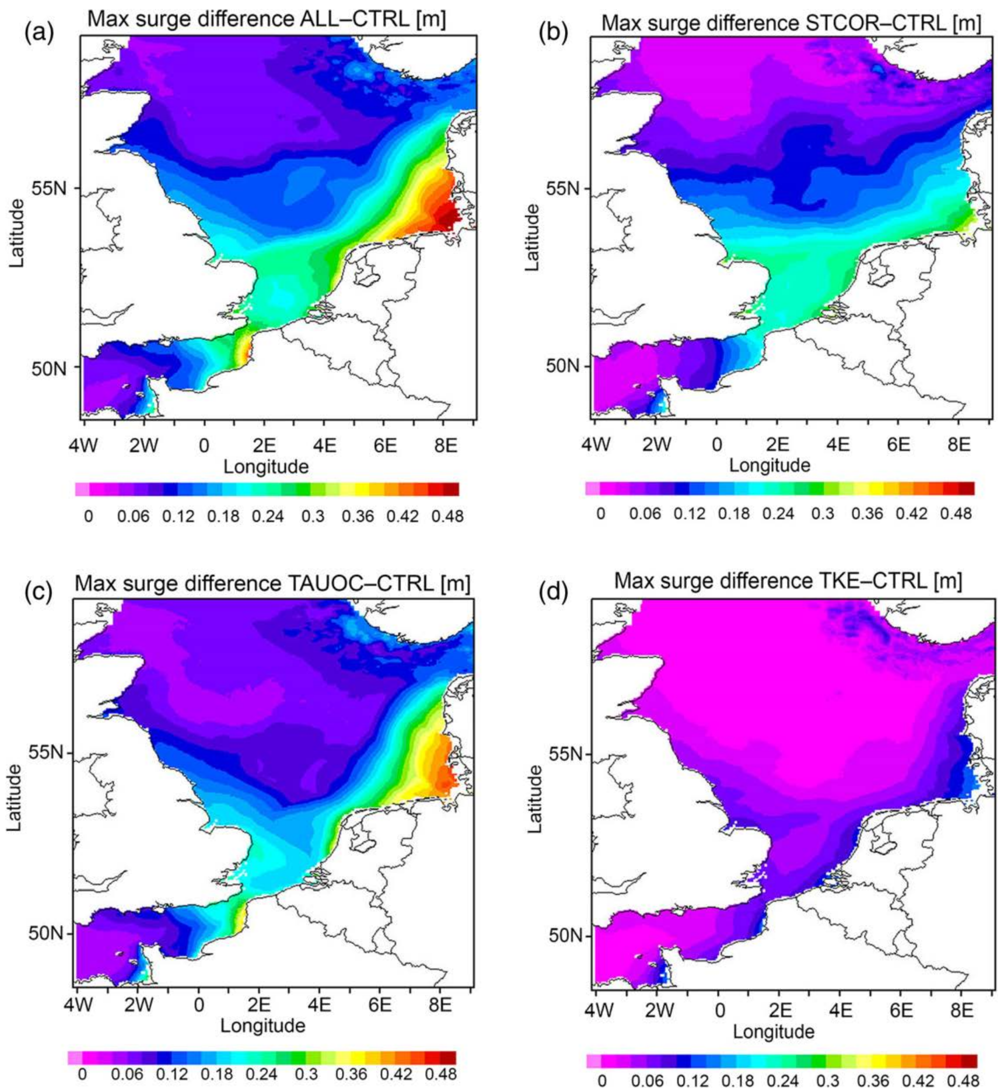




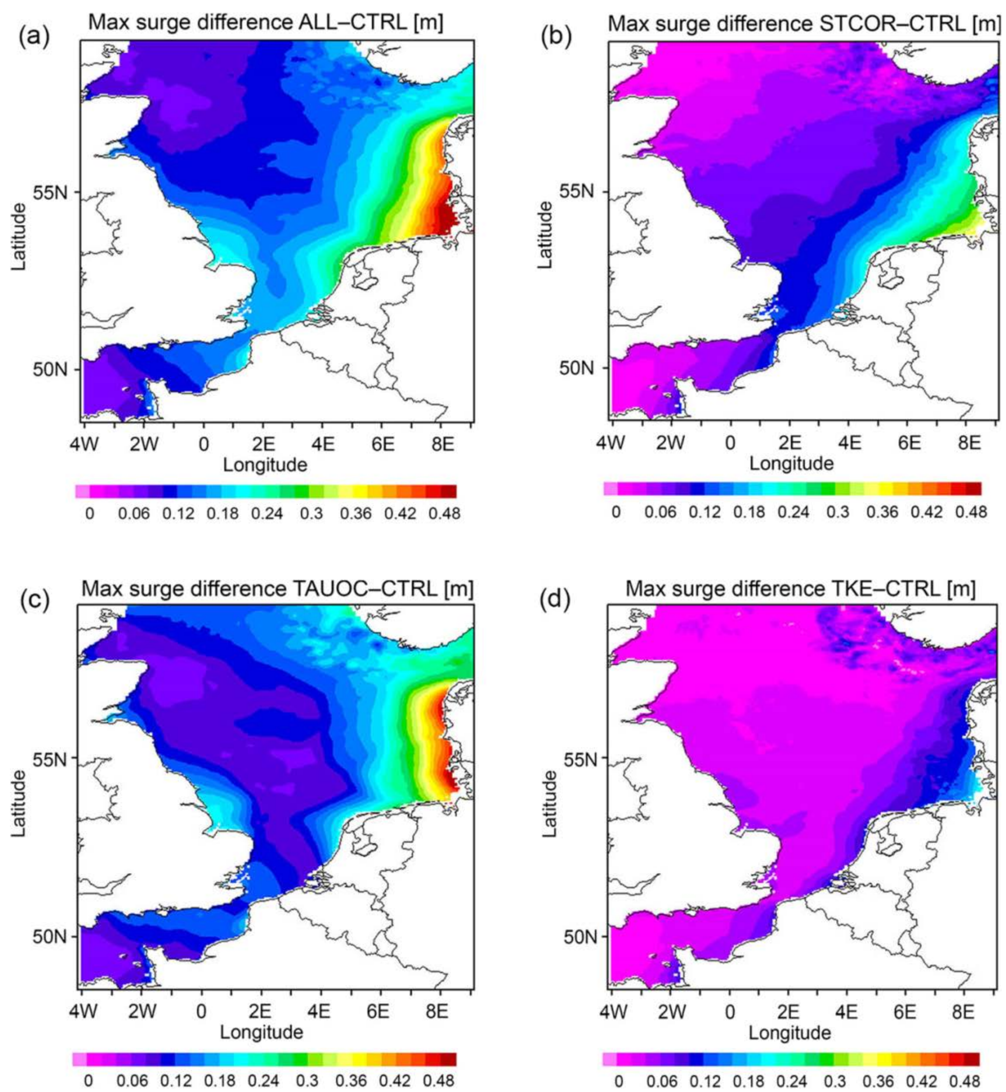
Maximum surge difference (m) during storms Cristian (left) and Xaver (right)

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Storm Christian (29.10.2013)



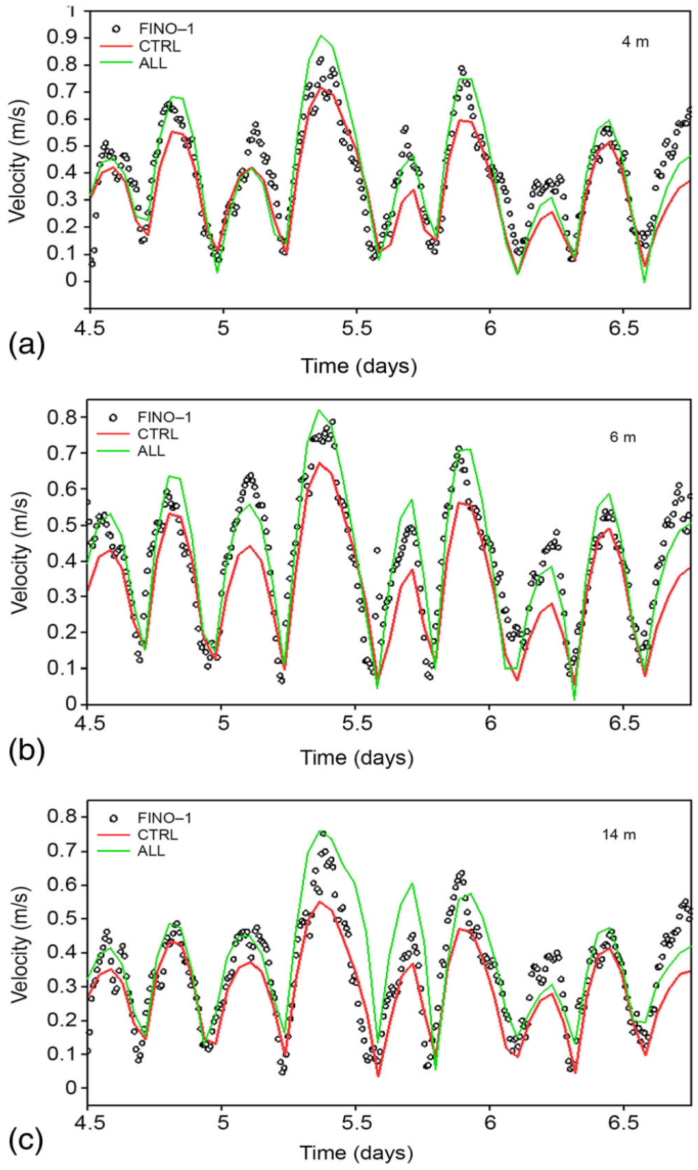
Storm Xaver (5-6.12.2013)

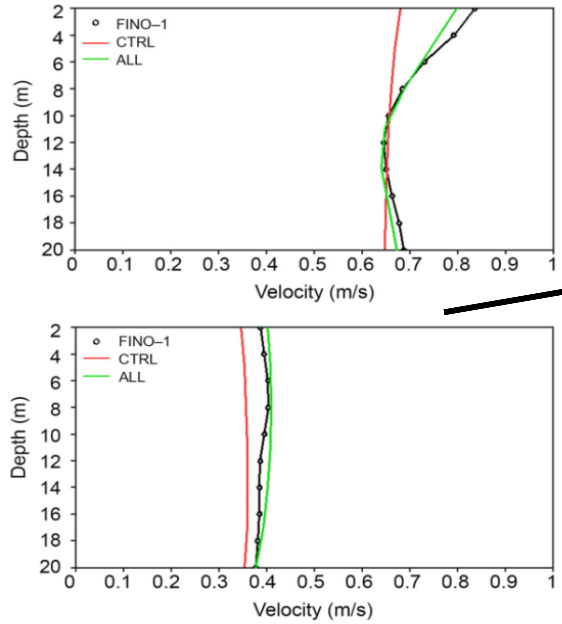


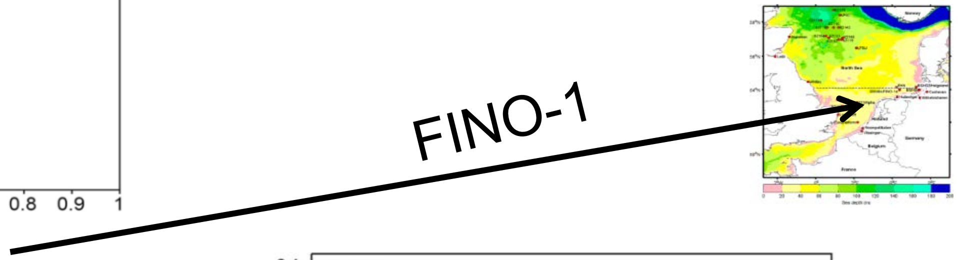
.

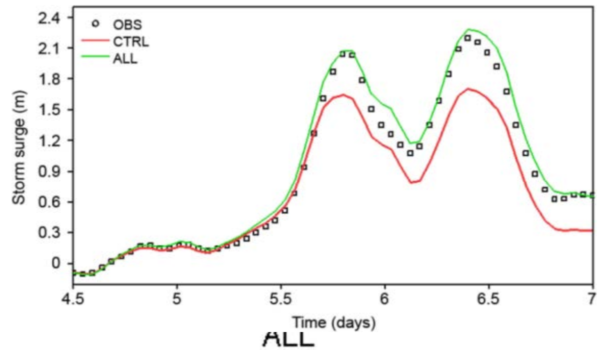
The impact of wind waves on hydrodynamics

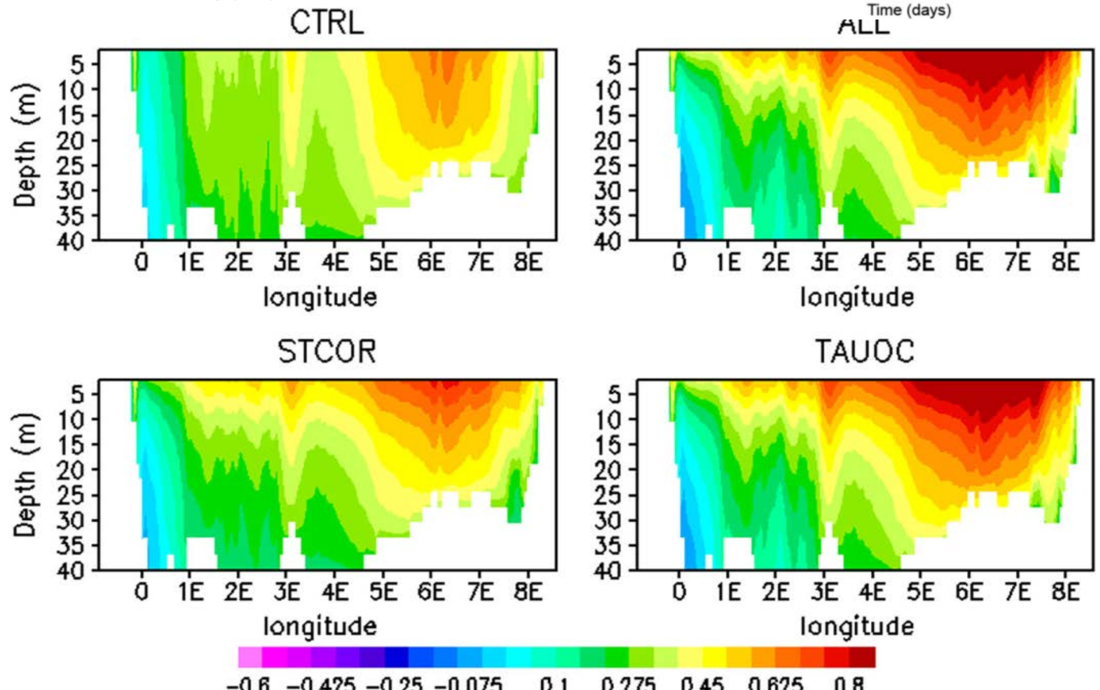
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research











•

The nonlinear source term contribution

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

The energy balance equation: $$\frac{\partial}{\partial t}F + \frac{\partial}{\partial \vec{x}} \cdot \left(\overrightarrow{v_g}F\right) = S_{in} + S_{nl} + S_{diss}$$

It implies that there is a balance in the high frequency tail between the input due to the wind but also due to nonlinear transfer from lower frequencies and dissipation.

The contribution from the nonlinear source term has been previously omitted, on the ground that it was thought to be small:

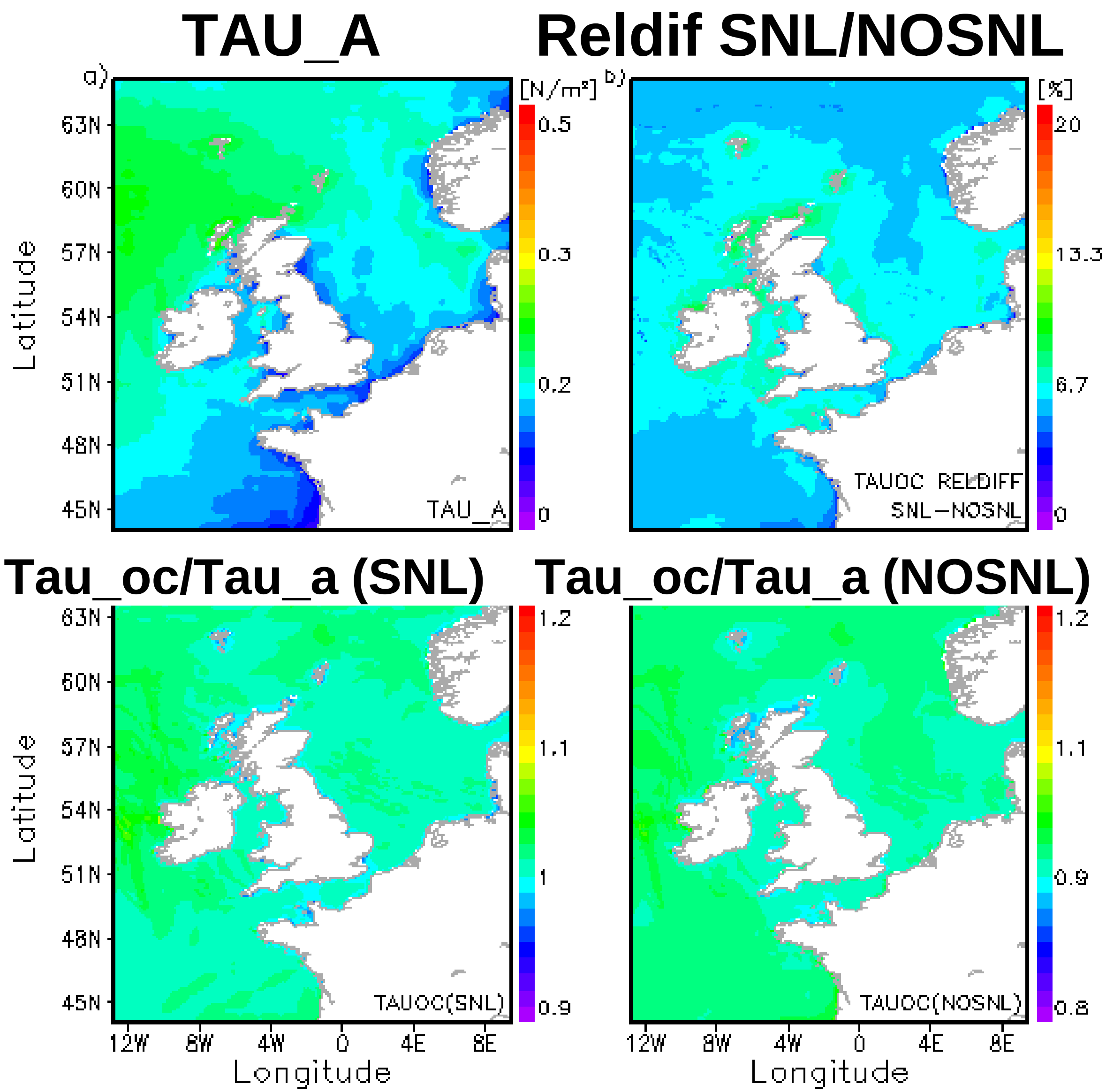
$$\overrightarrow{\tau_{oc}} = \overrightarrow{\tau_a} - \rho_w g \int_0^{2\pi} \int_0^{\omega_c} d\omega d\theta \frac{\vec{k}}{\omega} (S_{in} + S_{diss})$$

This cutoff frequency is not high enough - thus the contribution of the nonlinear source term needs to be considered.

The ocean side stress becomes:

$$\overrightarrow{\tau_{oc}} = \overrightarrow{\tau_a} - \rho_w g \int_0^{2\pi} \int_0^{\omega_c} d\omega d\theta \frac{\vec{k}}{\omega} (S_{in} + S_{diss} + S_{NL})$$

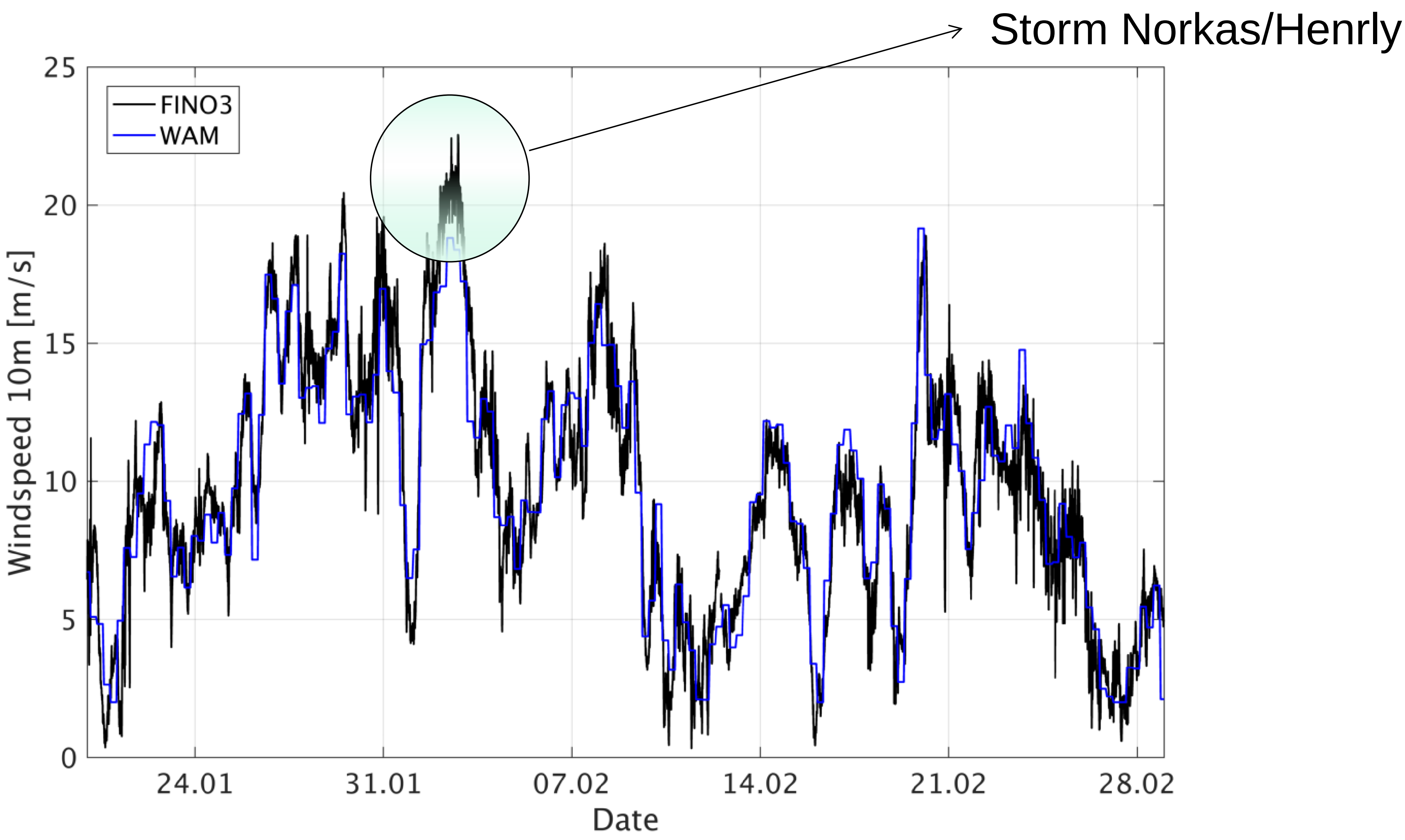
SNL/NSNL runs



Jan-Dec, 2016

Wind Speed 10 m: FINO-3 Station (20.01-28.02.2015)

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research



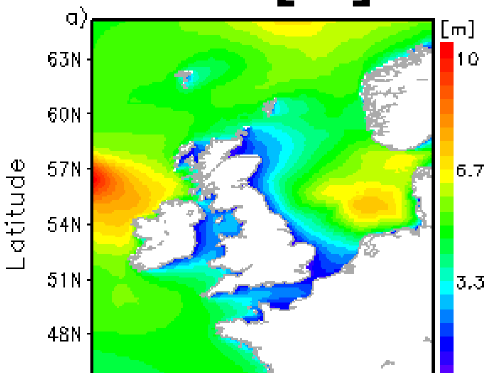
03 February, 2016 15:00 h

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

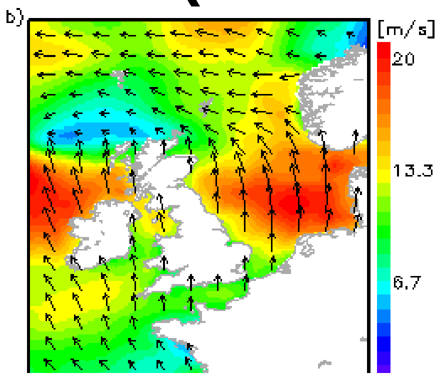
Forcing

NEMO (SSL-NOSSL runs)

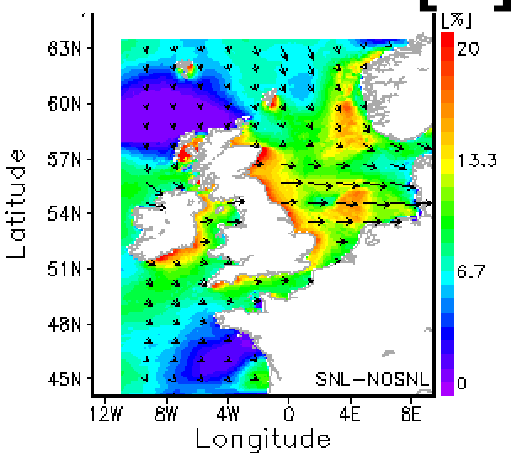
Hs [m]



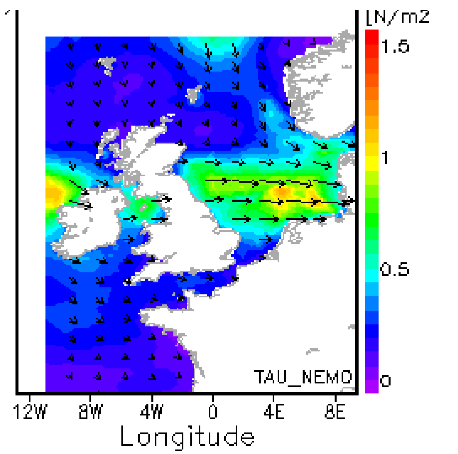
U10 (m/s



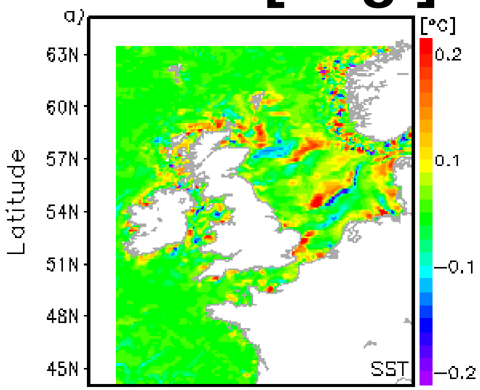
SNL/NOSNL[%]



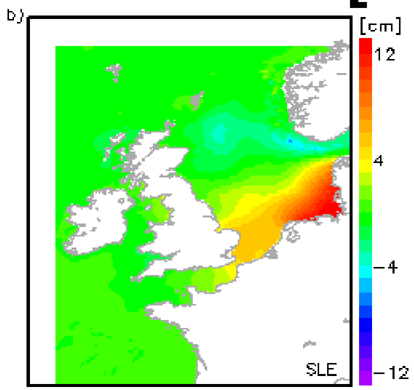
Moment flux



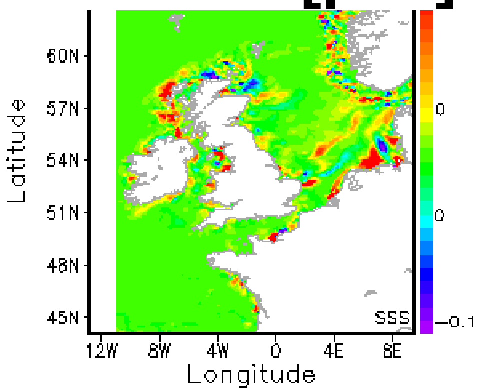
SST Diff [deg.]



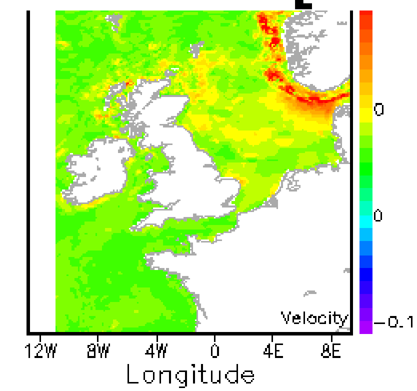
SLE Diff [m]



SSS Diff [psu]



Vel Diff [m/s]

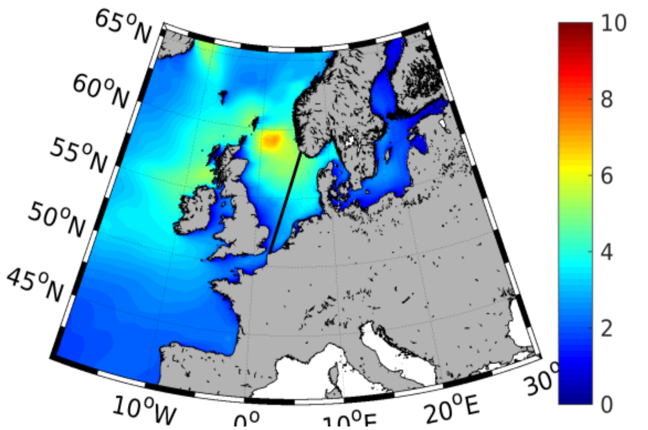


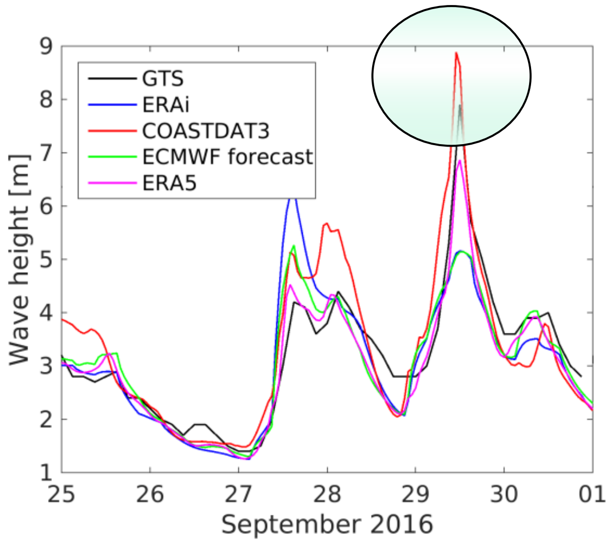
(a)

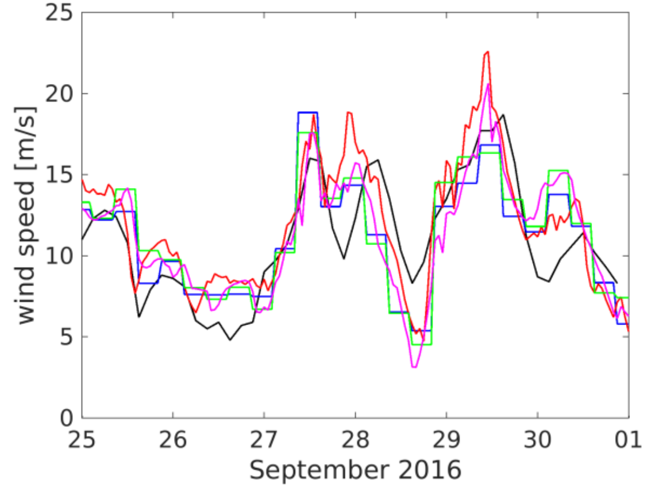
Storm Walpuga -29-30.09.2016 (Ex-Karl) Wave Model validations

Helmholtz-Zentrum Geesthacht

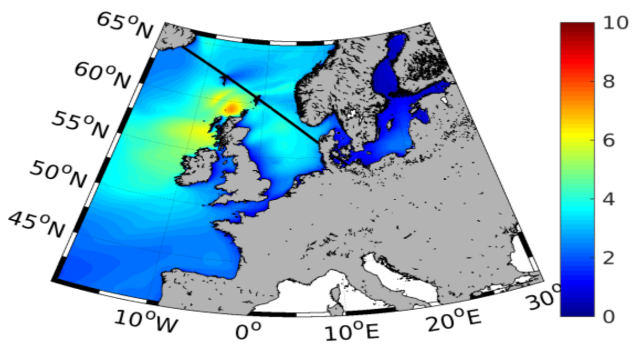
Centre for Materials and Coastal Research







Significant wave height (m) and wind speed (m/s) from GTS buoy (59.6°N 2.2°E)



Model significant wave height and satellite track of the

(top) Jason-2 on 29.09.2016 at 04:00:

(bottom) Sentinel-3 on 29.09.2016 at 10:30

29 September , 2016 15:00 h : Storm Walpuga

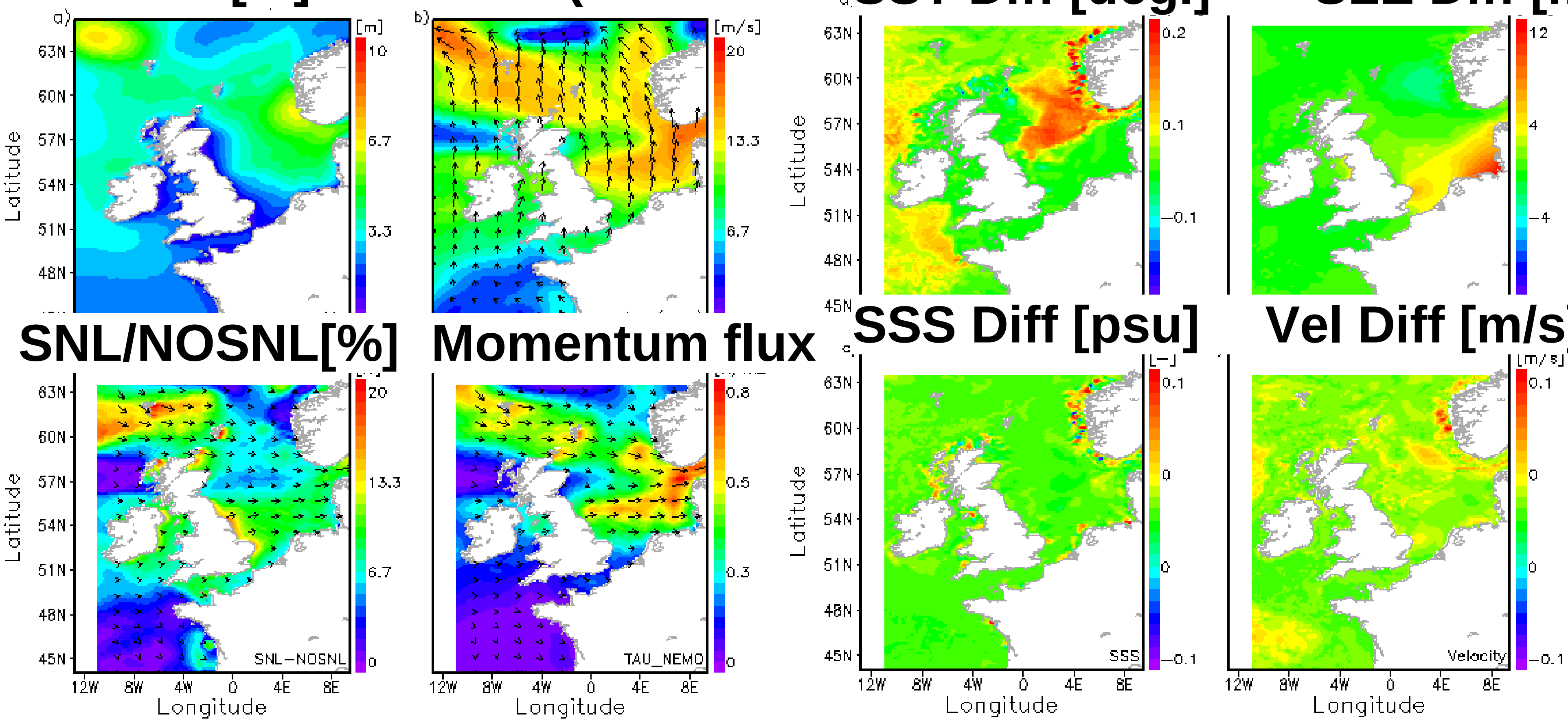
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Forcing

NEMO (SSL-NOSSL runs)

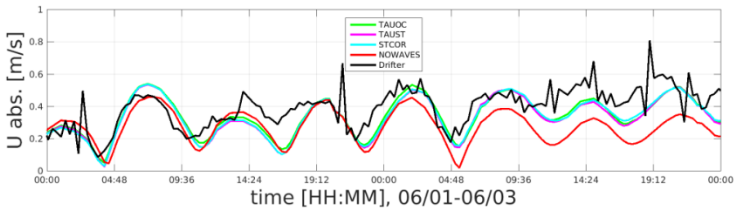
Hs [m] **U10 (m/s** **SST Diff [deg.]** **SLE Diff [m]**

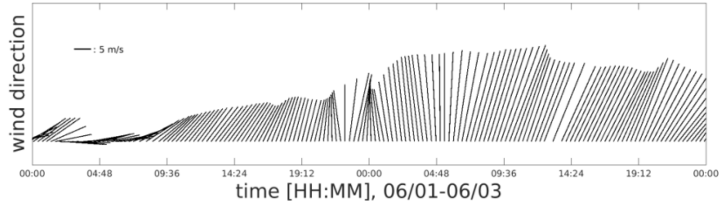
SNL/NOSNL[%] **Momentum flux** **SSS Diff [psu]** **Vel Diff [m/s]**

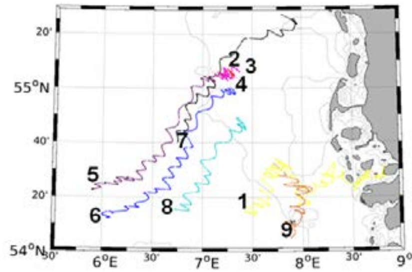


The role of wave-induced forcing on particle drift modelling

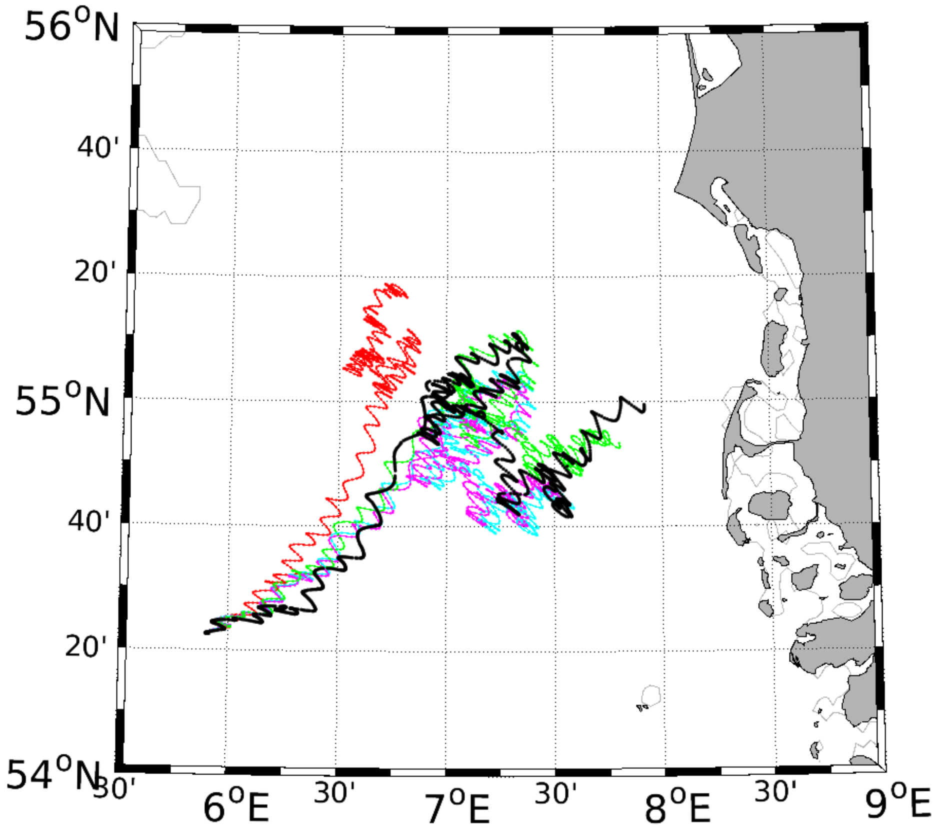
Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

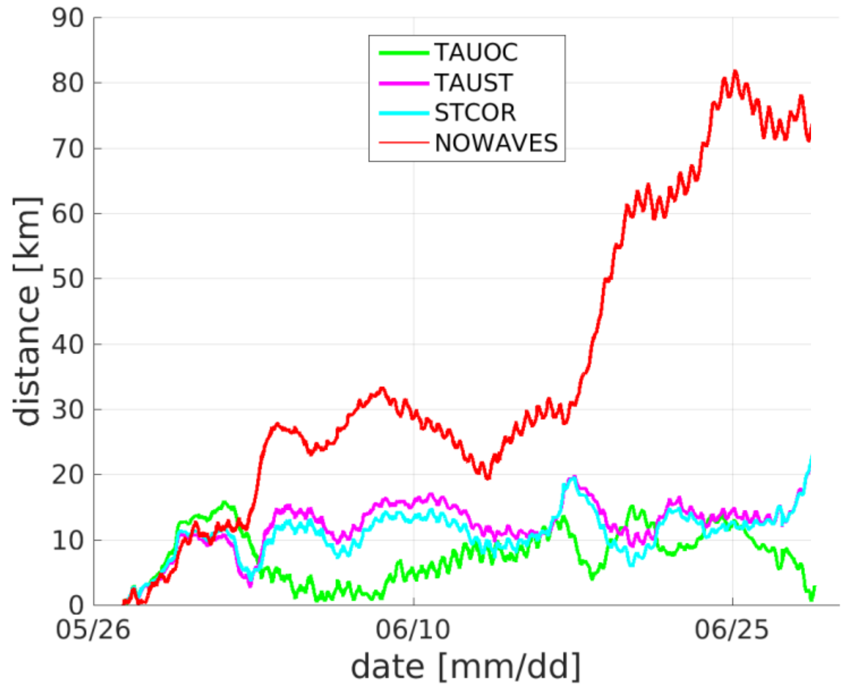




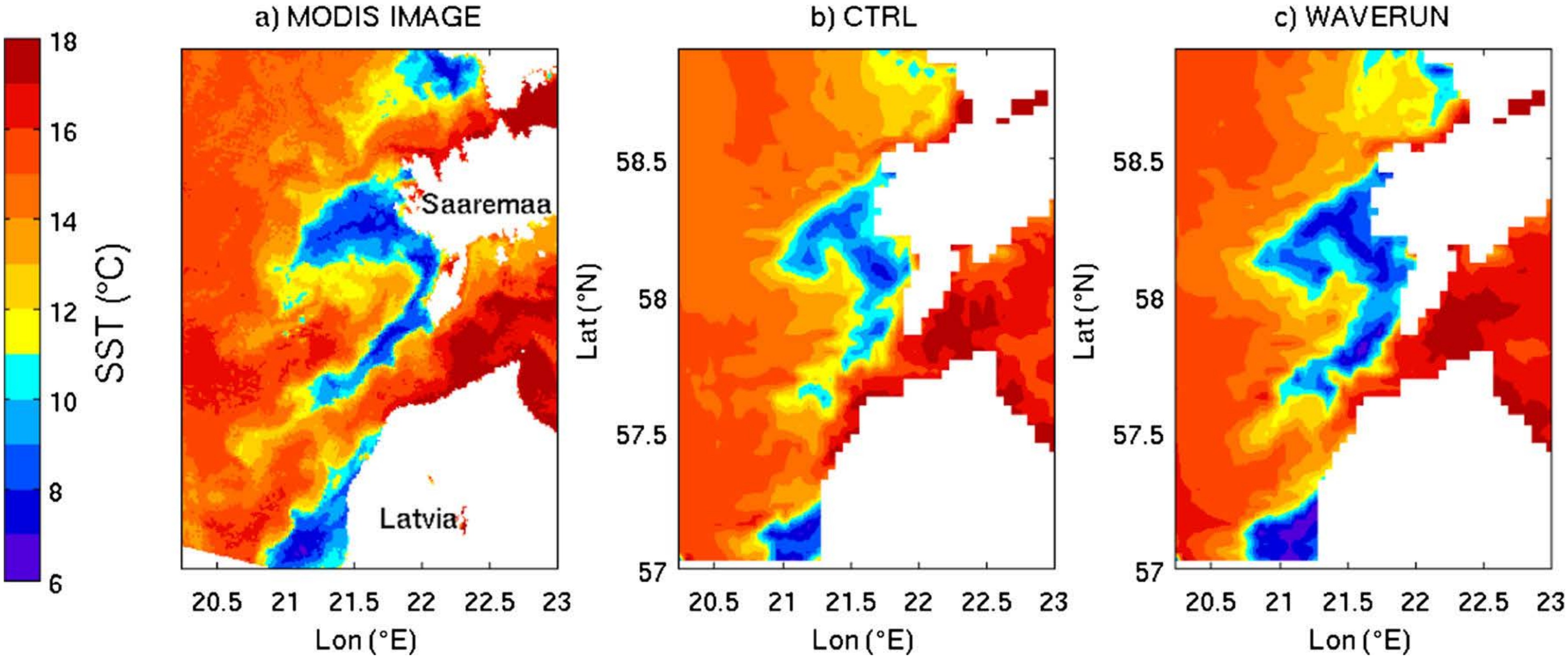


Drifter #5





Baltic Sea: Sea Surface Temperature



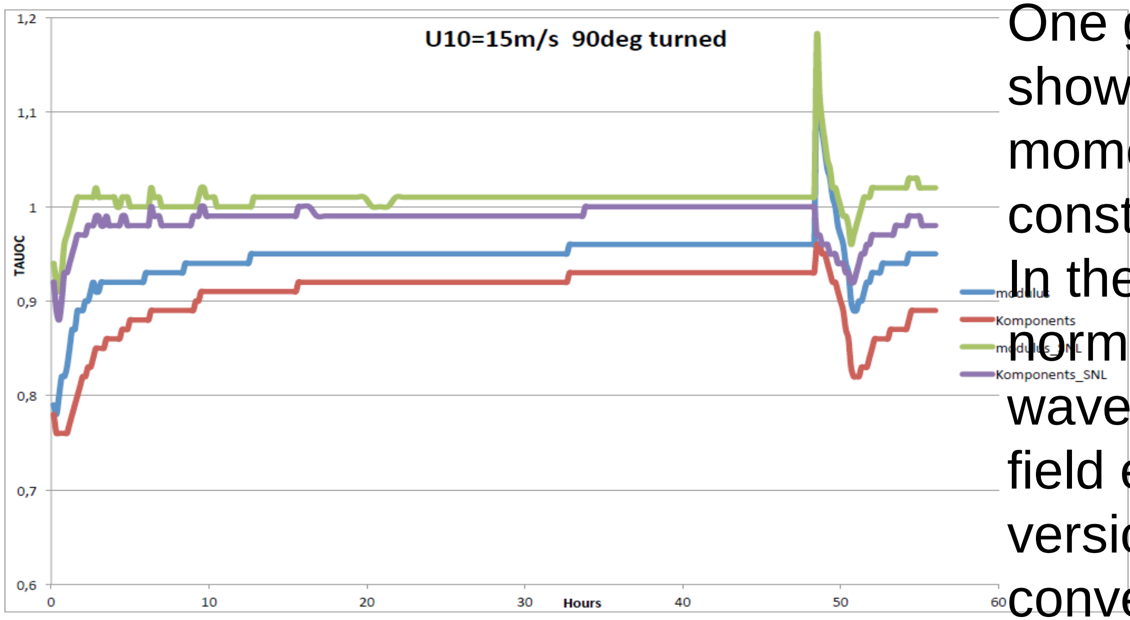
The comparison is for 24 July 2013, 12:00 UTC

Discussion

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

- Accounting for wind-waves forcing improve model predictions in the shallow coastal waters
- Effects of considering sea state and introducing wave-induced forcing on simulated storm surges and circulation are important, especially during extremes
- The inclusion of Snl in the momentum and energy fluxes, although small is not negligible
- Sea state dependent fluxes and the Stokes-Coriolis forcing introduced in the ocean model are important for the e.g. drift-model applications or better upwelling simulations.

Thank you
for your attention!

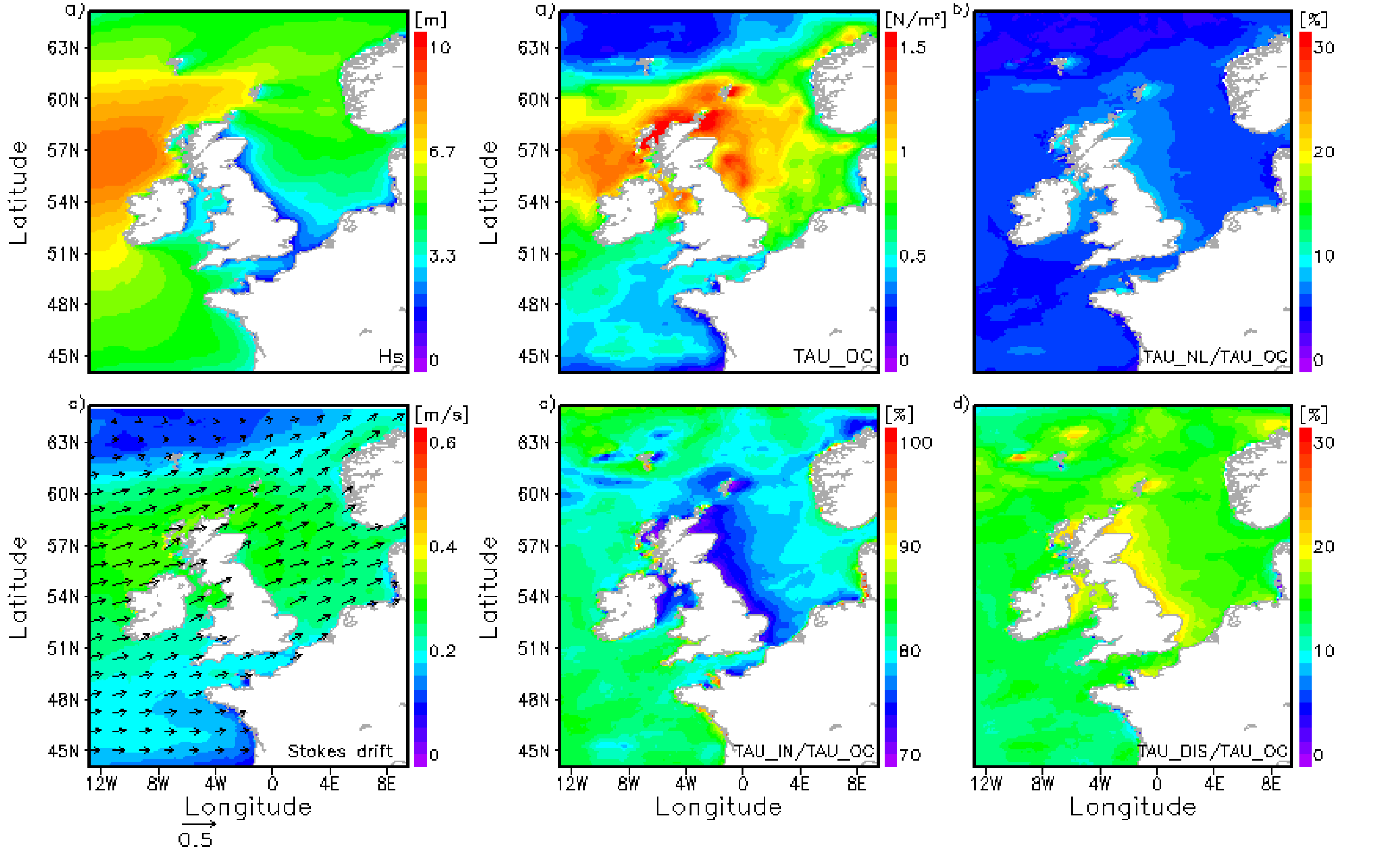


One grid point version of the model. Figure 1b shows the time evolution of the non-dimensional momentum flux into the ocean for different constant wind forcing starting from noise level. In the early stage of development, the normalized stress into ocean is below 1 as waves are rapidly growing (1 a). As the waves field evolves towards a fully developed state, the version without SNL in WAM (modulus) is converging towards a value around 0.96 (blue curves). Whereas when the nonlinear source term is accounted for, the convergence is now towards 1. Note also that in the early stage of development, τ_oc drops less below one than the current version.

Wind, wave and Fluxes

Storm Norkas/Henrly

30.01-03.02.2016



03 February, 2016 09:00 h

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Forcing

NEMO (SSL-NOSSL runs)