Response of water temperature to surface wave effects in the Baltic Sea: simulations with the coupled NEMO-WAM model

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Outline

- Motivation and objective
- Model setup for the North Sea-Baltic Sea
- Physical processes forming wave-circulation interaction
- Wave impact to temperature
- Conclusions
Motivation and objective

- Traditionally ocean models and wind wave models have been applied separately.

- Separating wave and ocean models is pragmatic, but leads to violation of energy and momentum conservation.

- During EU-FP7 project MyWave a coupled global scale wave-circulation model was developed (Breivik et al, 2015).

- Applying the coupled model to World Ocean, a reduction of bias between modelled and measured SST was noted.

- Here we demonstrate the importance of coupling on regional scales and focus on the Baltic Sea.
Model setup (1): geographical view

Blue solid lines – model open boundaries

Blue dashed box – our analysis area

Red dashed lines – vertical transects
## Model setup (2) : key information

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>NEMO (version 3.4)</th>
<th>WAM (version CY40R3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling period</td>
<td>01.10.2012-30.09.2013</td>
<td>Switched on at 01.05.2013</td>
</tr>
<tr>
<td>Horizontal grid</td>
<td>2 nautical miles covering North Sea and Baltic Sea</td>
<td>Same horizontal grid. Spectral resolution: 24 directions and 25 frequencies</td>
</tr>
<tr>
<td>Vertical grid</td>
<td>56 z layers</td>
<td>N/A</td>
</tr>
<tr>
<td>Integration timestep(s)</td>
<td>10 s for barotropic part; 180 s for baroclinic part</td>
<td>30 s</td>
</tr>
<tr>
<td>Initial field</td>
<td>Janssen et al. (1999) climatology for T &amp; S</td>
<td>Coldstart</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>OSU tides, Janssen et al. (1999) climatological periodic boundary</td>
<td>No</td>
</tr>
<tr>
<td>Atmospheric forcing</td>
<td>German Weather Service (DWD), 1 h. Meridional and zonal wind speed; shortwave and</td>
<td>Same source, but only wind components</td>
</tr>
<tr>
<td></td>
<td>longwave radiation; air temperature; humidity; air pressure</td>
<td></td>
</tr>
<tr>
<td>Vertical diffusion scheme</td>
<td>Generic Length Scale (k-(\varepsilon)), Umlauf and Burchard (2003)</td>
<td>N/A</td>
</tr>
<tr>
<td>Ice</td>
<td>LIM2</td>
<td>No ice, as wave model input was used starting from May</td>
</tr>
</tbody>
</table>
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Physical processes forming wave-circulation interaction (1)

1) Sea-state dependent momentum flux
2) Sea-state dependent energy flux
3) Stokes-Coriolis forcing

Physical processes forming wave-circulation interaction (2): ocean side stress

\[ \bar{\tau} = c_{aw}^d \rho_a |\bar{U}_{10}| \bar{U}_{10} \]

\[ c_{aw}^d \times 10^3 = \begin{cases} 1.2 & 0 < |\bar{U}_{10}| \leq 11 \text{ m/s} \\ 0.49 + 0.065|\bar{U}_{10}| & 11 < |\bar{U}_{10}| \leq 22 \text{ m/s} \end{cases} \]

\[
\frac{\partial U}{\partial t} - fV = -gH \frac{\partial \xi}{\partial x} + \tau_x - \tau_{xb} \\
\frac{\partial V}{\partial t} + fU = -gH \frac{\partial \xi}{\partial y} + \tau_y - \tau_{yb}
\]

\[
\tau_{oc} = \tau_a - \rho_w g \int_0^{2\pi} \int_0^\infty \frac{k}{\omega} (S_{in} + S_{ds}) \, d\omega \, d\theta
\]

\[
\frac{\partial U}{\partial t} - fV = -gH \frac{\partial \xi}{\partial x} + \tau_{ocx} - \tau_{xb} \\
\frac{\partial V}{\partial t} + fU = -gH \frac{\partial \xi}{\partial y} + \tau_{ocy} - \tau_{yb}
\]
Physical processes forming wave-circulation interaction (3): storm on 22 July 2013

In uncoupled NEMO, \(\alpha\) is constant = 100

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

\[
K_q \frac{\partial q^2}{\partial z} = 2\alpha_{CB} u_r^3, \quad z = 0.
\]
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## Simulations

<table>
<thead>
<tr>
<th>Simulation name</th>
<th>Description of simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>Control simulation, without wave model</td>
</tr>
<tr>
<td>ALLWAVE</td>
<td>All three wave processes included</td>
</tr>
<tr>
<td>TAUOC</td>
<td>Sea state dependent momentum flux included only</td>
</tr>
<tr>
<td>BREAK</td>
<td>Sea state dependent energy flux included only</td>
</tr>
<tr>
<td>STCOR</td>
<td>Stokes-Coriolis forcing included only</td>
</tr>
</tbody>
</table>
Results (1): Baltic Proper, water temperature

Time-depth profiles of measured temperature, control run (CTRL) and the all-wave processes (ALLWAVE) run at a buoy station in Baltic Proper
Results (2): BIAS of SST

Bias (model mean minus mean of measurements) of simulated SST with respect to OSTIA data in the Baltic Proper.
Results (3): Impact of waves to SST

Sea surface temperature differences between ALLWAVE and CTRL averaged over a 3-month period, from 01 June 2013 to 31 August 2013.
Results (4): Impact of waves to bottom temperature

Sea bottom temperature differences between ALLWAVE and CTRL averaged over a 3-month period, from 01 June 2013 to 31 August 2013.
Results (5): Impact of waves, vertical/transect

a) ALLWAVE-CTRL @ lat 56.0917°

b) BREAK-CTRL @ lat 56.0917°

c) STCOR-CTRL @ lat 56.0917°

d) TAUOC-CTRL @ lat 56.0917°
Results (6): Impact of waves, vertical/transect

- a) ALLWAVE-CTRL @ lon 19.3472°
- b) BREAK-CTRL @ lon 19.3472°
- c) STCOR-CTRL @ lon 19.3472°
- d) TAUOC-CTRL @ lon 19.3472°
Conclusions

- The effects of wind waves on the Baltic Sea water temperature has been studied by coupling the hydrodynamical model NEMO with the wave model WAM.

- The results indicate a pronounced effect of waves on surface temperature, on the distribution of vertical temperature and on upwelling’s.

- In northern parts of the Baltic Sea a warming of the surface layer occurs in the wave included simulations. This in turn reduces the cold bias between simulated and measured data. The warming is primarily caused by sea-state dependent energy flux.

- During the summer the wave induced water temperature changes were up to 1 °C.