Coastal hazards: coupling of ocean and atmosphere through a dynamic wave interface

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2nd International Workshop on Waves, Storm Surges and Coastal Hazards
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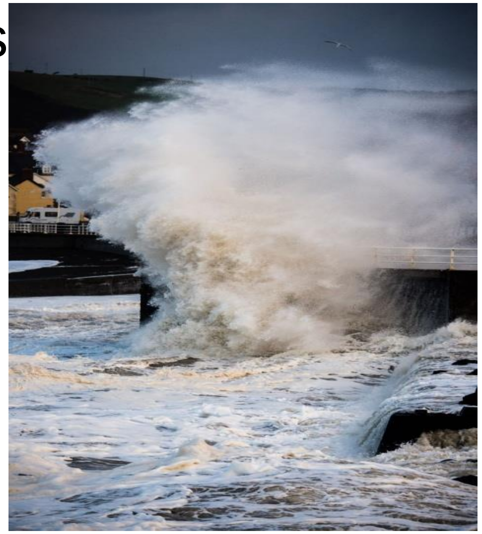
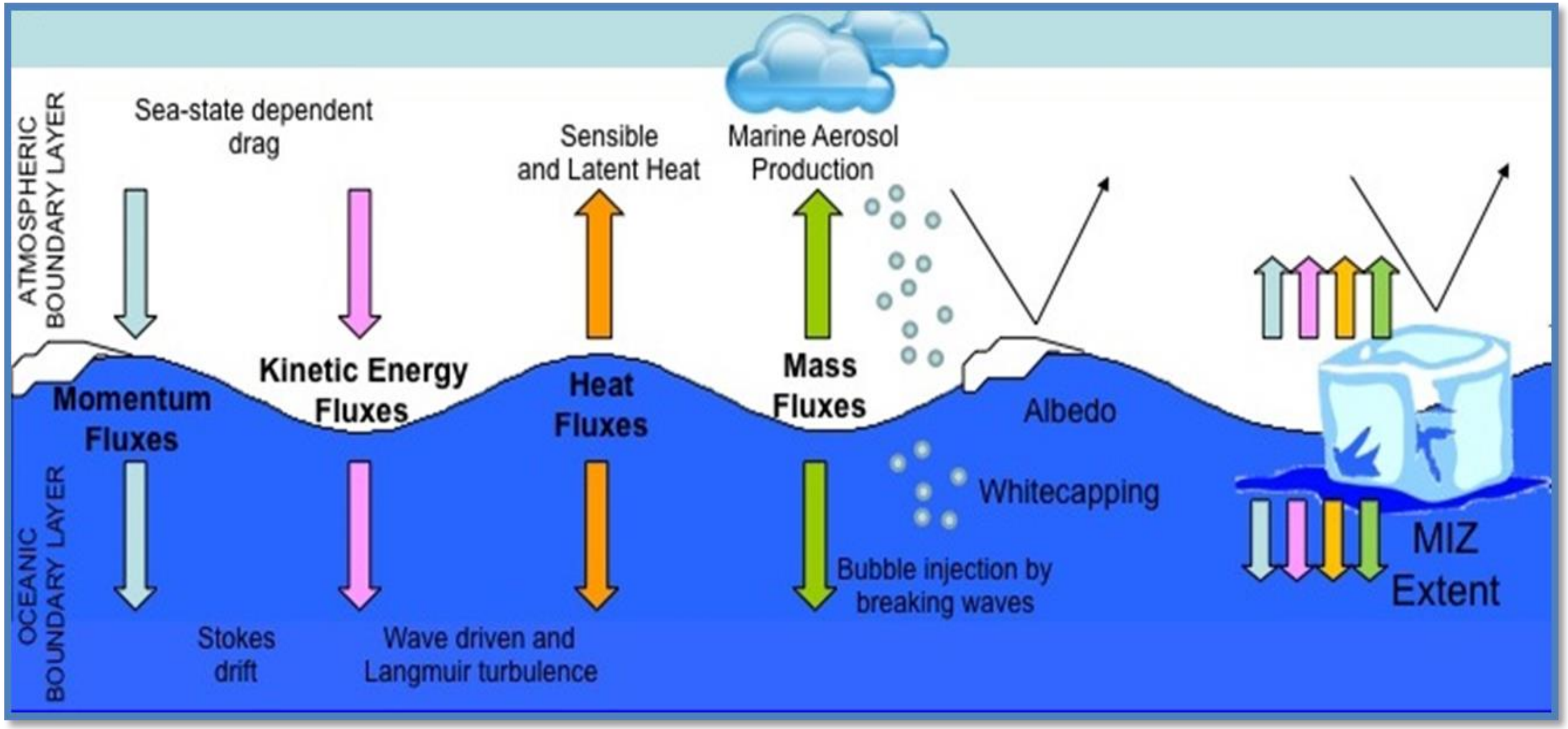
Relevance of ocean-wave coupling for coastal predictions

- Increased interest in reducing prediction errors of state estimates
- Study the impact of interaction processes
- Substantial effects also on mean fields -energy and momentum transfer
- Extreme weather events in the marine realm





Cavaleri, Fox-Kemper and Hemer, 2012: Wind-waves in the Coupled Climate System, BAMS

GCOAST Modell system

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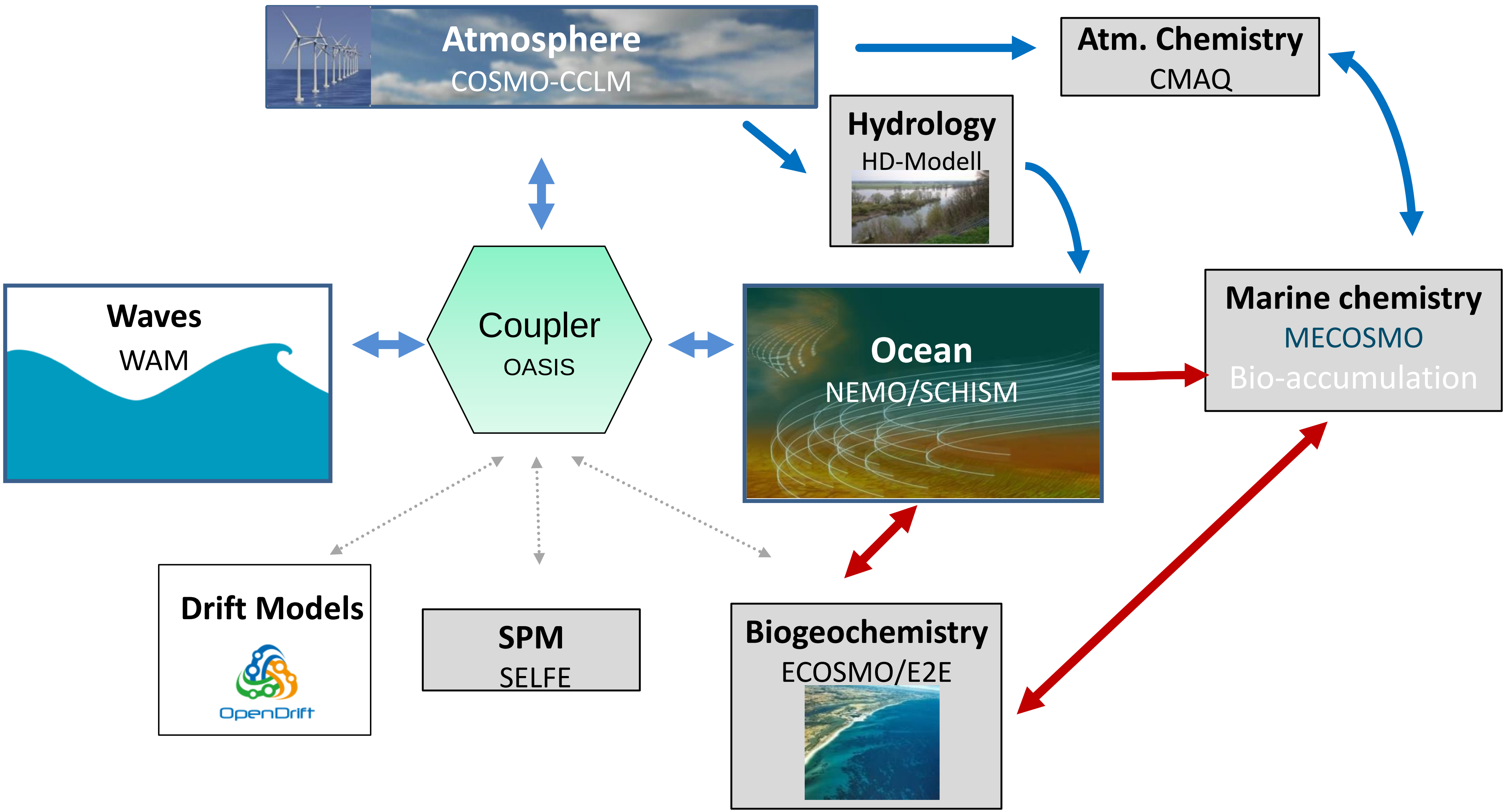
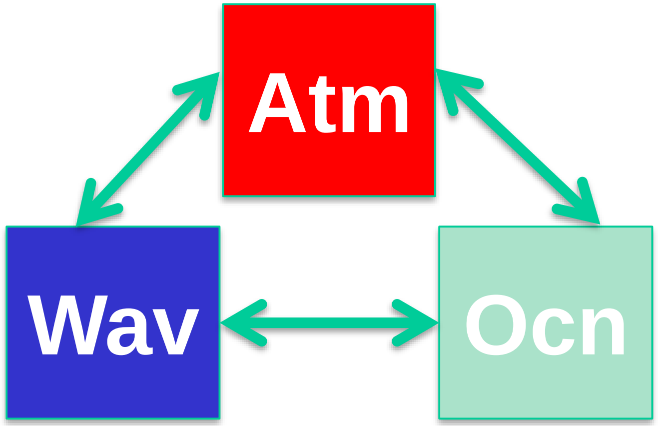
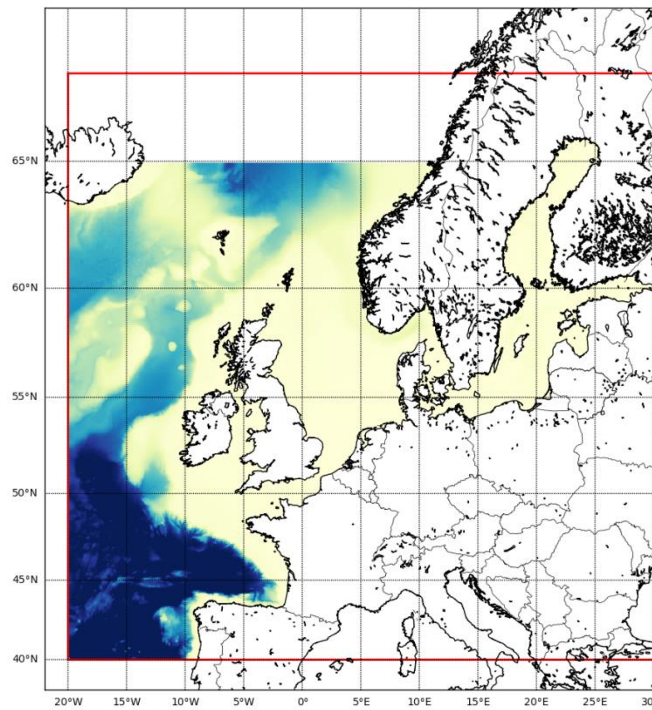


Coupled Model Setup

	NEMO 3.6	WAM 4.7	COSMO-CCLM
Horizontal grid	3.5 km covering North Sea and Baltic Sea, 900 m German bight	Same	7 km covering NW European seas
Vertical grid	56 s layers, emphasis on surface	N/A	55 levels
Initial field	CMEMS NWS Data	EWAM wave data	COSMO-EU Model
Boundary condition	OSU tides, CMEMS NWS Data for T,S, u,v, SLH	EWAM wave data	ERA-5 data
Forcing	ERA-5, COSMO	Same	ERA-5 Boundary data
Vertical diffusion scheme	GLS (*k-eps*)	N/A	
Ice	LIM-3	WAM ice parameterization	NA





External Forcing

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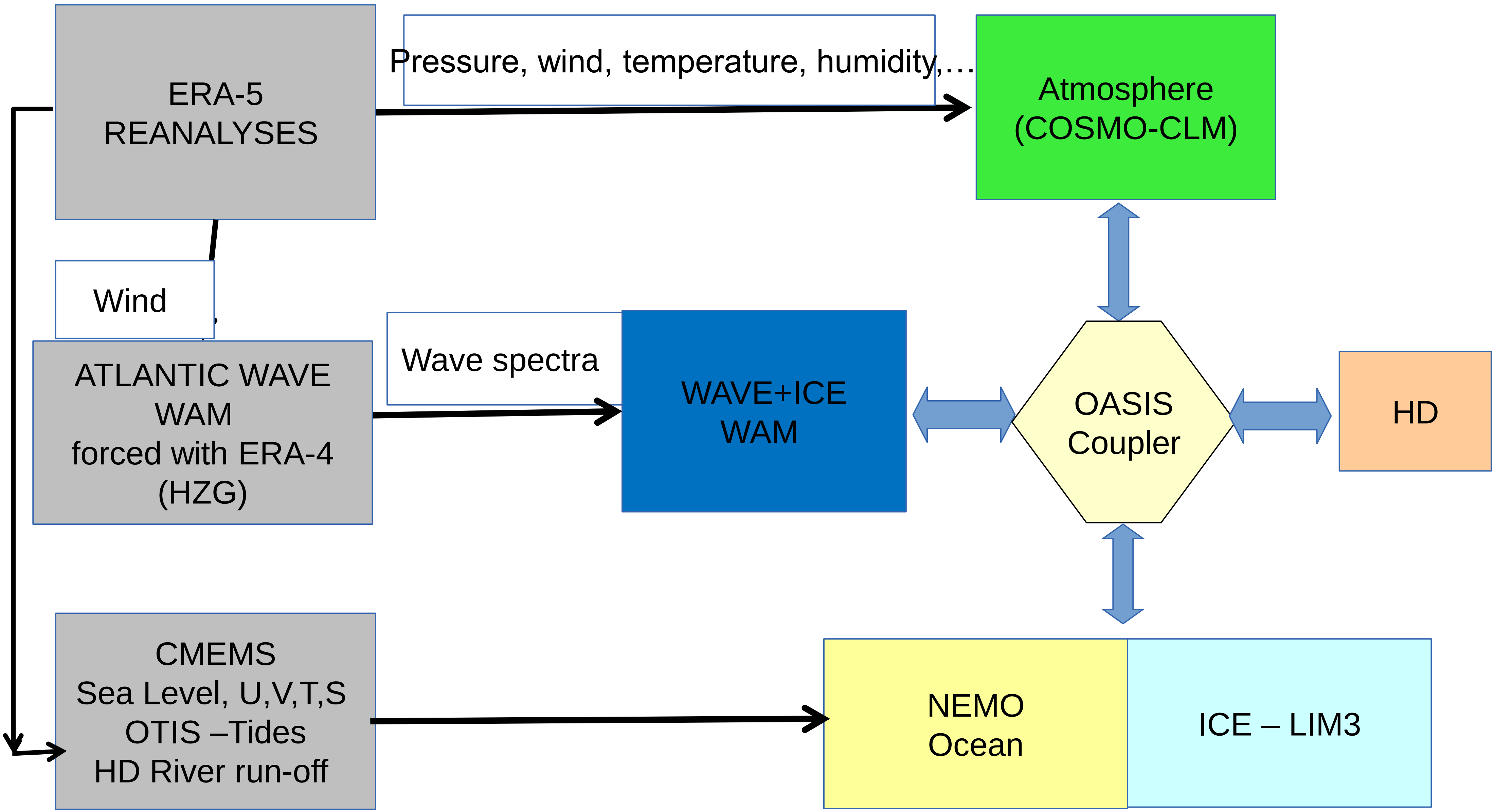

Two-way coupling and Downscaling via OASIS

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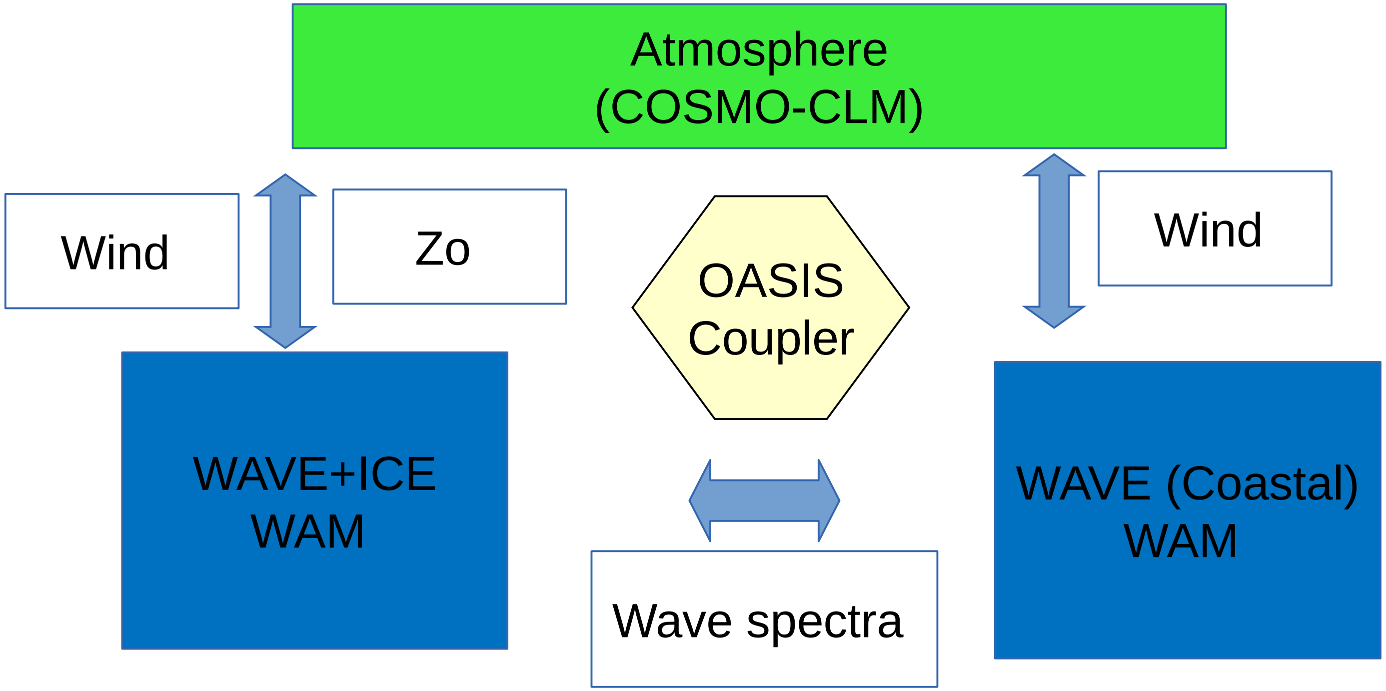
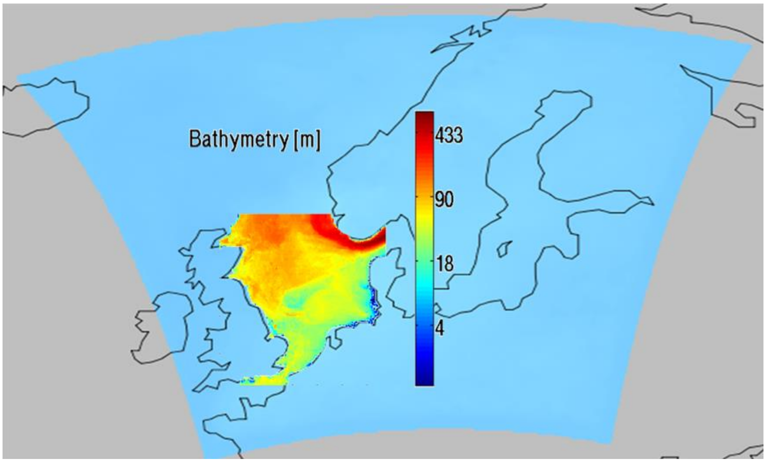
→Waves extract energy and momentum from the atmosphere.
→The effect is largest for young sea states and high wind speeds.

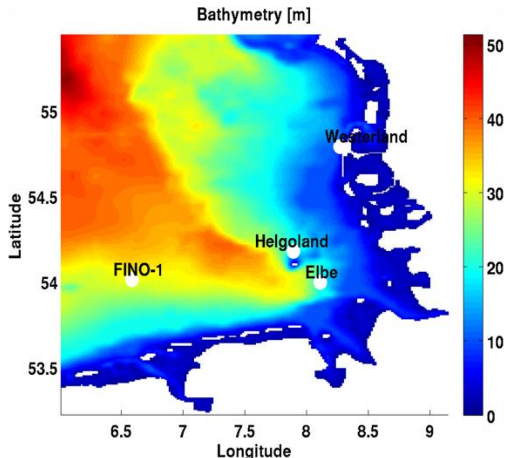


$$U(z) = \sqrt{\frac{\tau}{C_D(z)}}$$

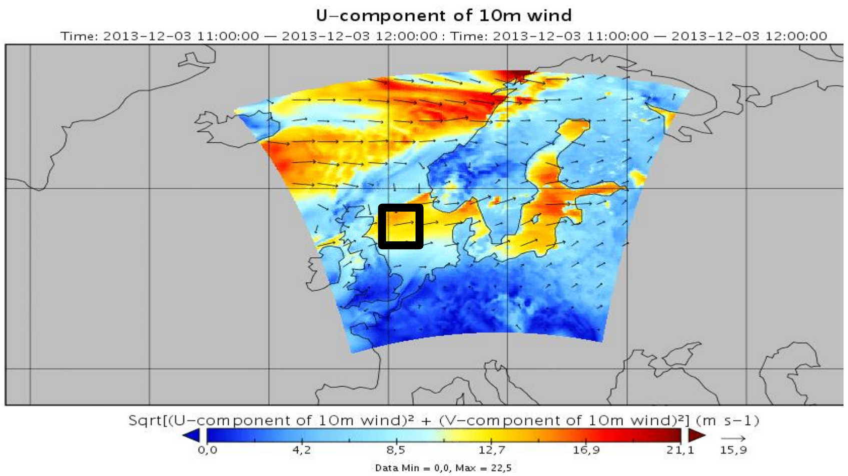
$$C_D(z) = \frac{\kappa^2}{ln^2(z/z_0)}$$

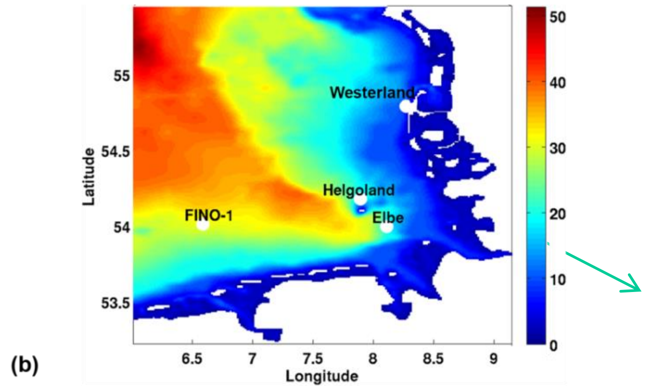
$$z_0 = \frac{\alpha\tau}{g} \quad = \frac{1}{\sqrt{1-\tau_w/\tau}}$$

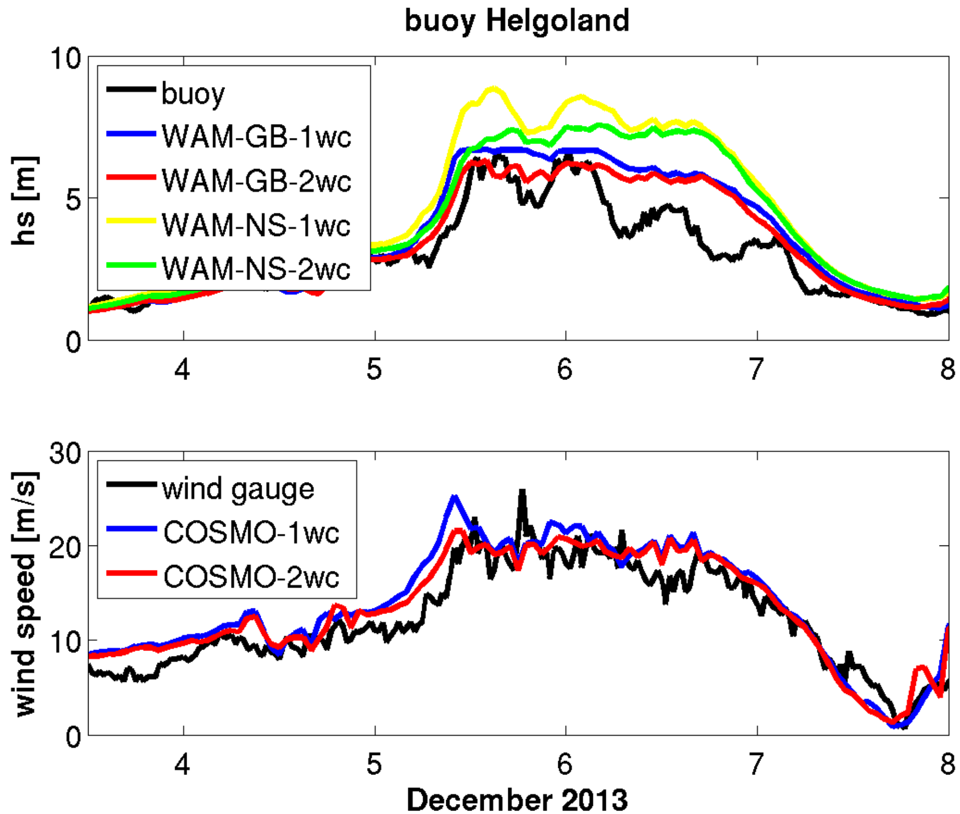




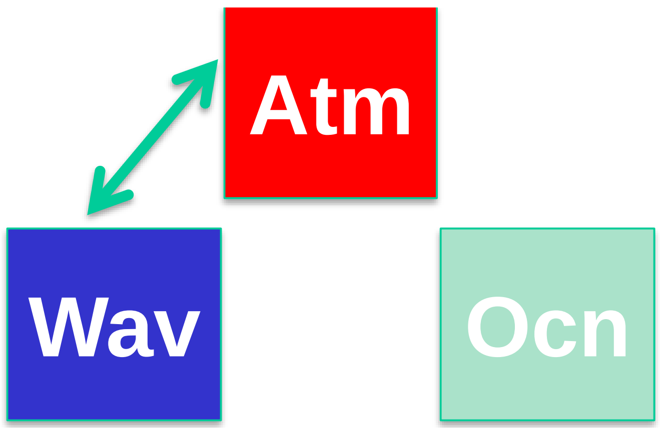
Impact of two-way coupling between waves and atmosphere







mean hs	Hel:1.95		Fino-1:1.42		Wes: 1.63	
	1-way	2-way	1-way	2-way	1-way	2-way
bias hs [m]	-0.14	-0.03	-0.07	-0.01	-0.13	-0.03



Wahle et al. (2017)
Wiese et al., /2019)

Bias: GCOAST versus Satellite data

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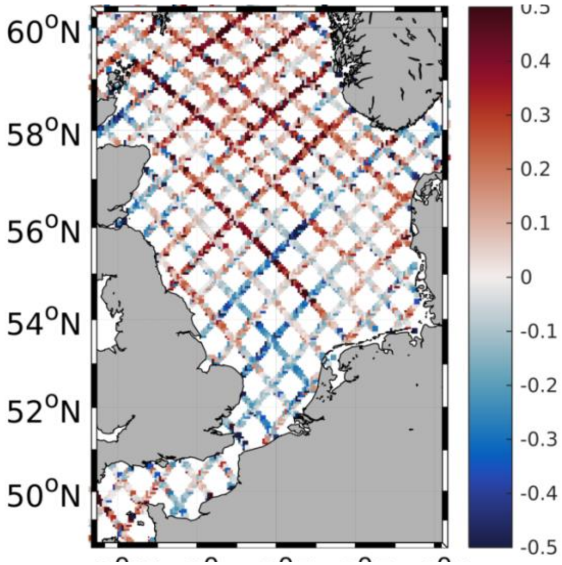
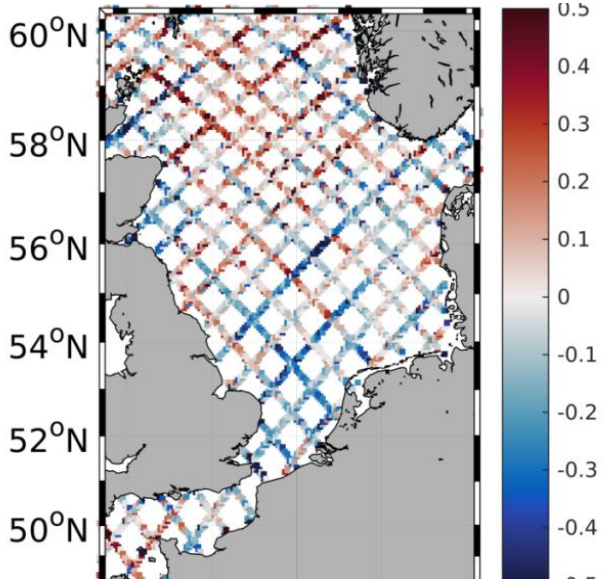
Jun.2016
-
Nov.2016

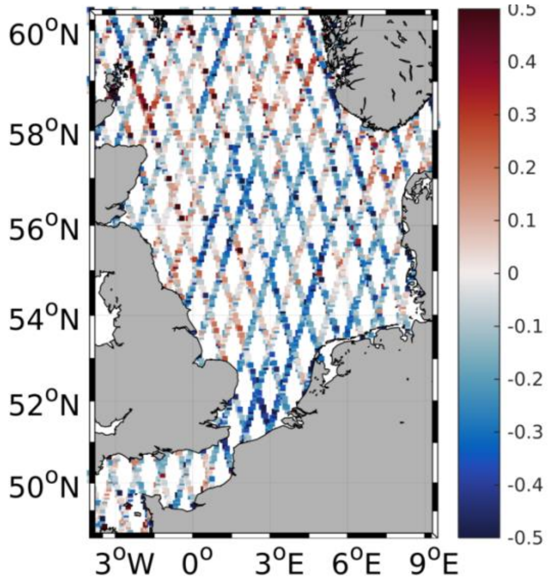
JASON-2 – One-way



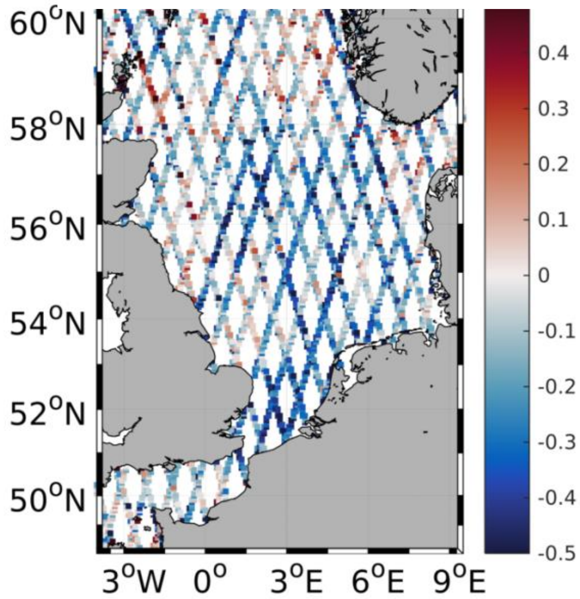
JASON-2 – Two-way



SENTINEL-3 – One-way

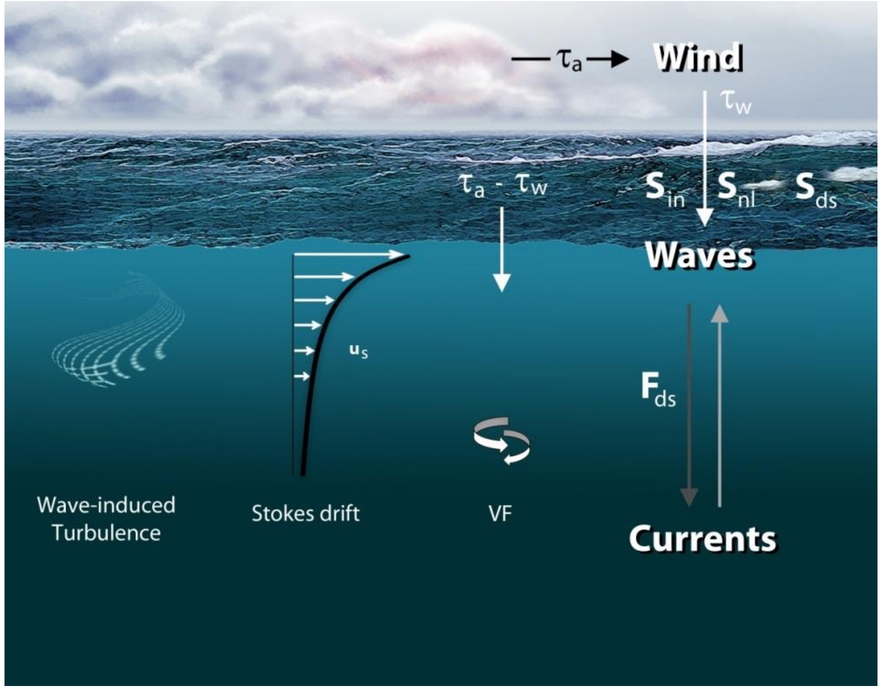


SENTINEL-3 – Two-way

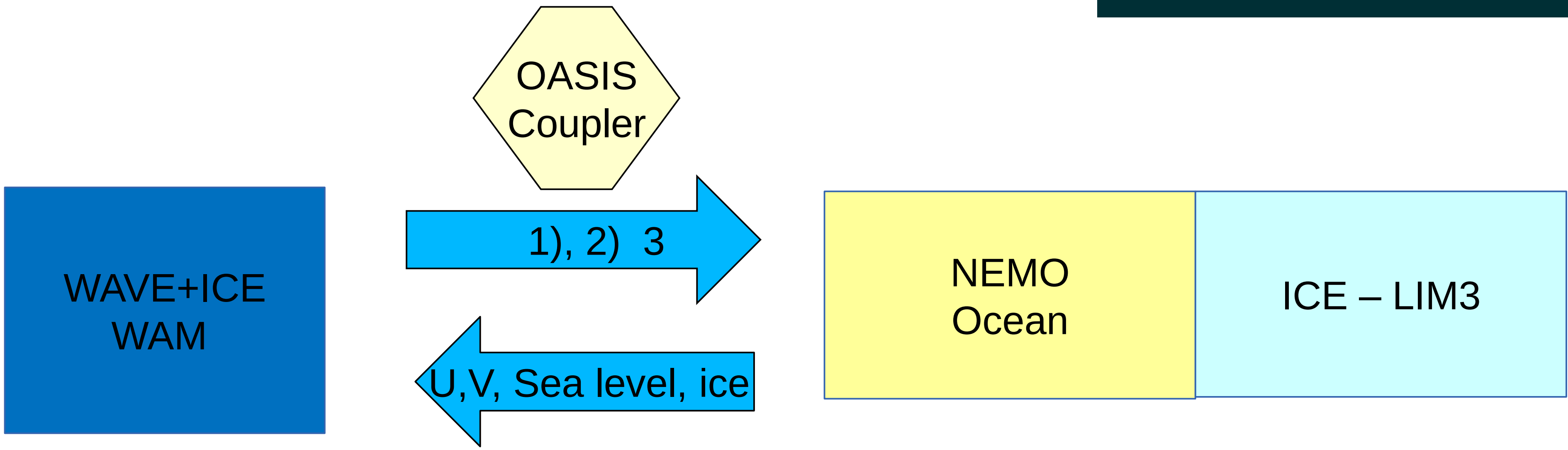


Wave-current interaction:

(1) The Stokes-Coriolis forcing incl, Stokes Coriolis contribution to the advection term
(2) Sea state dependent momentum flux
(3) Sea state dependent energy flux
(4) Wave-induced mixing
(5) Wave-induced bottom fluxes from WAM



Implementing two-way coupling with OASIS



Impact of waves to sea surface stress:

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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

Validation
Tide Gauge Stations

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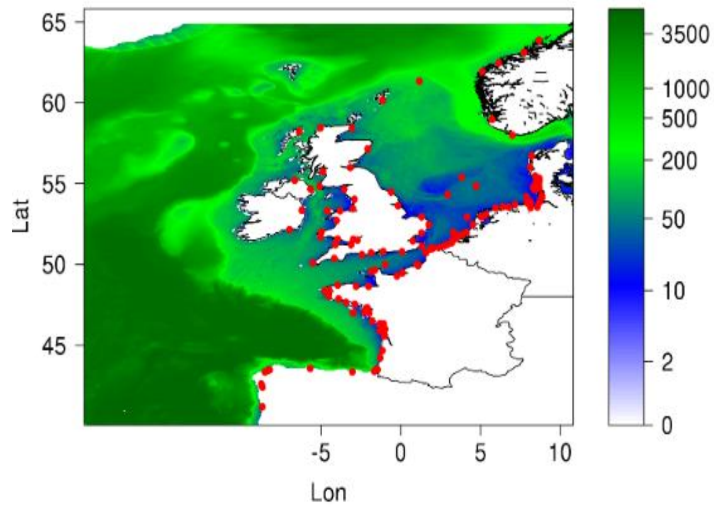
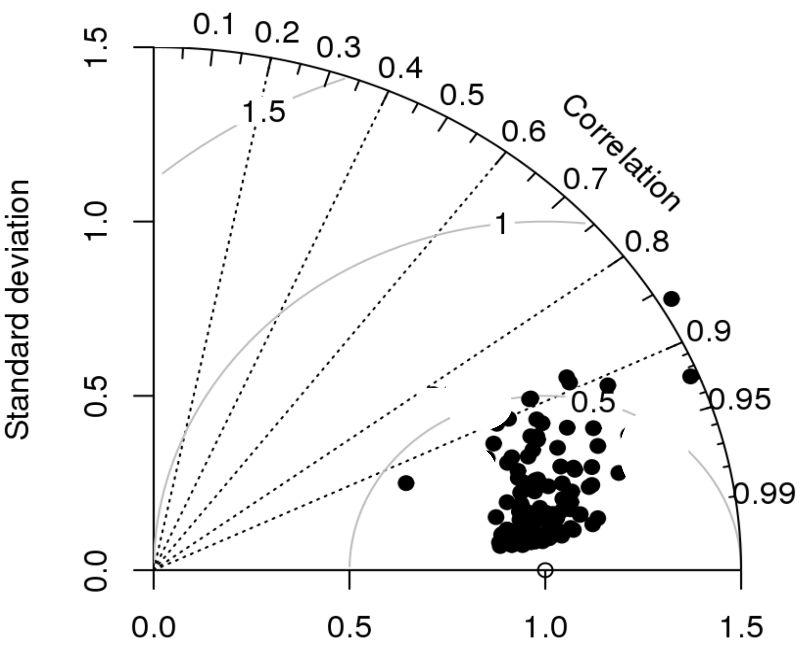
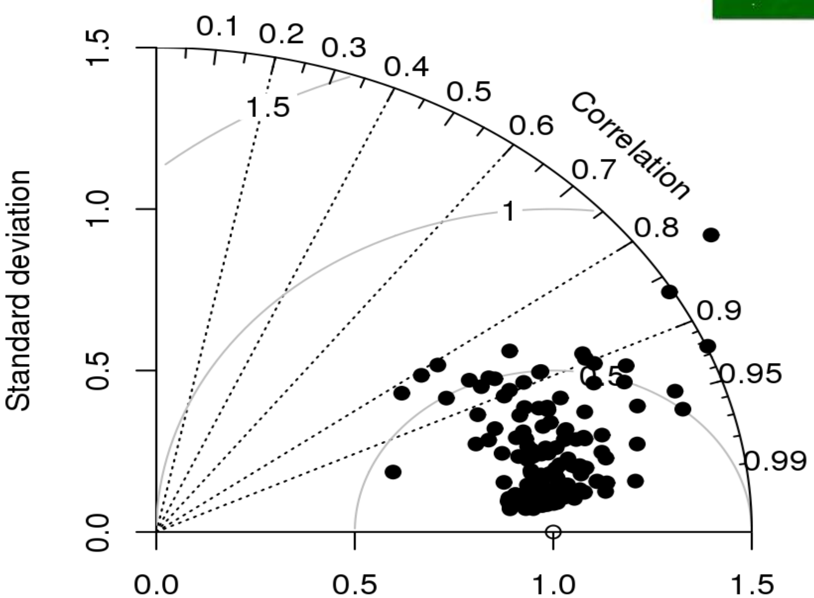


COUPLED 2018



UNCOUPLED 2018



Storm Axel in January, 2017

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“Storm Axel brings worst Baltic Sea flooding in decade”

Source: DPA /The Local, @thelocalgermany, 5 January 2017, 10:00 CET+01:00

A car underwater in Wismar. Photo: DPA.

Waves hit a ferry dock in Schleswig-Holstein. Photo: DPA.

Storm Axel in January, 2017

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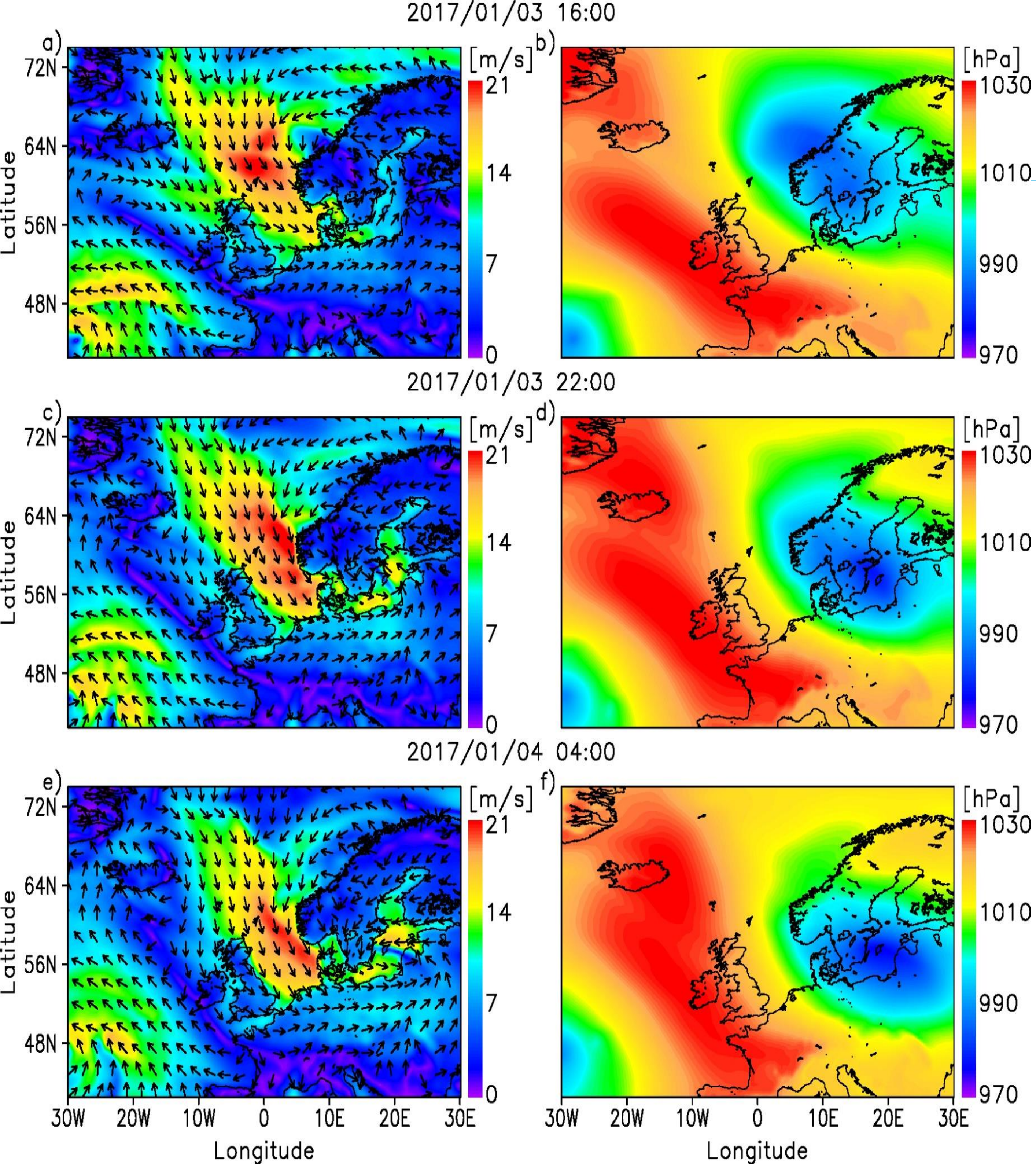
Hamburg port city’s historic fish market was filled with knee-deep water, while cars and busses driving along the water front flooded through the high tides.

Thousands of plastic eggs containing small toys have appeared on the tiny German North Sea island of Langeoog. (bbc.com)



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Snapshots of ERA5 wind and surface pressure forcing during the storm 'Axel'. Highest wind speed was at 22:00 2017/01/03

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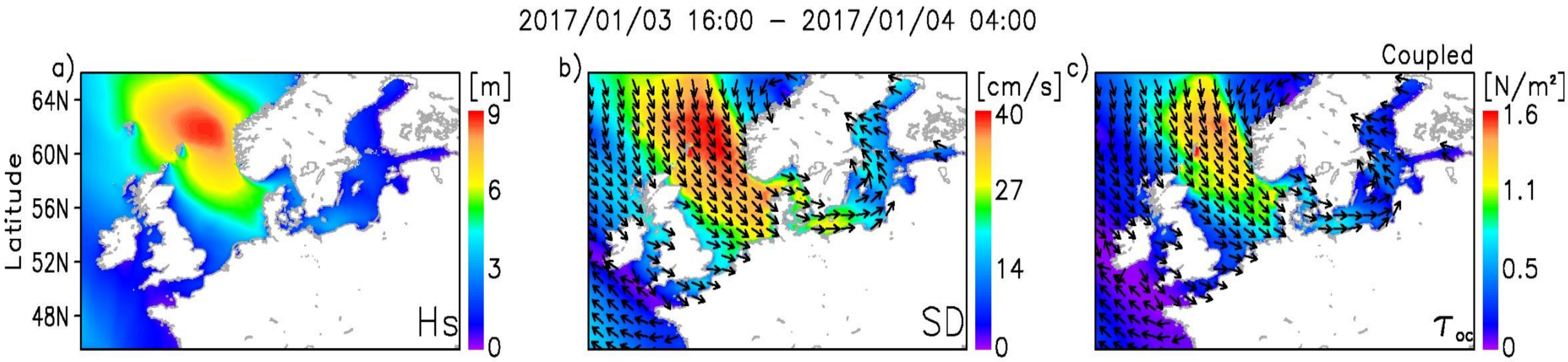

Mean significant wave height, stokes drift and tau_oc simulated by the coupled RUN

Impact of waves on Surge

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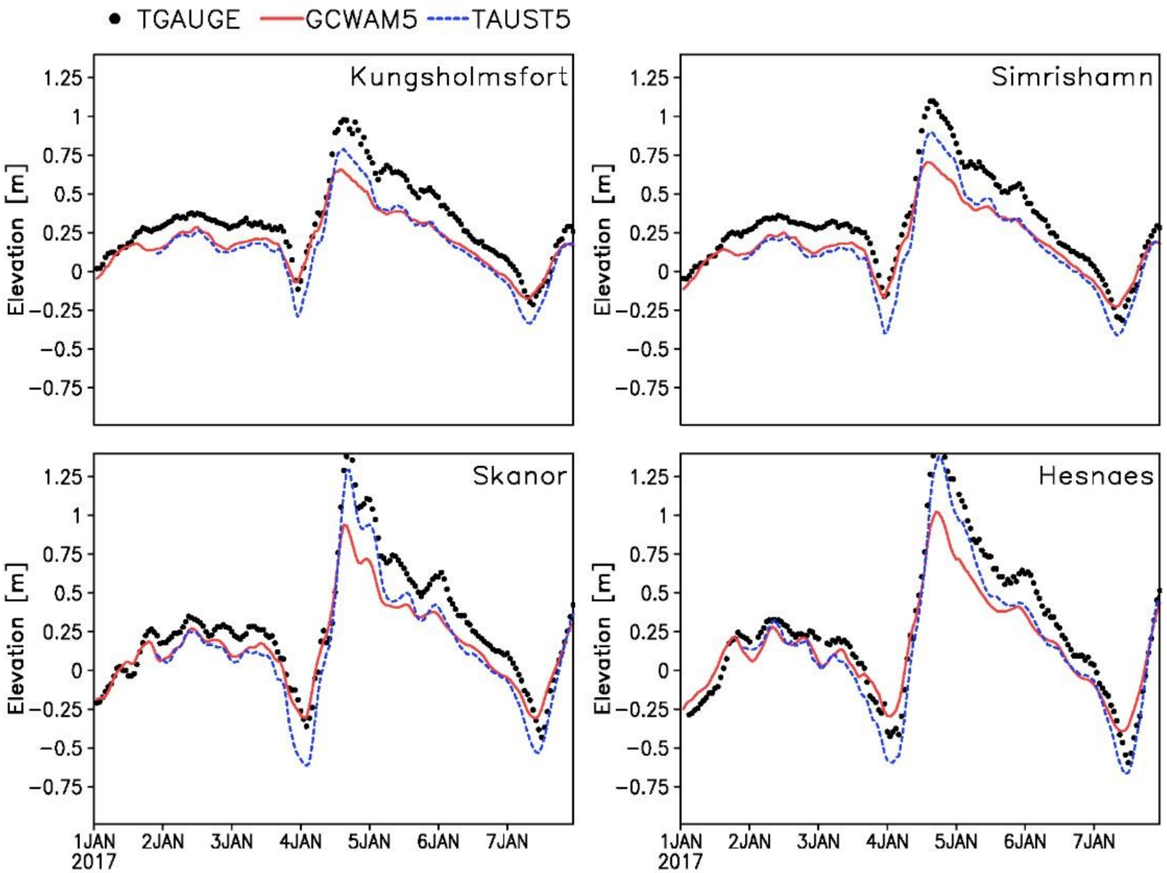

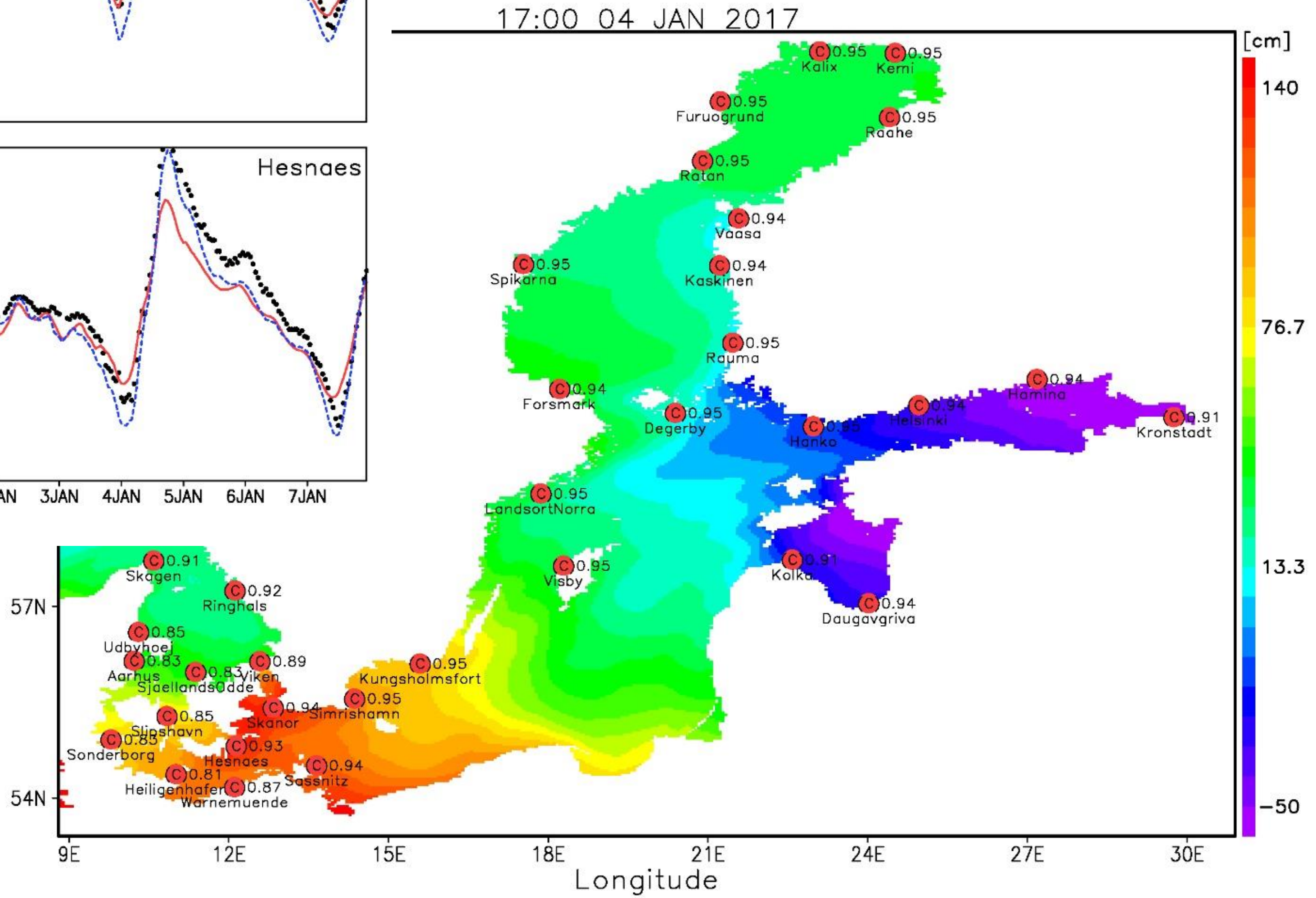

The nonlinear source term contribution

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

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:

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

29 September, 2016 15:00 h: Storm Walpuga

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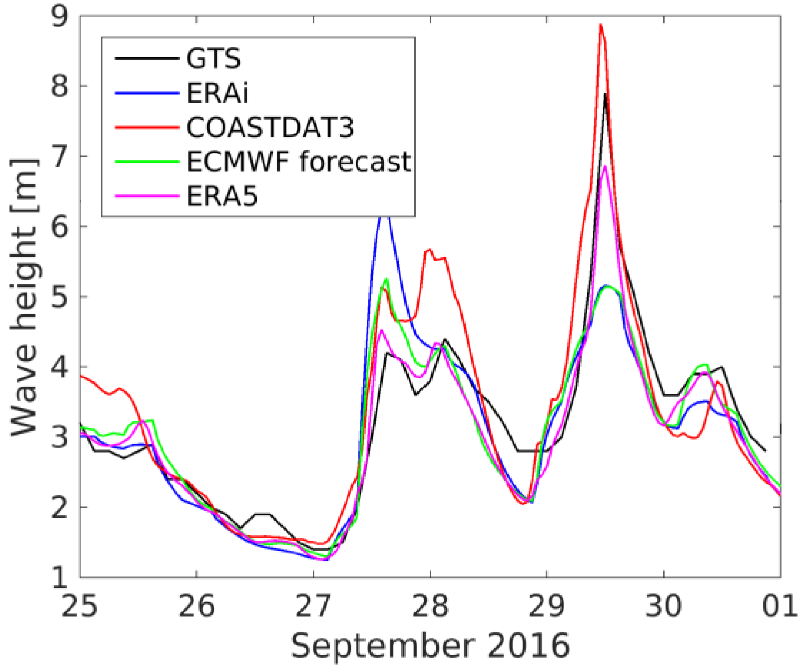
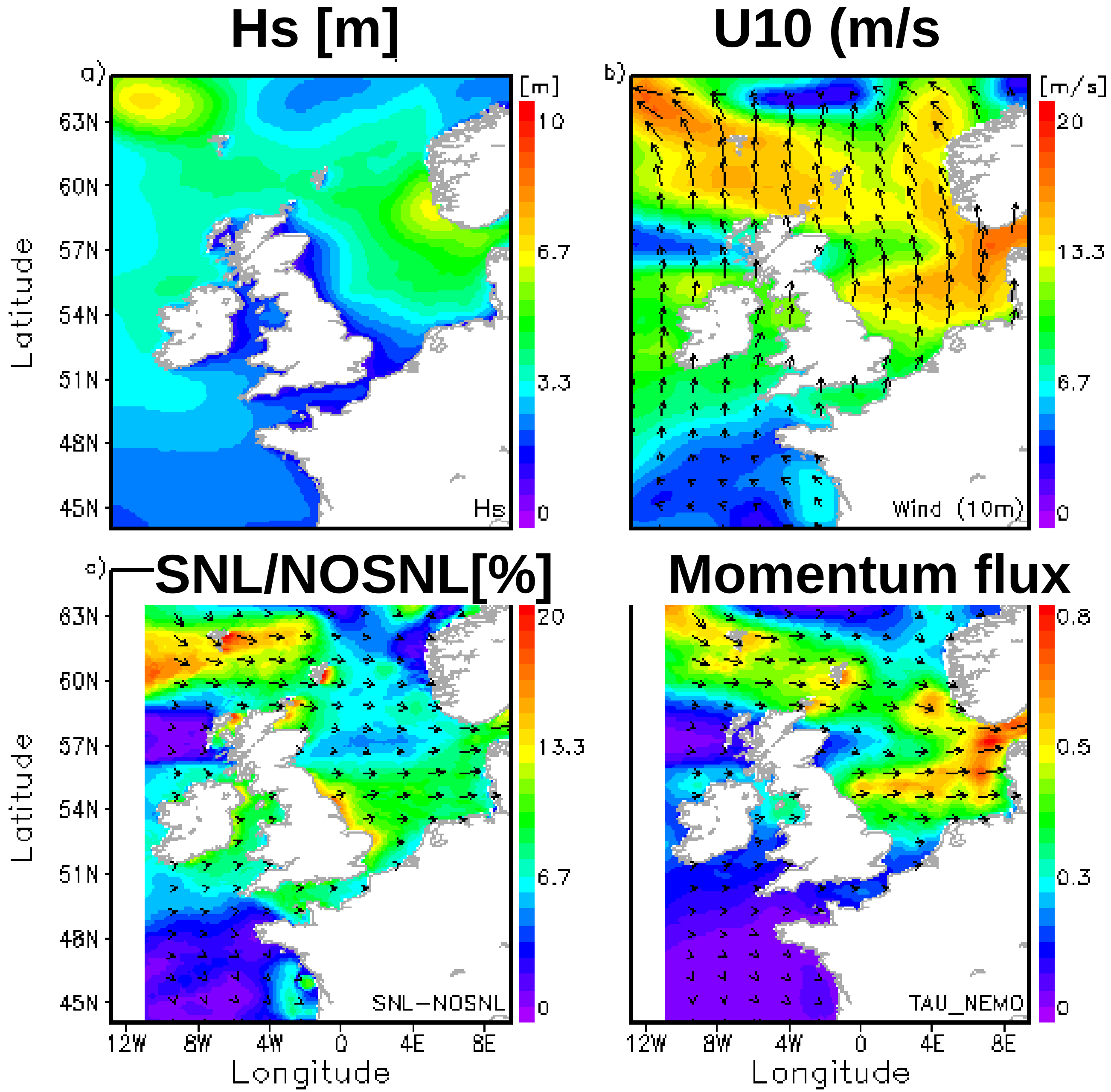
Forcing





Experiments

Experiment	NEMO	+STCOR	+STFULL	+TAUOC	+TAUVEC	+PHYOC	ALL
CTRL							
Stokes-Coriolis in Momentum Eq							
Stokes.-Coriolis also in tracers Eq							
Sea State momentum – scalar							
Sea state momentum from WAM							
Wave-induced mixing							
ALLRUN							

Impact of wave-induced forcing on Sea Level
Different meteo-conditions during 2016

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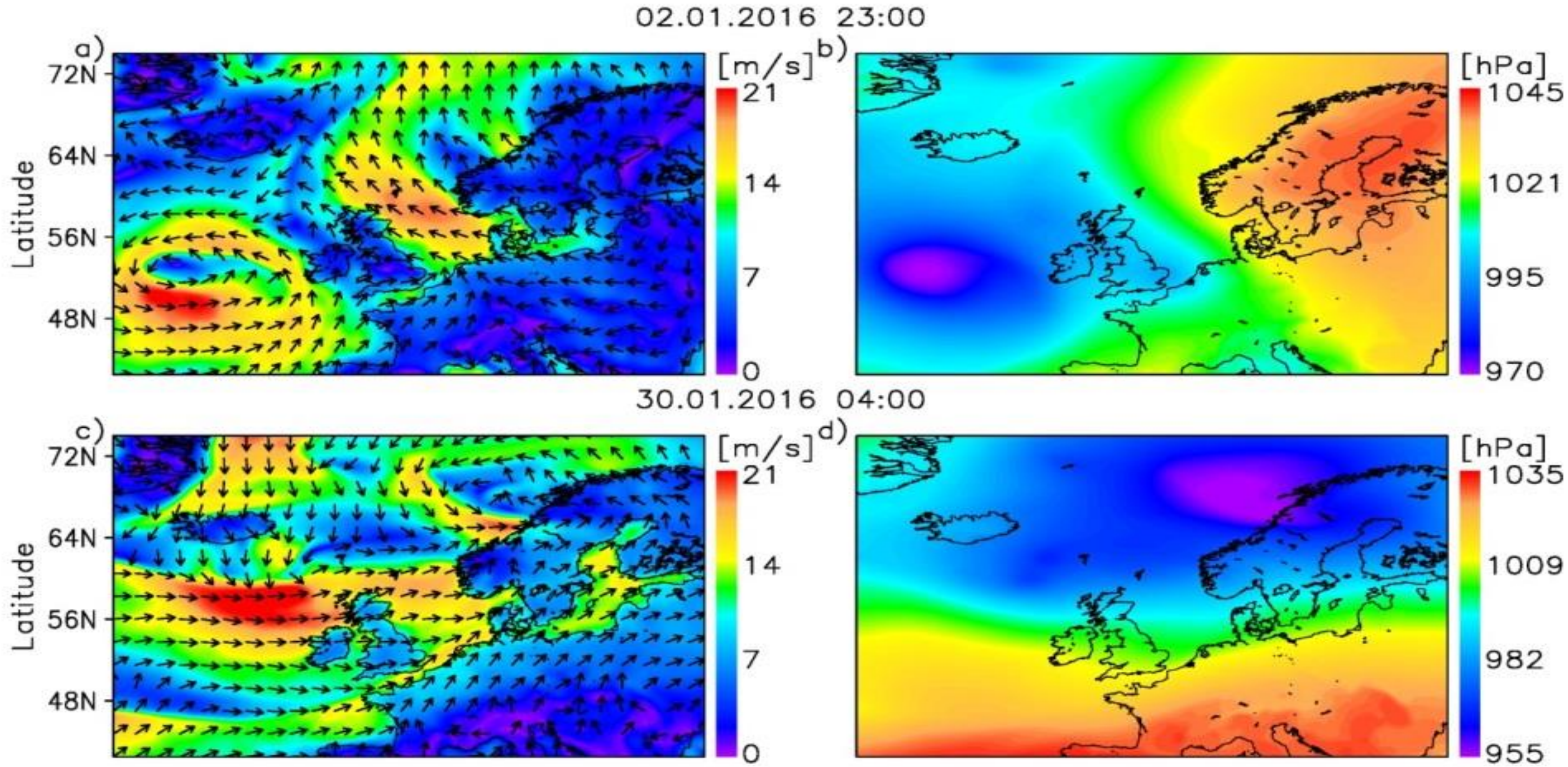

Staneva et al., (2019)

Impact of wave-induced forcing on Sea Level
Different meteoconditions during 2016

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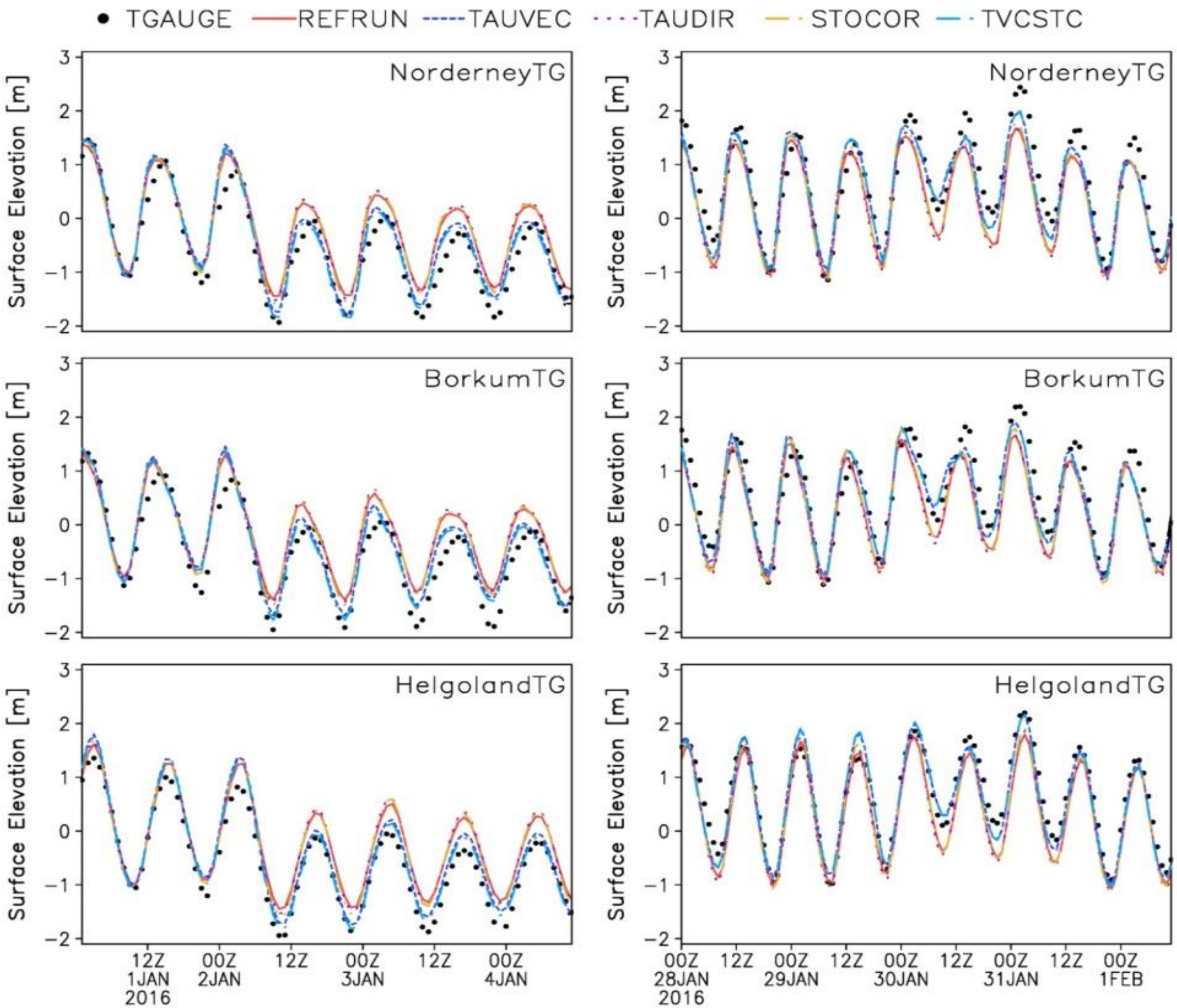

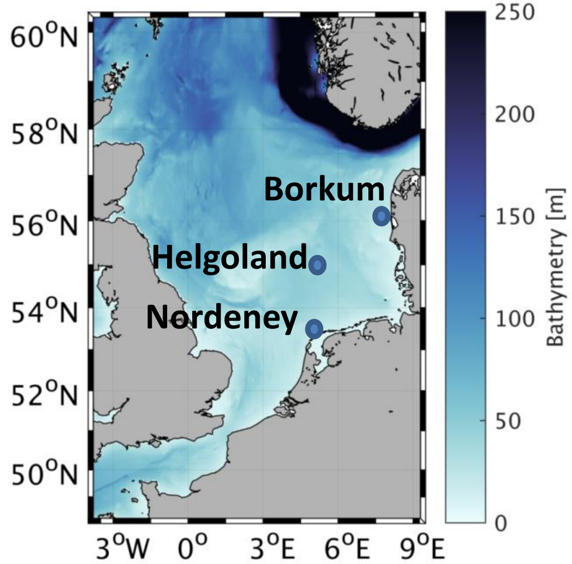

Staneva et al. (2019)

Impact of wave-induced forcing on Sea Level
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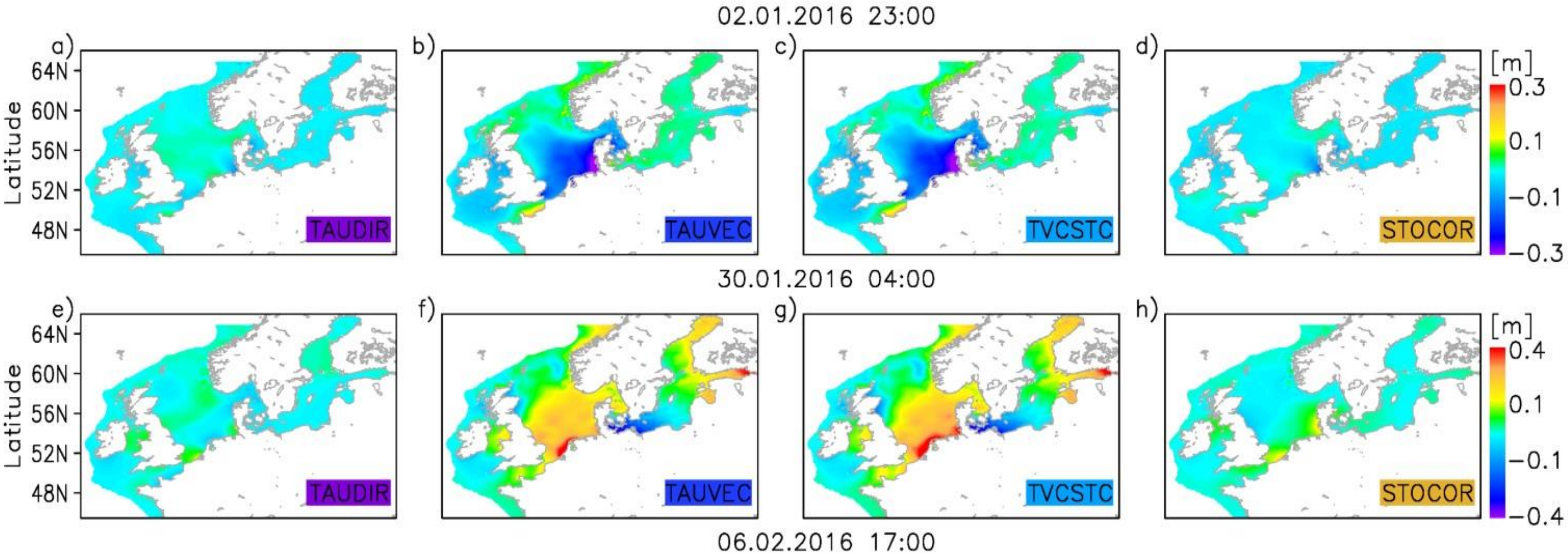

TAUOC **TAUVEC** **ALLWAVE** STCOR

Impact of wave coupling: SSH Surge 2010-2018 (PCT95 OND)

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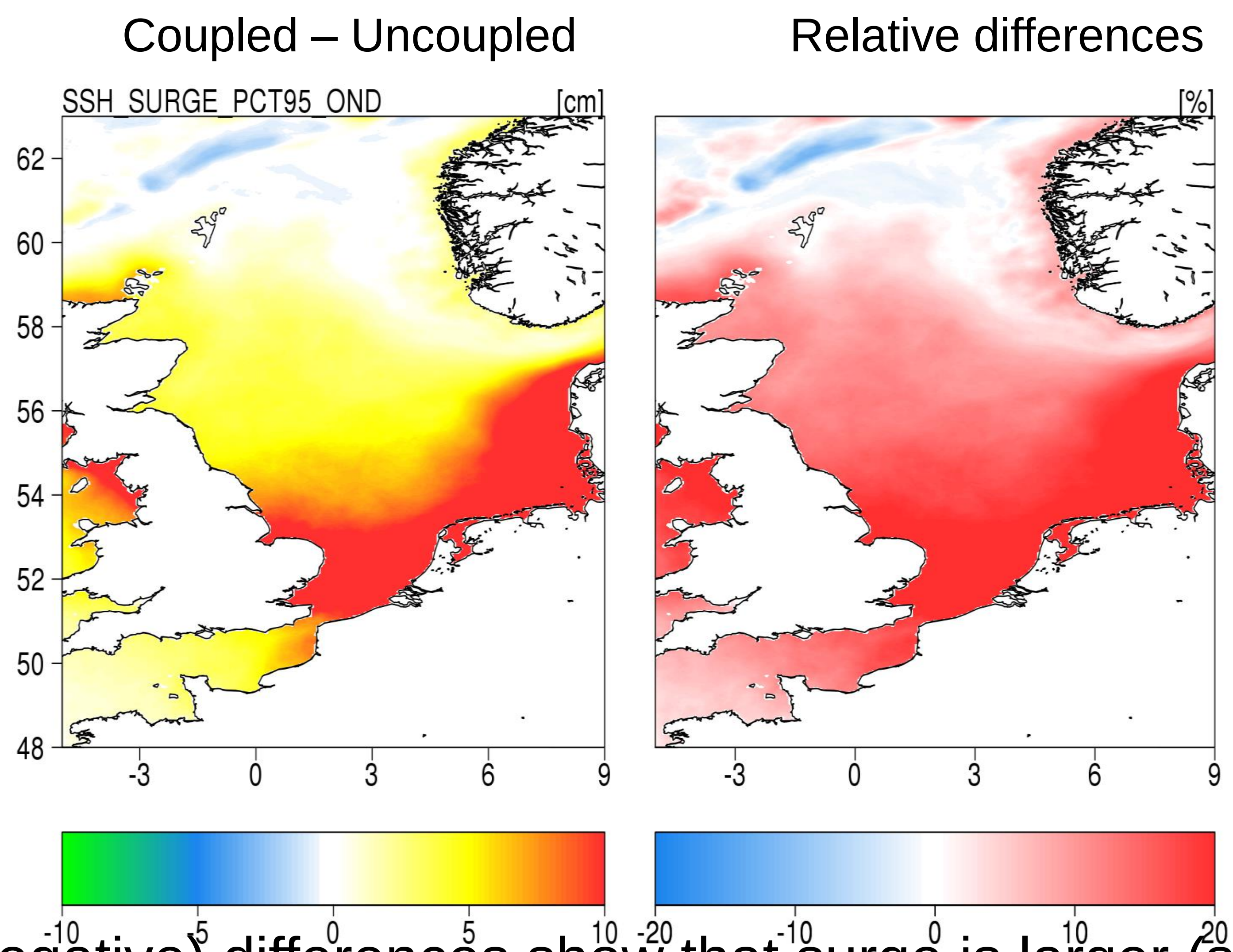
PCT 95 GCOAST



Positive (negative) differences show that surge is larger (smaller) due to wave-coupling

Impact of wave coupling: SSH Surge 2010-2018 (PCT95 JAS)

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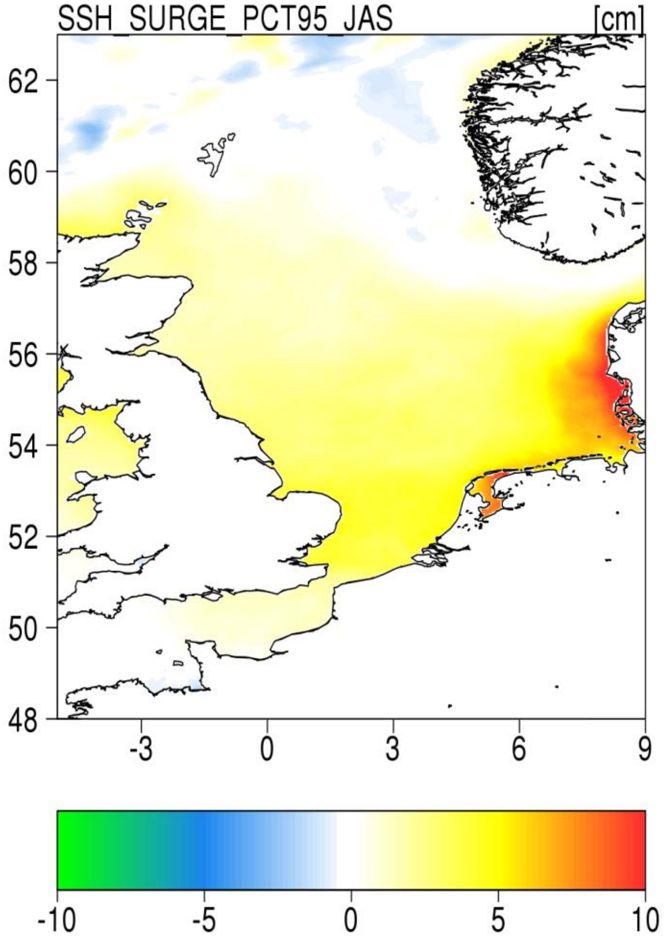
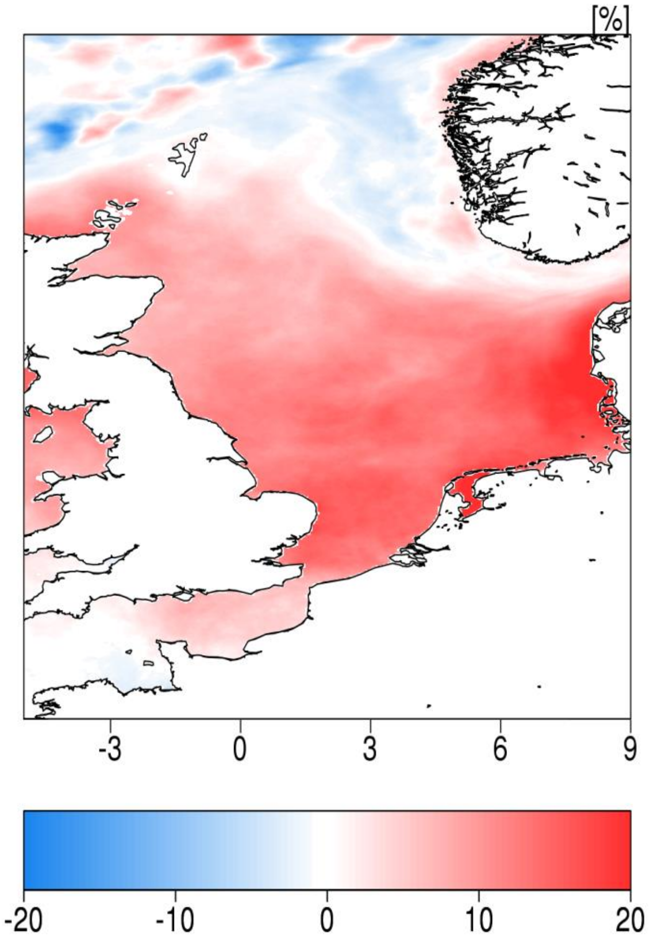
PCT 95 GCOAST NEMO-WAM V/S NEMO

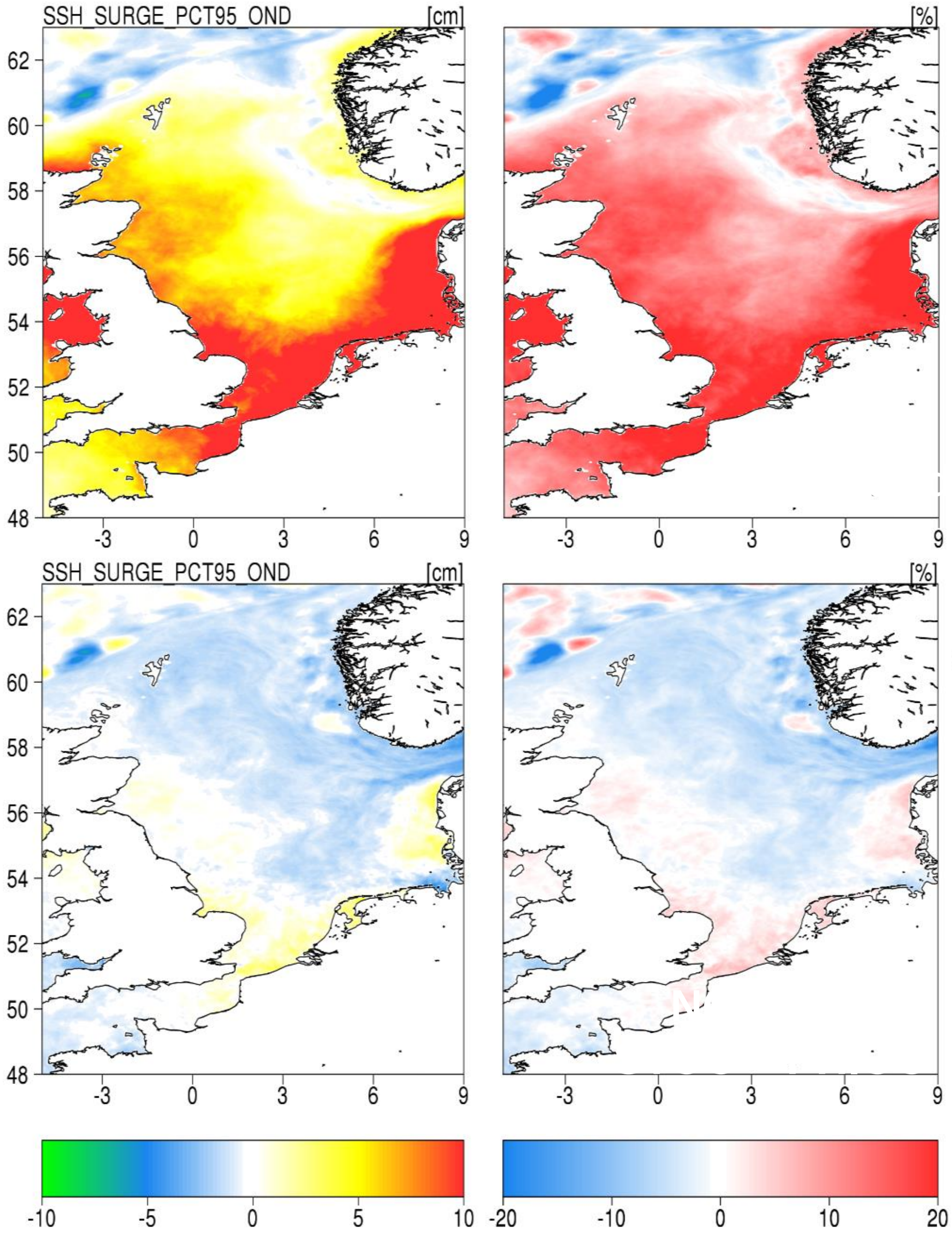
Coupled – Uncoupled

Relative differences





Impact of wave coupling: SSH Surge (PCT95 OND)



PCT95
Fully Coupled versus NEMO only

NO Sea-state dependent momentum flux

Left Panels (a) and (c): Coupled – Uncoupled

Right Panels (b) and (d): Relative differences

Impact of wave coupling: SSH Surge (PCT95 OND)

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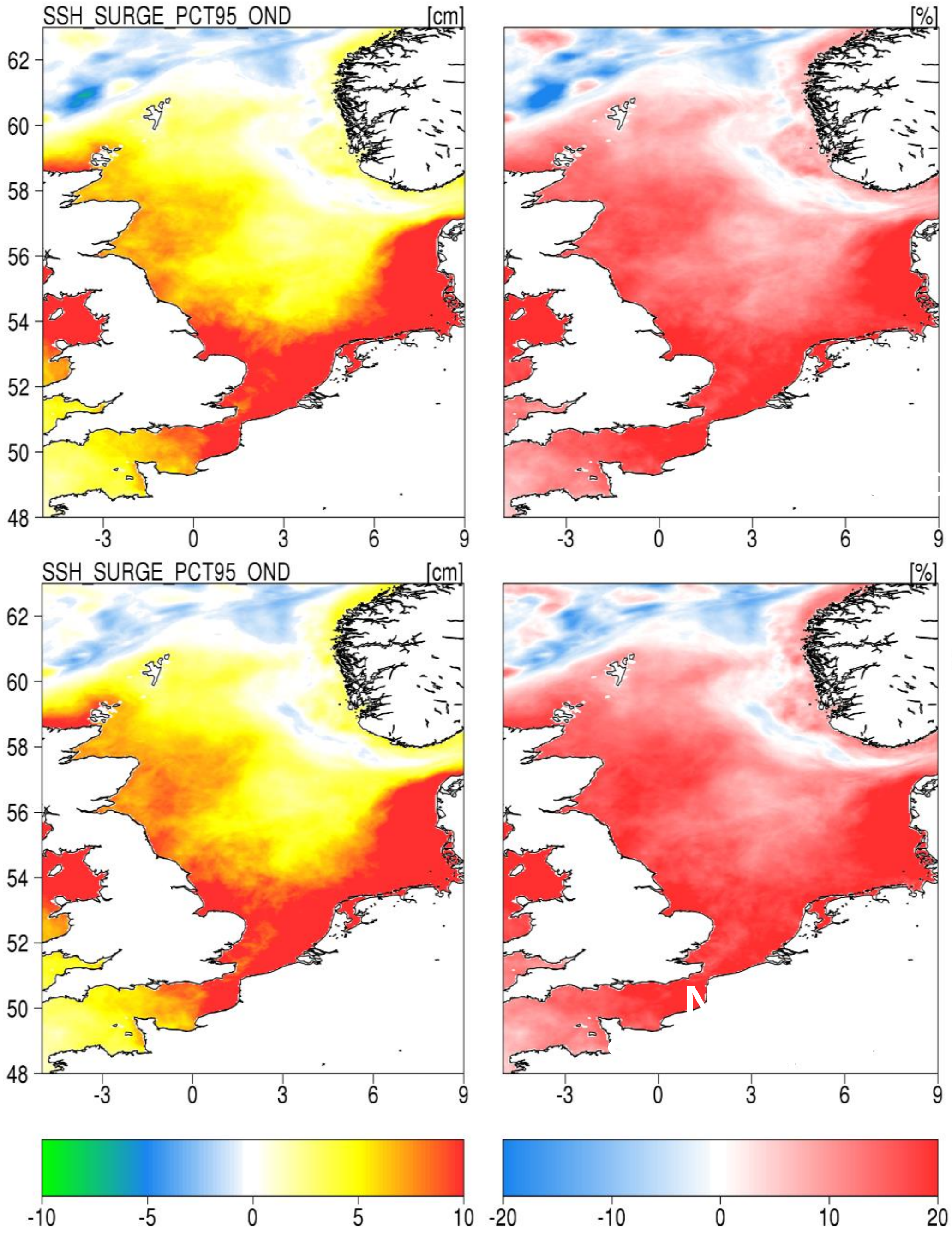

PCT95
Fully Coupled versus NEMO only

NO Sea-state dependent energy flux

Left Panels (a) and (c): Coupled – Uncoupled

Right Panels (b) and (d): Relative differences

EXTREME RIVER RUN-OFF

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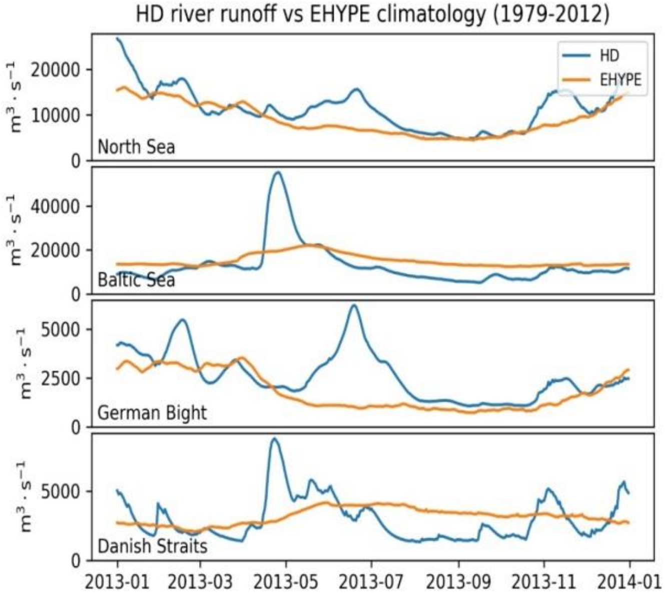
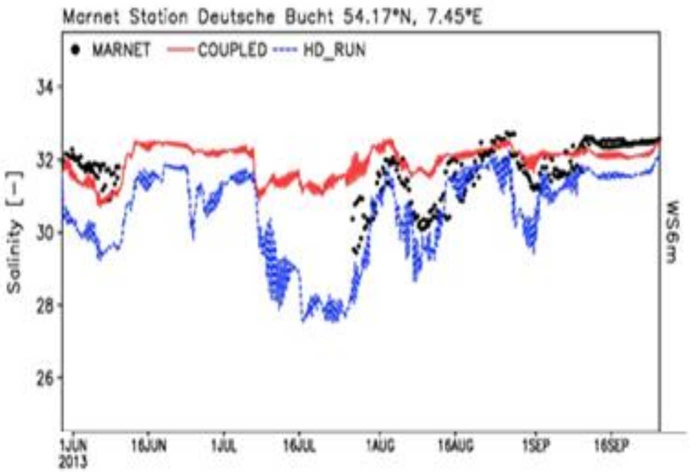
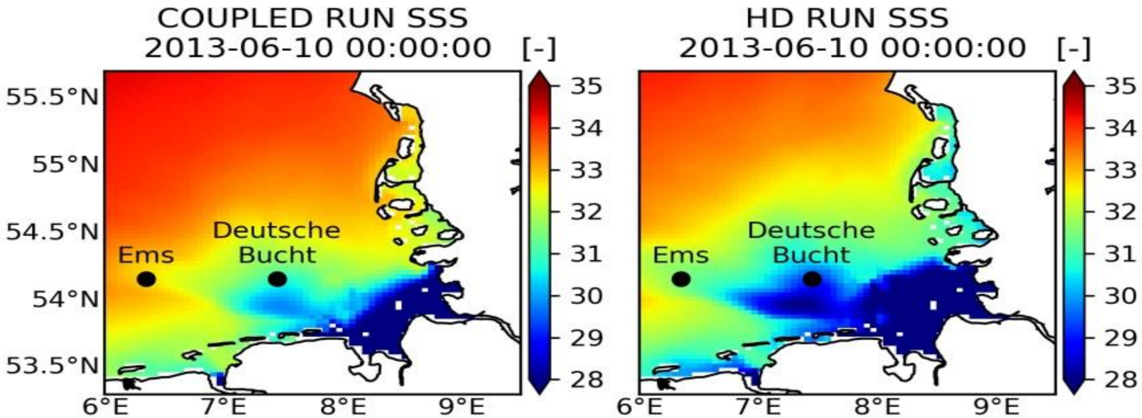
Zentrum für Material- und Küstenforschung

Elbe Flood June, 2013







Lauenburg old town (welt.de &landeszeitung,de)

Summary

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- A coupled WAM-(COSMO)-NEMO- model has been implemented and applied for the North Sea - Baltic Sea and new parameterizations added and tested.
- Several wave impacts on the upper ocean, i.e., Stokes-Coriolis forcing, sea-state-dependent momentum and TKE flux, and Stokes tracer and mass advection, are introduced into the coupled system.
- The sea-state-dependent momentum flux (momentum) proved to be of greater importance than the energy flux (TKE)) and Stokes drift influences in terms of Stokes-Coriolis forcing and Stokes tracer and mass advection for the surge.
- Storm surge of coupled model simulations showed better agreement with observations that the stand-alone NEMO.
- Paves the road to more realistic simulations in both operational forecasting systems and climate studies

Thank you
for your attention!

Challenge: keep in mind the questions

- Can coupled predictions improve atmospheric, wave, ocean, and/or hydrological predictability?
- How do physical processes effect storm surge predictions – improving of forecasting skills - do we consider the most important ones while making water level predictions?
- What are the optimal scales/resolution (coastal applications)?
- How do we deal with open boundary conditions problem (nested-grid v/s unstructured grid modelling)?
- What is an optimal integrated system for the coastal ocean predictions?
- What is the impact of severe weather on coasts?
- How to add Land/Hydrography models?
- What are the users demands

Impact of Hydrodynamic Forcing on Waves

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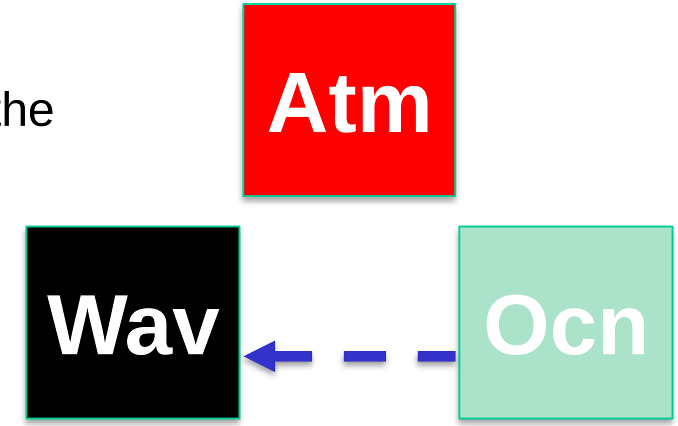
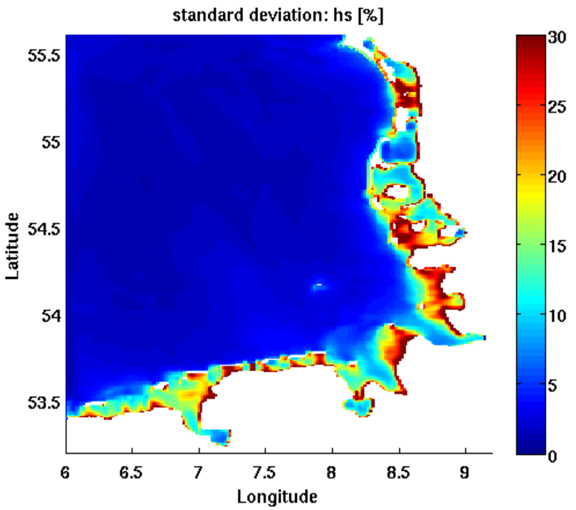
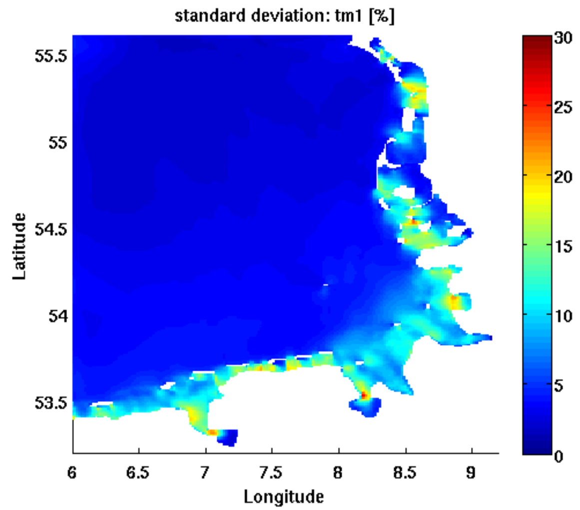
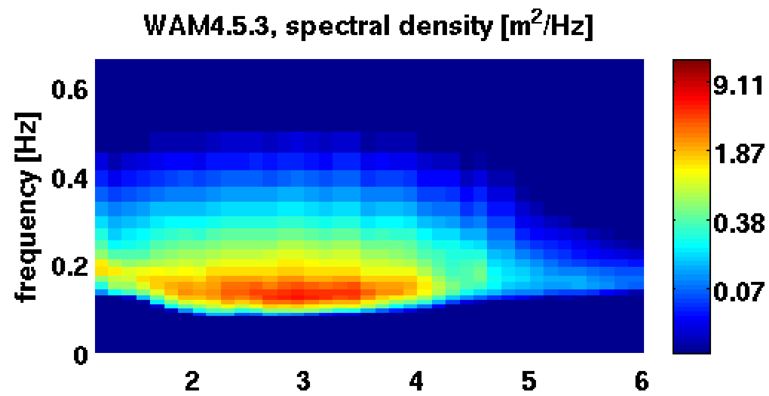
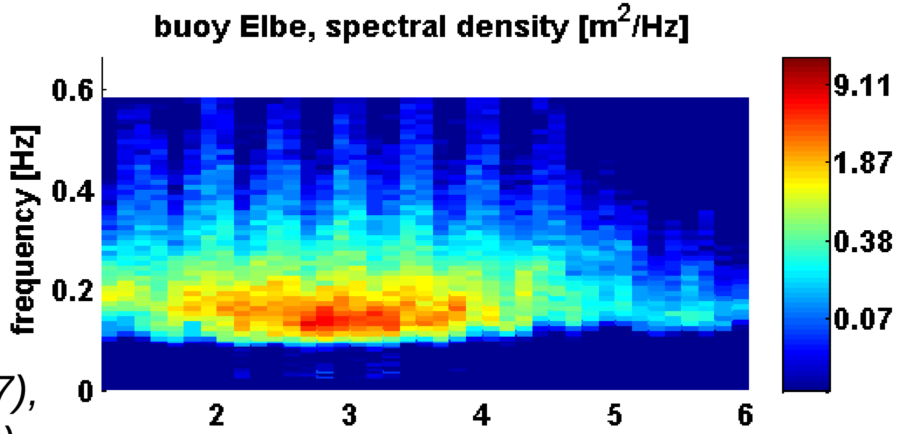
- in the open North Sea nearly no difference is found
- significant differences (30% hs, 10-15% tm1) near the coast and in the Wadden Sea
  (mainly due to water depth changes)
- small areas where STD of tm1 up to 30% (Doppler Shift)

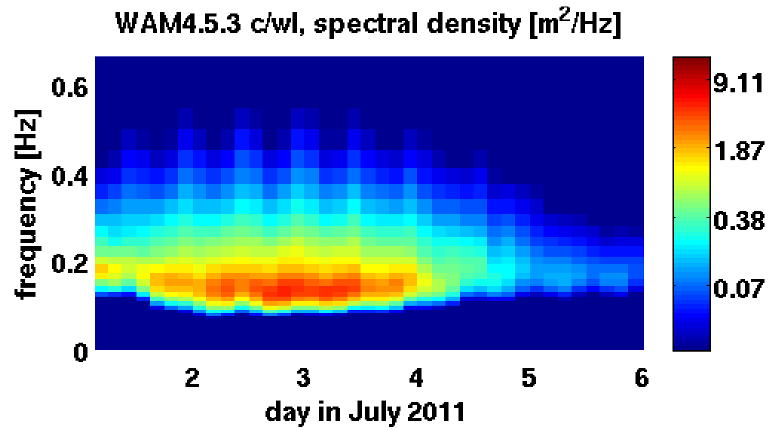












Staneva et al. (2017), Staneva et al. (2019)

Sinergy with observations:
wave-circulation coupling for drift estimation

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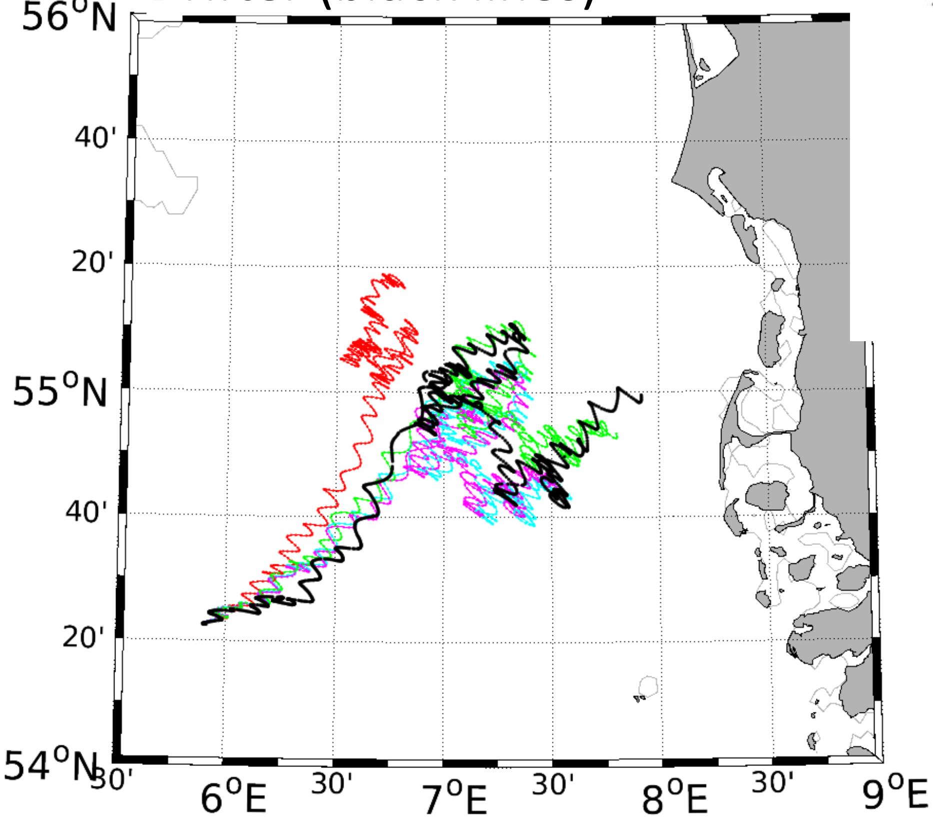
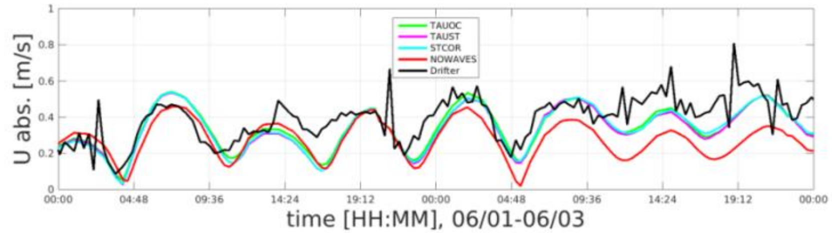
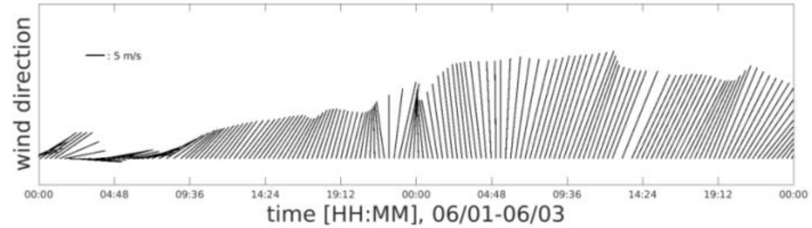
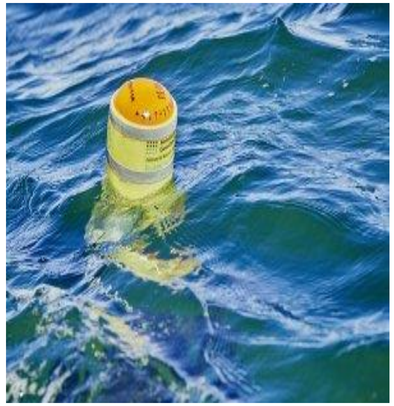
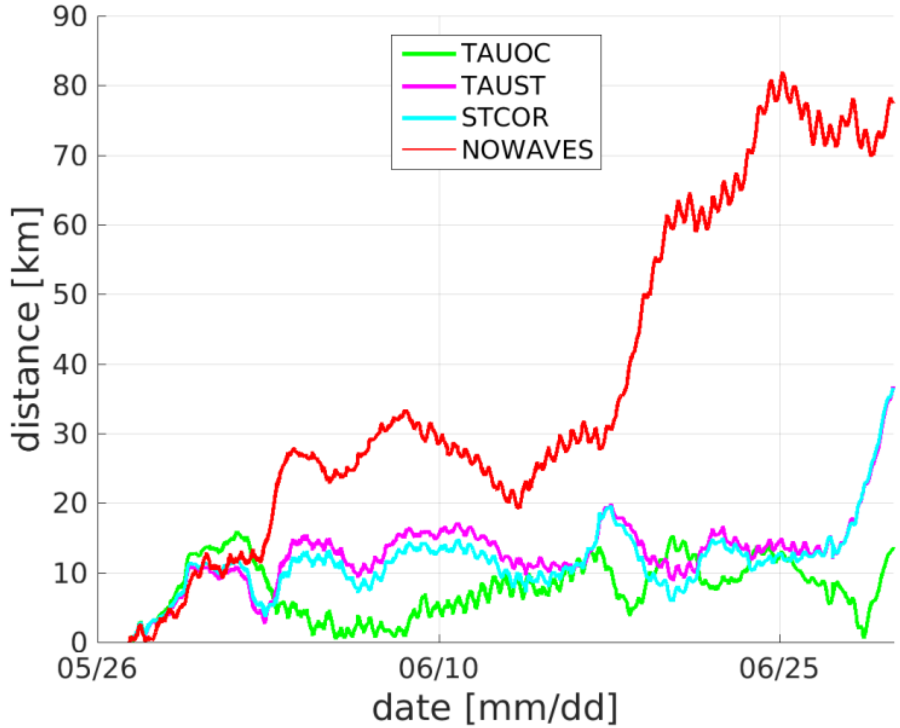
Drifter (black lines)











Example:
- Search&rescue prediction
- Oil spill

Stokes-Coriolis forcing

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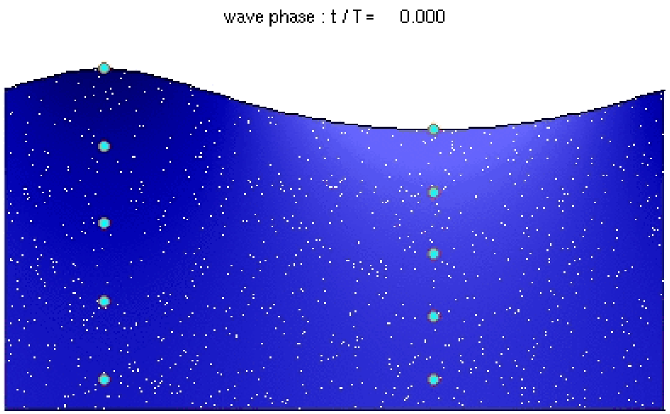
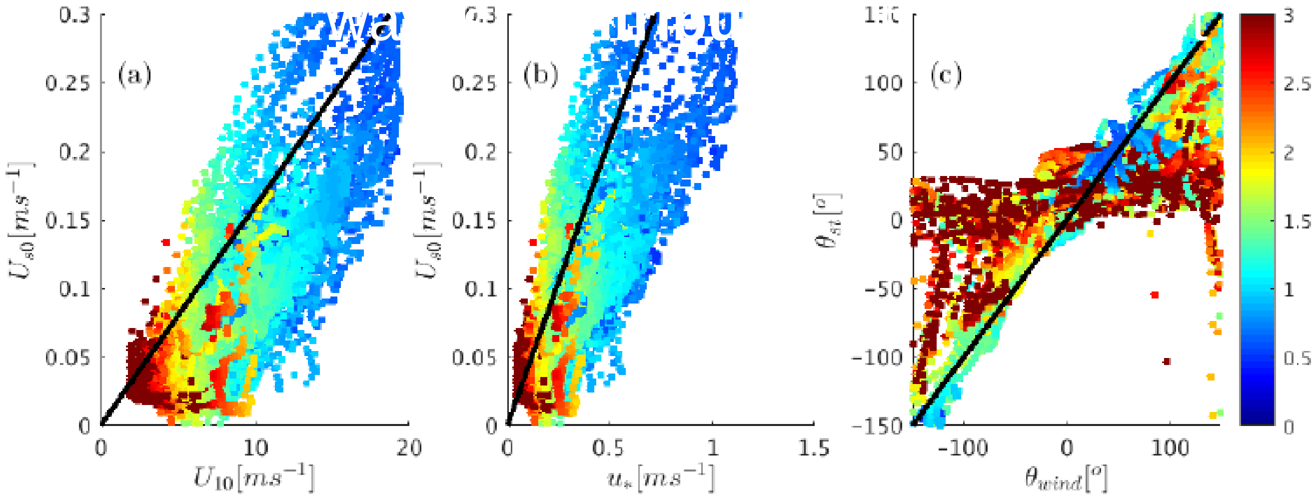


http://en.wikipedia.org/wiki/Stokes_drift

The Stokes drift –> WAM



Momentum equations in NEMO:

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho_w}\nabla p + \mathbf{u} \times f\hat{\mathbf{z}} + \mathbf{u_S} \times f\hat{\mathbf{z}} + \mathbf{D^u} + \mathbf{F^u}$$

Stokes drift profile under Phillips approximation: Breyvik et al., (2016)

$$u_S(z) = u_{s0}\left[e^{-2\bar{k}|z|} - \beta\sqrt{2\pi\bar{k}|z|}\,\mathrm{erfc}(\sqrt{2\bar{k}|z|})\right]$$

Adding Ust in advection terms!

$$\frac{Dc}{Dt} = -\mathbf{u}_s \cdot \nabla c + \mathbf{D^c} + \mathbf{F^c}$$

Wu et al. (2019)

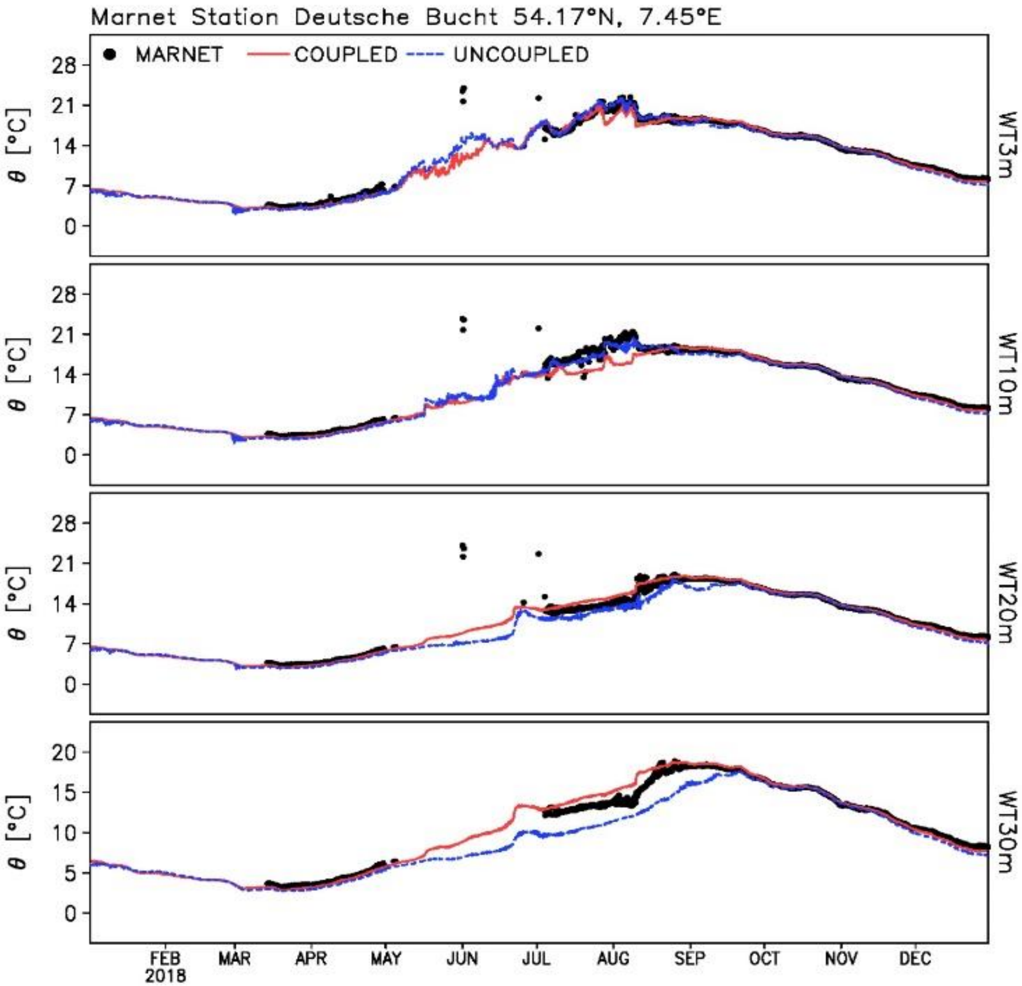
The relationship between U10 and the magnitude of the surface Stokes drift :

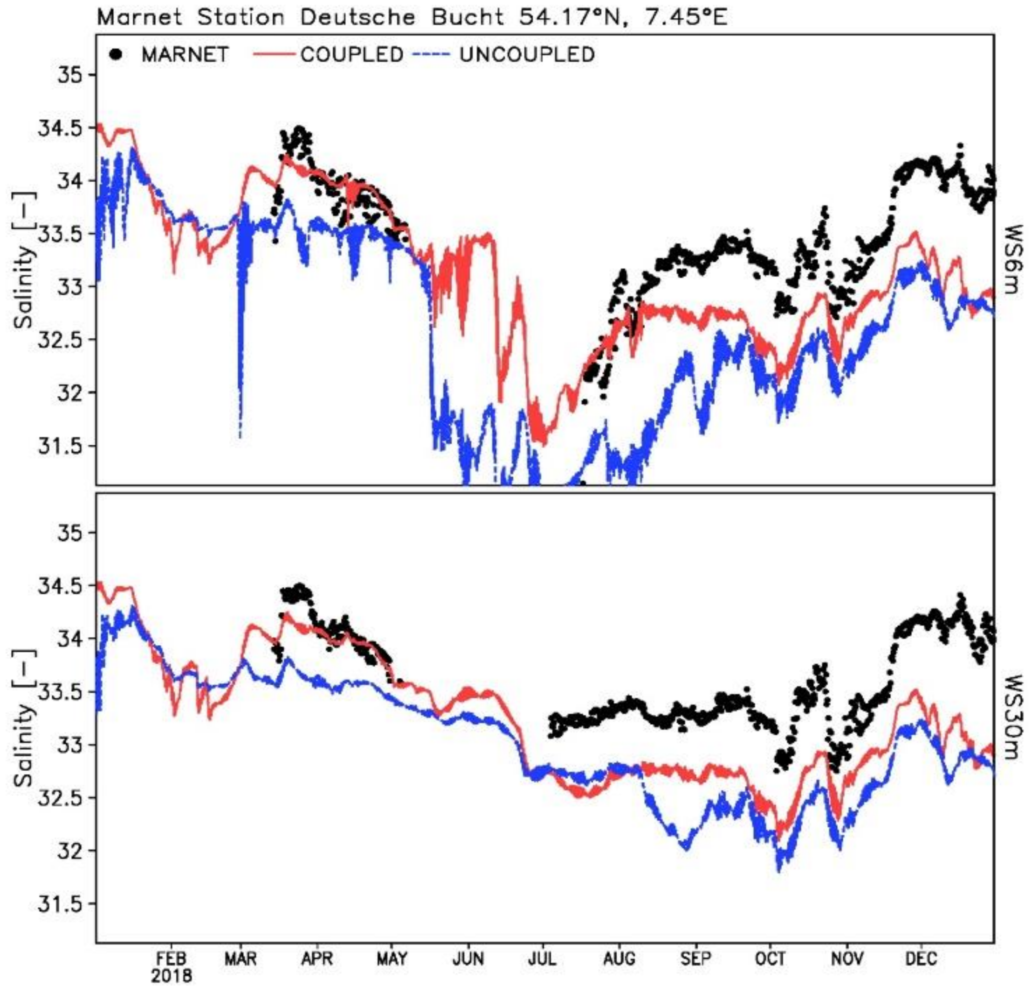
(a) black line represents the Ust =0:016 U10 (Li and Garrett, 1993);

(b) Ust = 0:377 Tau $^{1/2}$ (Madec et al., 2015);

(c) the surface Stokes drift direction and the direction of U10 The color represents the wave age

Validation MARNET (Deutsche Bucht)





Physical processes forming wave-circulation interaction: Momentum Flux

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The wave modified drag coefficient: (computed from WAM)

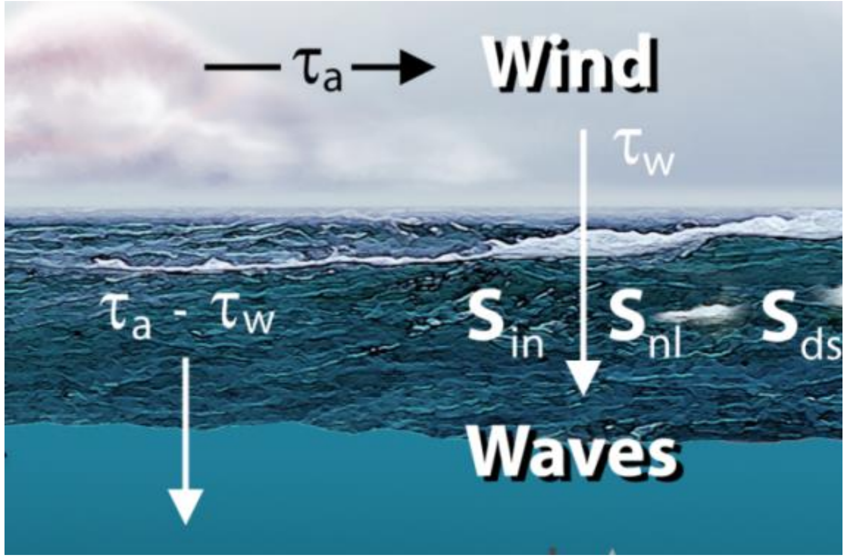
$$C_D = \frac{\kappa^2}{\log^2(10/z_0)}$$

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 contribution of non-linear term Snl has been recently considered

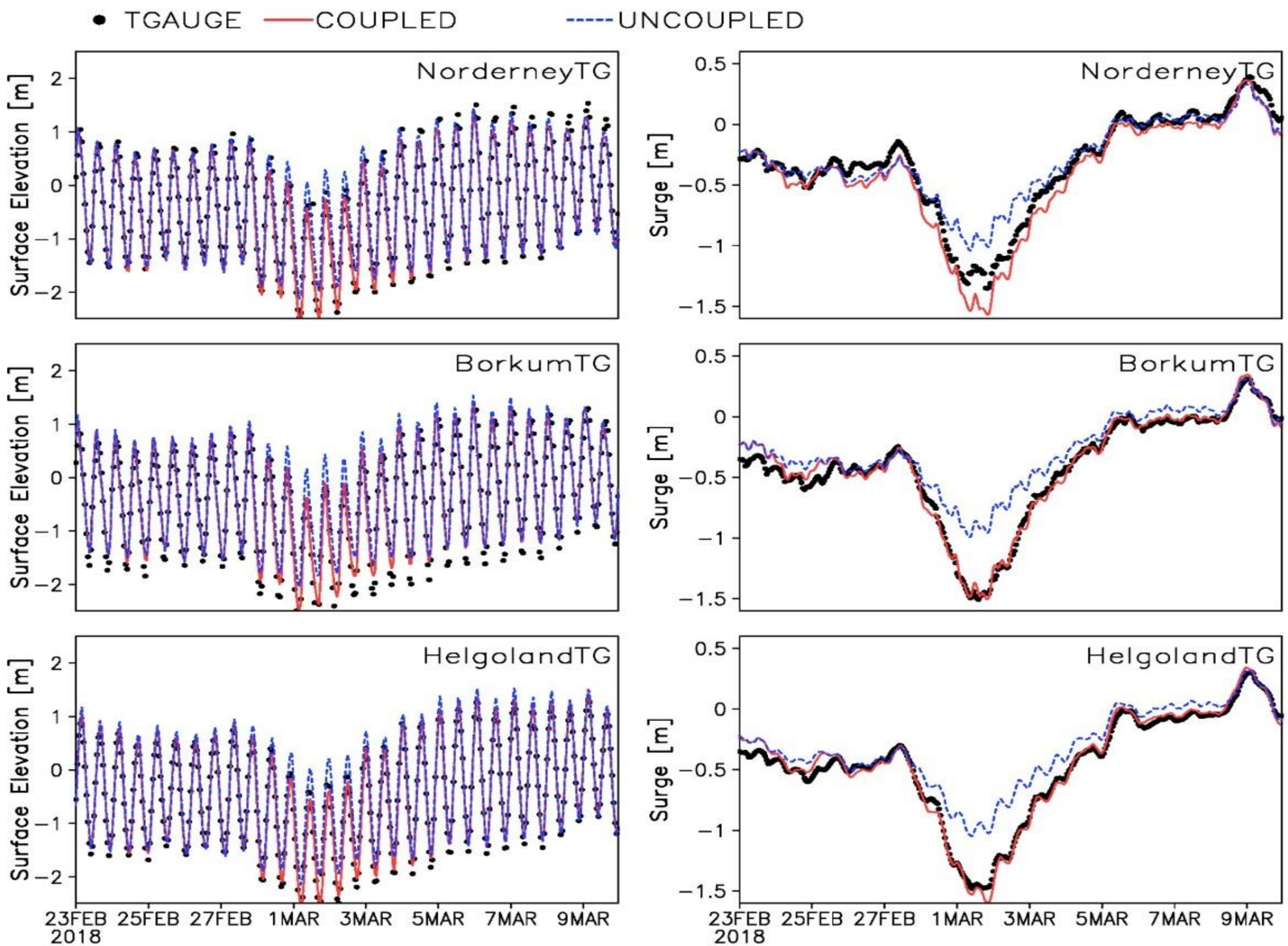
The stress is now estimated by WAM (4.6.2) and applied in NEMO is a vector instead a scalar: tau_oc_x, tau_oc_y



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

The stress from waves as a normalized quantity (normalized momentum flux) applied as a factor to the air-side stress in NEMO

VAL


TGAUGE
COUPLED
UNCOUPLED
NorderneyTG
BorkumTG
HelgolandTG
Surface Elevation [m]
Surge [m]
23FEB 2018
25FEB
27FEB
1MAR
3MAR
5MAR
7MAR
9MAR

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

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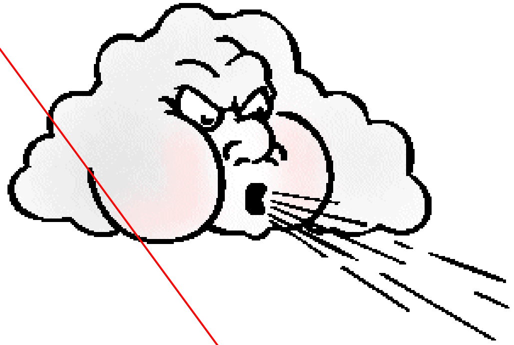
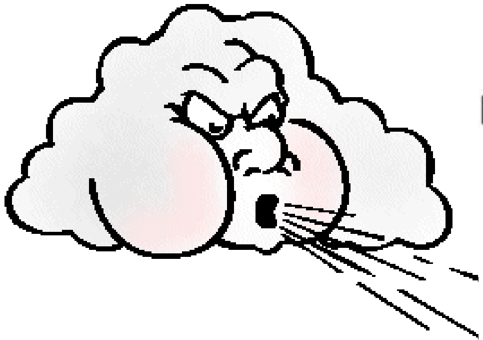


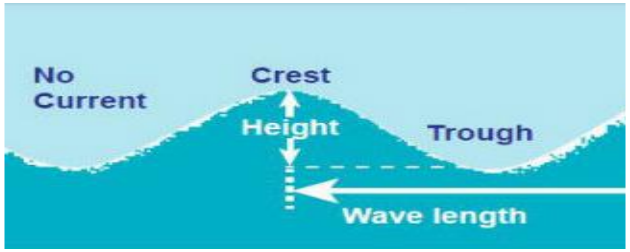
$$\vec{\tau} = c_{aw}^{d} \, \rho_a \left|\vec{U}_{10}\right| \vec{U}_{10}$$

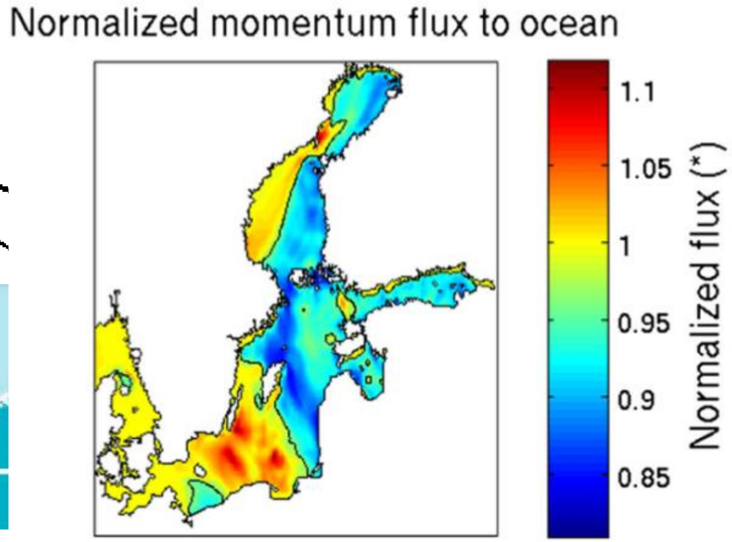
$$c_{aw}^{d} \times 10^3 = \begin{cases} 1.2 & : 0 < \left|\vec{U}_{10}\right| \le 11 m/s \\ 0.49 + 0.065\left|\vec{U}_{10}\right| & : 11 < \left|\vec{U}_{10}\right| \le 22 m/s \end{cases}$$

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

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







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

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

Storm Surge in Hamburg 1962

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

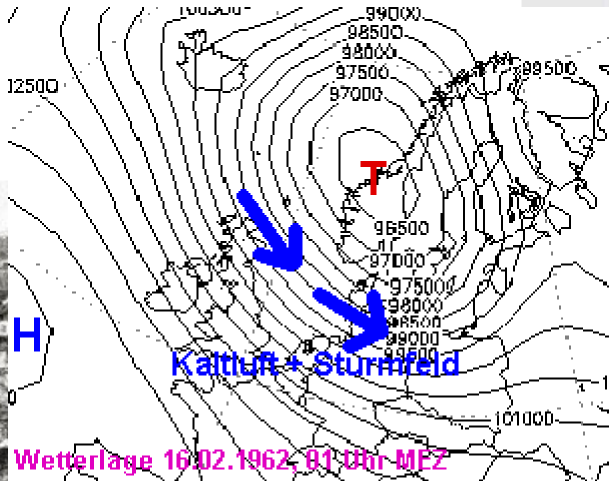

Bild Zeitung

400 Tote

Seuchentrupps im Flutgebiet!

Chlor für die tote Zone

Drei Tage Staatstrauer in Hamburg



More extreme weather and rising sea levels

Impact of wave coupling: SSH Surge (PCT95 JAS)

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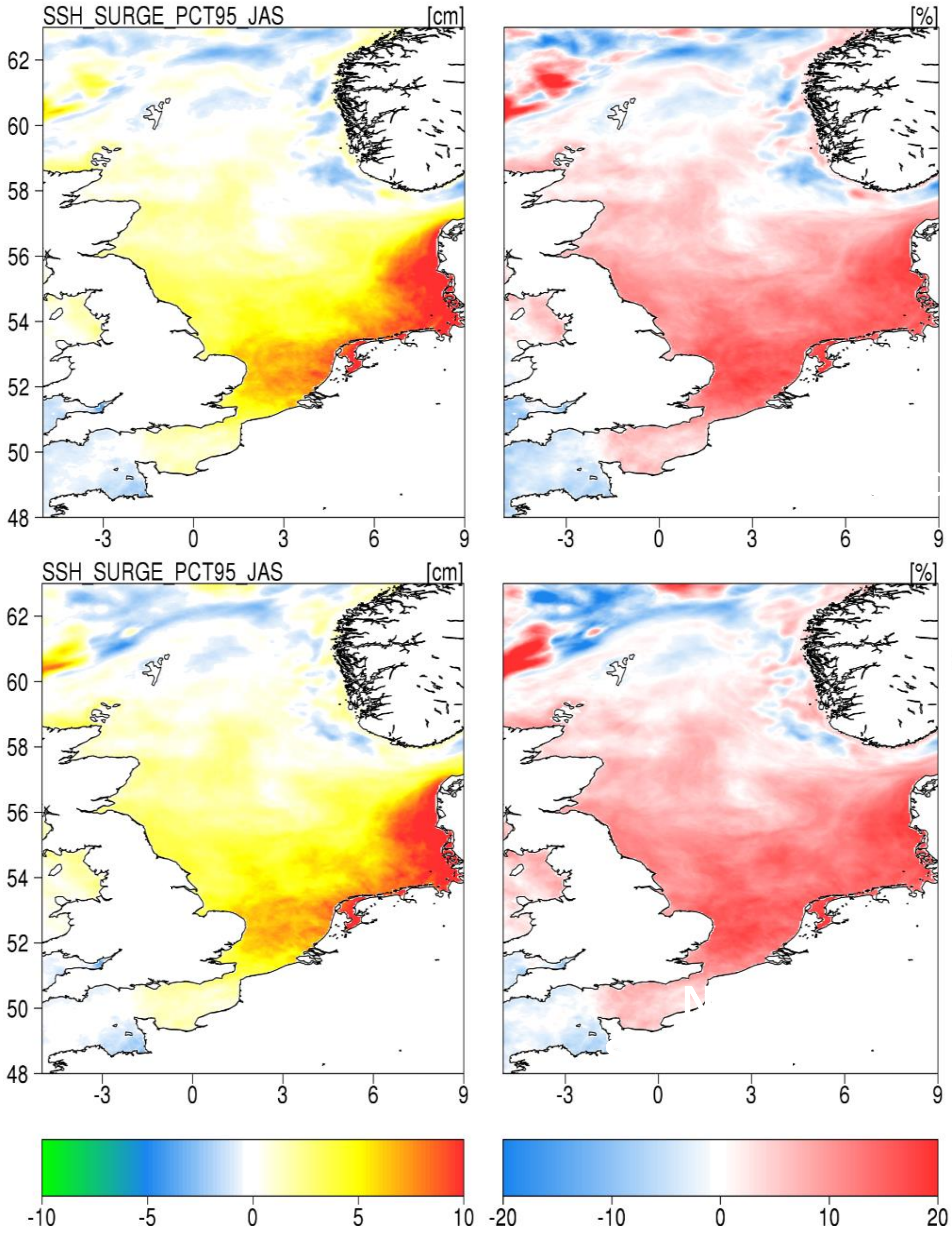

PCT95
Fully Coupled versus NEMO only

NO Sea-state dependent energy flux

Panels (a) and (c): Coupled – Uncoupled

Panels (b) and (d): Relative differences

29 September, 2016 15:00 h : Storm Walpuga

Helmholtz-Zentrum Geesthacht
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NEMO
(SSL-NOSSL runs)