Storm surge modelling in the Baltic Sea using the high resolution PM3D model

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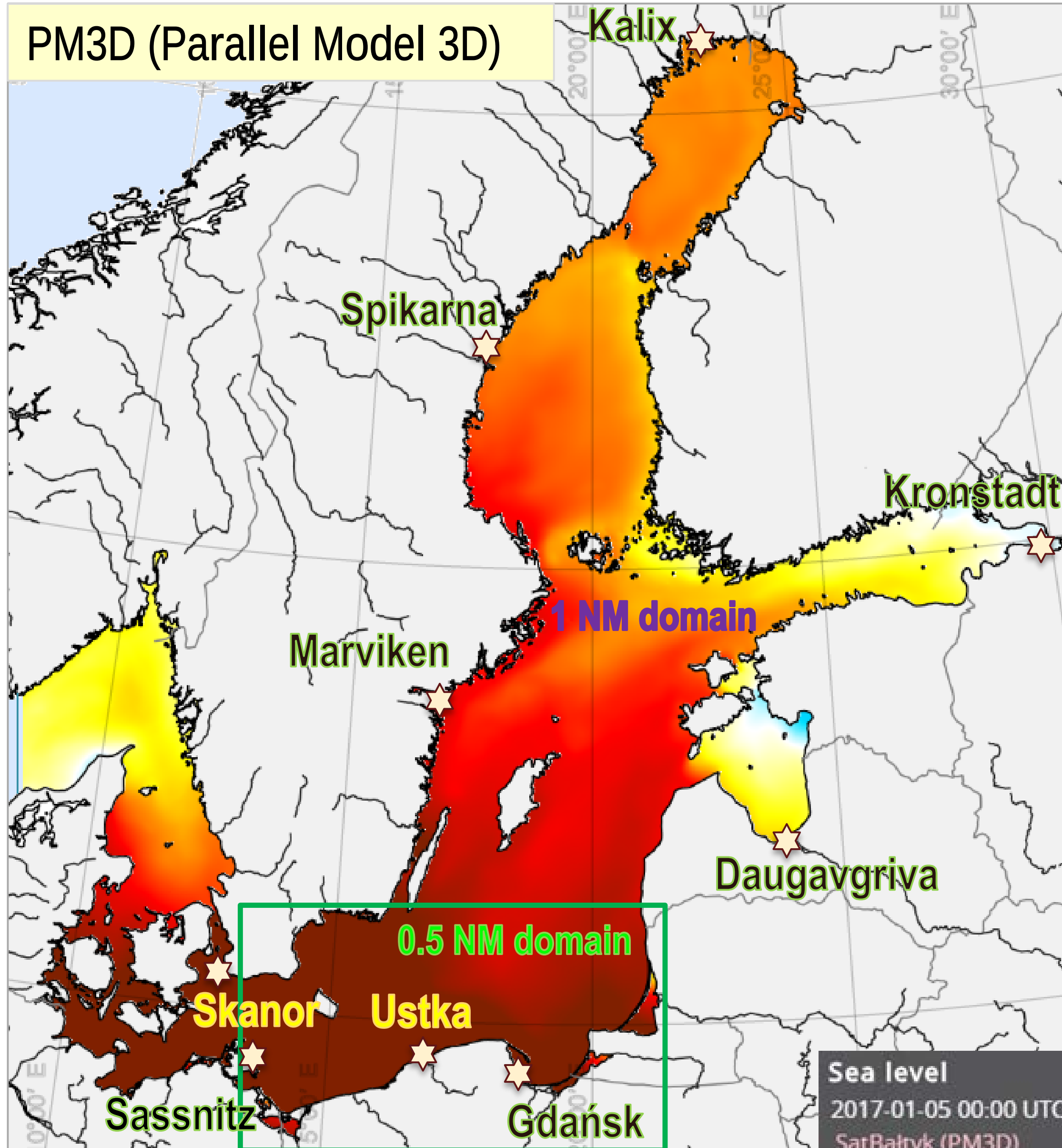
- Parallel version of the 3D hydrodynamic model of the Baltic Sea (PM3D);
- Developed at Institute of Oceanography, UG, Poland;
- Based on the Princeton Ocean Model (Blumberg and Mellor, 1987);
- Adapted to the Baltic Sea by Kowalewski (1997);
- The operational version of the M3D model run in 1999;
- The operational version of the PM3D model run in 2015 within the SatBałtyk System;
- Two grids with different spatial resolution used: 1 NM (c. 1.8 km) for the Baltic Sea and the Skagerrak, and 0.5 NM (c. 0.9 km) for the southern part of the Baltic.



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PM3D (Parallel Model 3D)

- At the open boundary located between the North Sea and the Skagerrak, radiation boundary condition for the vertically averaged flows with hourly sea level readings applied;
- Meteorological data (wind, atmospheric pressure, air temperature, and vapour pressure) supplied by the operational 4 km resolution grid Unified Model (UM), run by ICM, University of Warsaw (Herman-Iżycki et al., 2002);
- Climatic monthly mean runoffs of more than 150 rivers discharging into the Baltic Sea involved (http://nest.su.se/bed/);
- The solar energy input derived from the diagnostic SolRad model which estimates the solar energy radiation flux using cloudiness determined from METEOSAT satellite data (Krężel et al., 2008);
- Assimilation of the satellite sea surface temperature data retrieved from the AVHRR and MODIS radiometers;
- As parallel calculations were used in the PM3D, the computation time for 1 day simulations in two domains, 1 NM and 0.5 NM, took 64 minutes for a computer equipped with 12-core Intel Xeon CPU X5670@2.93 GHz procesor;
- Outputs of the PM3D compared with hourly sea level readings collected at 9 tide gauges located along the Baltic coast in 2010-2015 as well as with simulations produced by the previous 3 NM grid resolution model version (M3D).

Statistical measures of the model performance

- Correlation coefficient (R):

  where s_x, s_y – standard deviations for observed and simulated values

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{s_x s_y}$$

- Root mean square error (RMSE):

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}}{N}$$

- Normalized root mean square error (NRMSE) - computed by dividing RMSE by sea level range (Z)
- Central frequency (CF) - illustrated how often the simulated water level differed from the readings by not more than ±0.15 m
- Positive outlier frequency (POF) - showed how often it was higher than the observed level by more than 0.3 m
- Negative outlier frequency (NOF) - demonstrated how often it was lower than the measured level by more than 0.3 m
- Simulations compared to sea level fluctuations recorded by tide gauges during the extreme positive and negative storm surges that occurred in 2010-2015.

Model Validation

Station	M3D	PM3D
	3 NM	1_0.5 NM
	Correlation coefficient	
Gdańsk	0.906	0.928
Ustka	0.919	0.938
Sassnitz	0.906	0.930
Skanor	0.883	0.901
Marviken	0.904	0.913
Spikarna	0.920	0.936
Kalix	0.933	0.943
Kronstadt	0.917	0.934
Daugavgriva	0.949	0.953

Model Validation

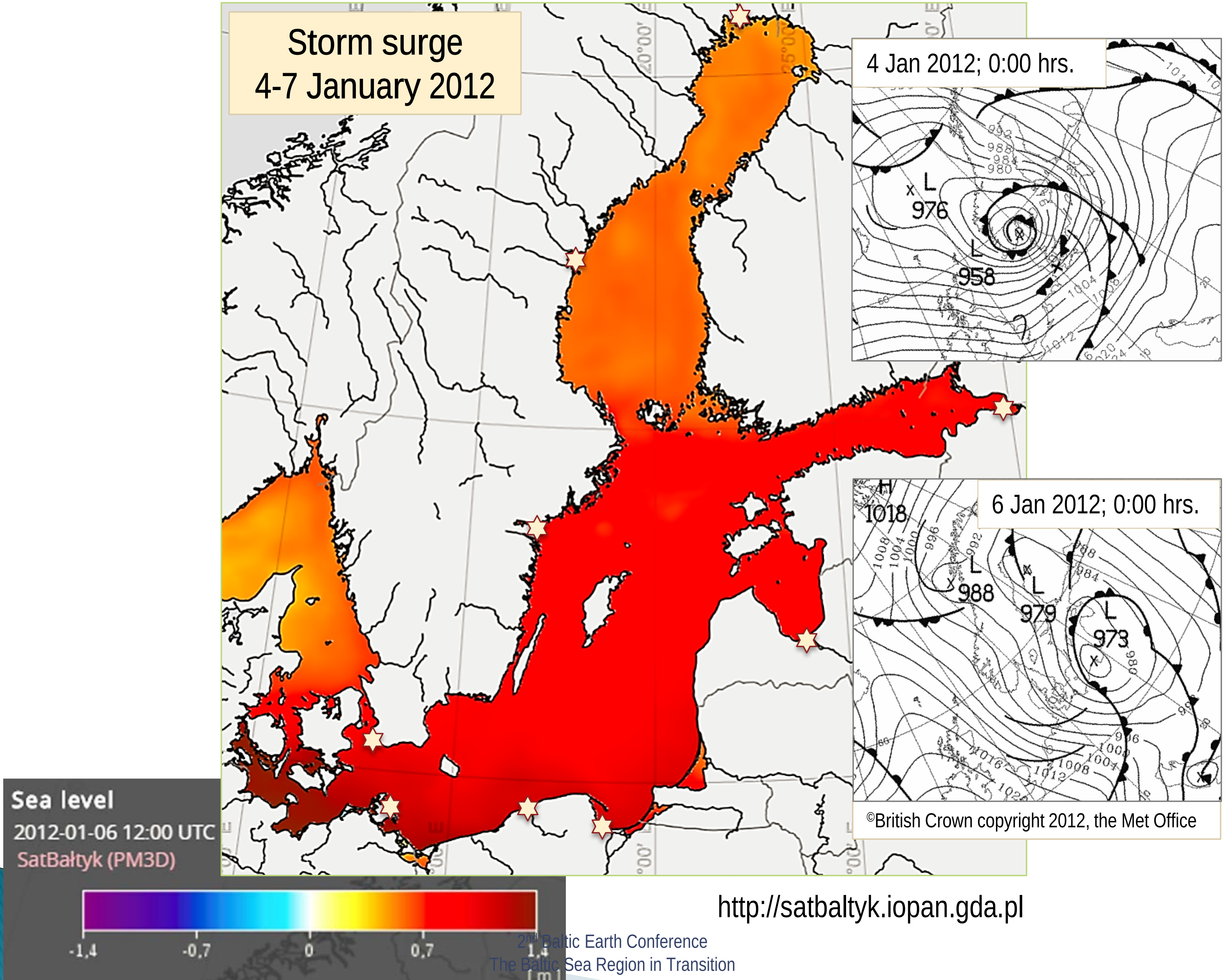
Station	M3D		PM3D	
	3 NM		1_0.5 NM	
	RMSE (m)	NRMSE (%)	RMSE (m)	NRMSE (%)
Gdańsk	0.086	4.4	0.077	3.9
Ustka	0.083	4.2	0.074	3.8
Sassnitz	0.100	4.2	0.086	3.7
Skanor	0.117	4.4	0.107	4.0
Marviken	0.081	6.3	0.078	6.1
Spikarna	0.085	4.6	0.079	4.2
Kalix	0.112	4.8	0.112	4.8
Kronstadt	0.133	5.5	0.129	5.3
Daugavgriva	0.093	4.2	0.096	4.3

Model Validation

Station	M3D			PM3D		
	3 NM			1_0.5 NM		
	CF	POF	NOF	CF	POF	NOF
Gdańsk	91.5	0.09	0.02	94.3	0.02	0.01
Ustka	92.2	0.13	0.00	95.2	0.00	0.02
Sassnitz	87.1	0.42	0.11	91.7	0.08	0.07
Skanor	81.1	1.02	0.27	84.6	0.52	0.24
Marviken	92.9	0.12	0.02	93.6	0.02	0.02
Spikarna	91.5	0.11	0,00	94.1	0.00	0.00
Kalix	82.5	0.69	0.49	82.5	0.49	0.54
Kronstadt	79.4	1.22	1.44	80.3	0.72	1.43
Daugavgriva	89.8	0.18	0.15	87.7	0.09	0.21

Extreme sea levels at the Baltic Sea coast in 2010-2015

Station	Minimum		Maximum		Sea level range
	Date	Level (m, msl)	Date	Level (m, msl)	(m)
Gdańsk	24 Nov 2014	-0.66	14 Jan 2012	1.31	1.97
Ustka	10 Dec 2014	-0.72	14 Jan 2012	1.25	1.97
Sassnitz	28 Jan 2010	-1.14	14 Jan 2012	1.22	2.36
Skanor	27 Jan 2010 6 Dec 2013	-1.48	11 Feb 2011	1.19	2.67
Marviken	27 Jan 2010	-0.59	5 Jan 2012	0.70	1.29
Spikarna	23 Mar 2013	-0.66	9 Dec 2011	1.20	1.86
Kalix	15 Oct 2010	-1.00	14 Dec 2011	1.34	2.34
Kronstadt	24 Nov 2010	-1.08	16 Nov 2010	1.36	2.44
Daugavgriva	29 Jan 2014	-0.92	7 Dec 2015	1.32	2.24



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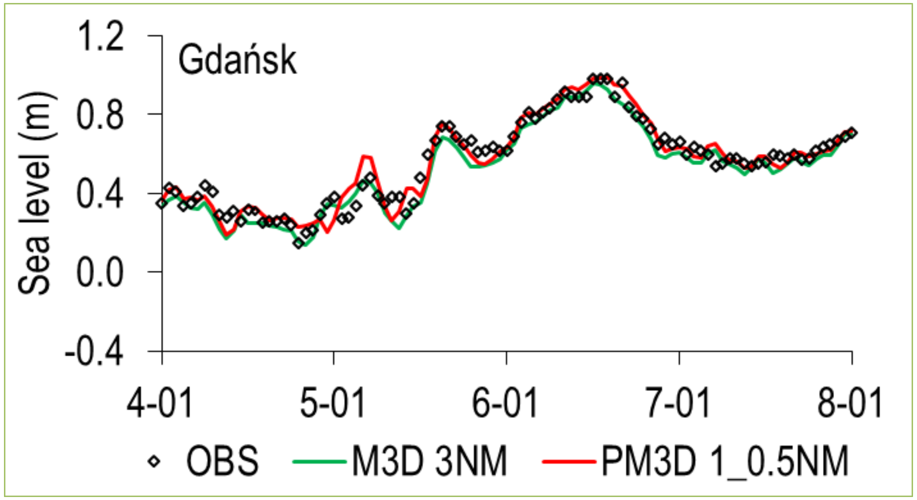
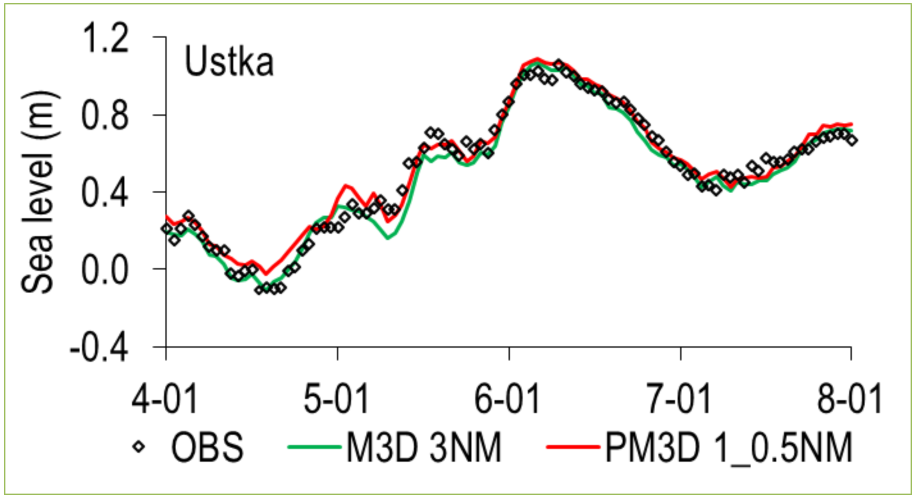
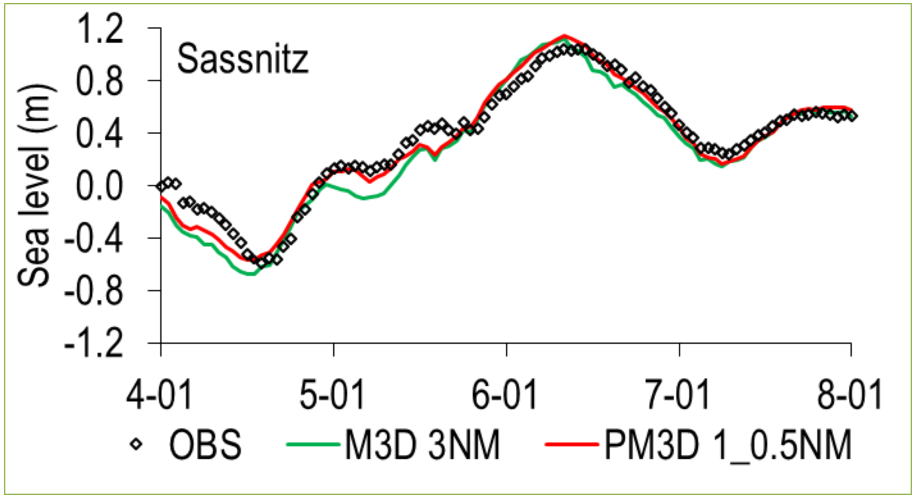
Sea level changes

4 – 7 January 2012







Sea level changes

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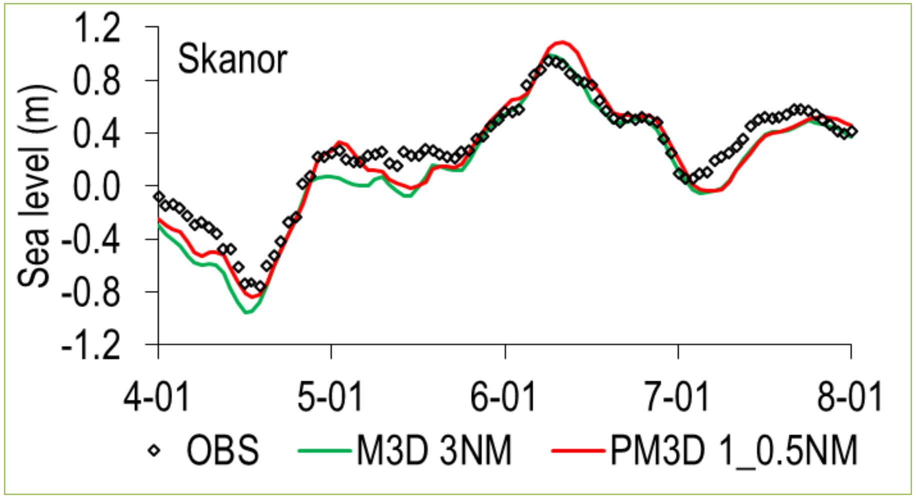

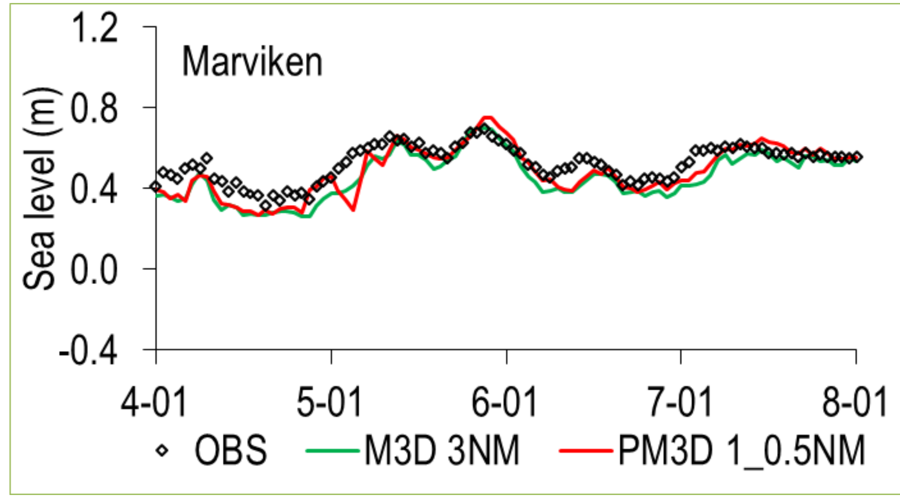

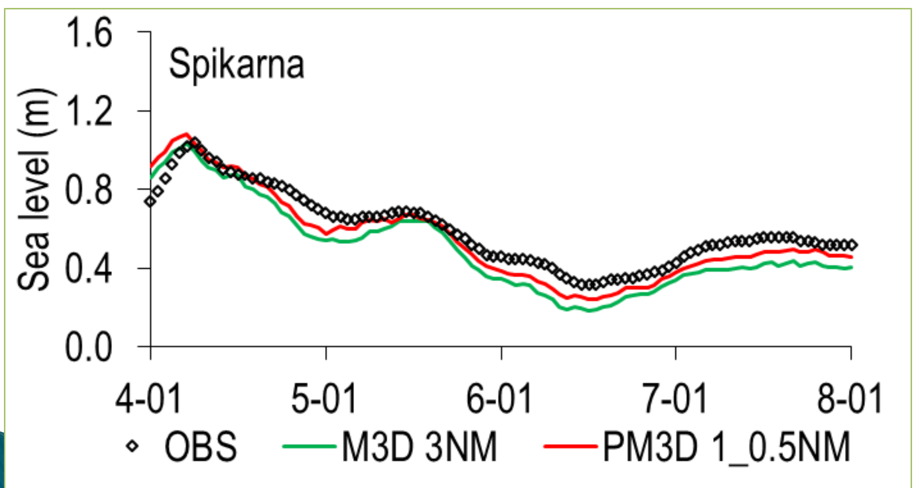

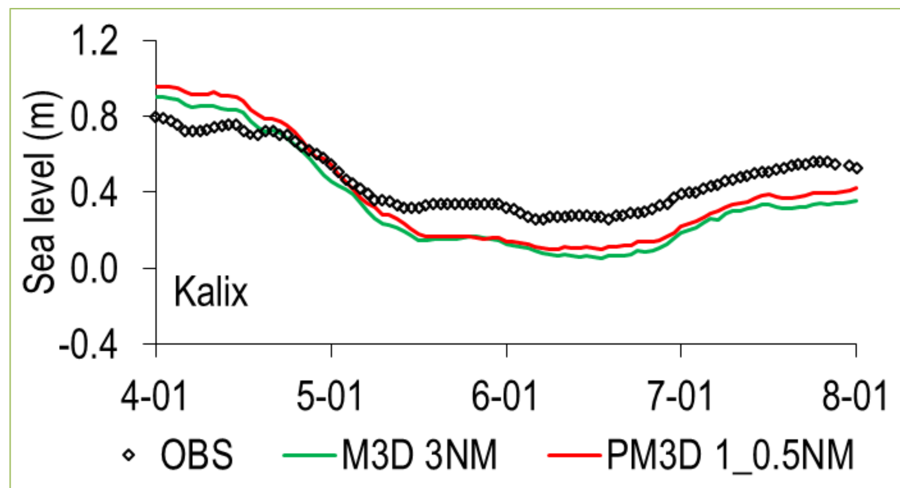

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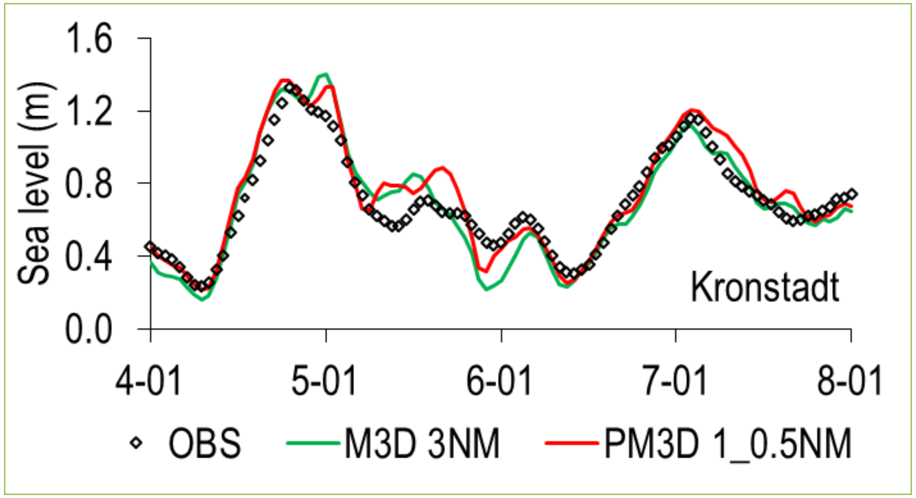
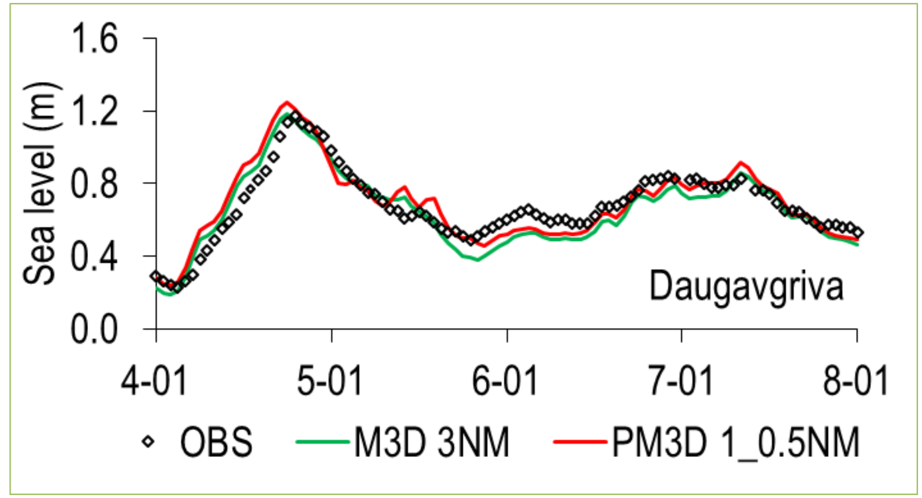
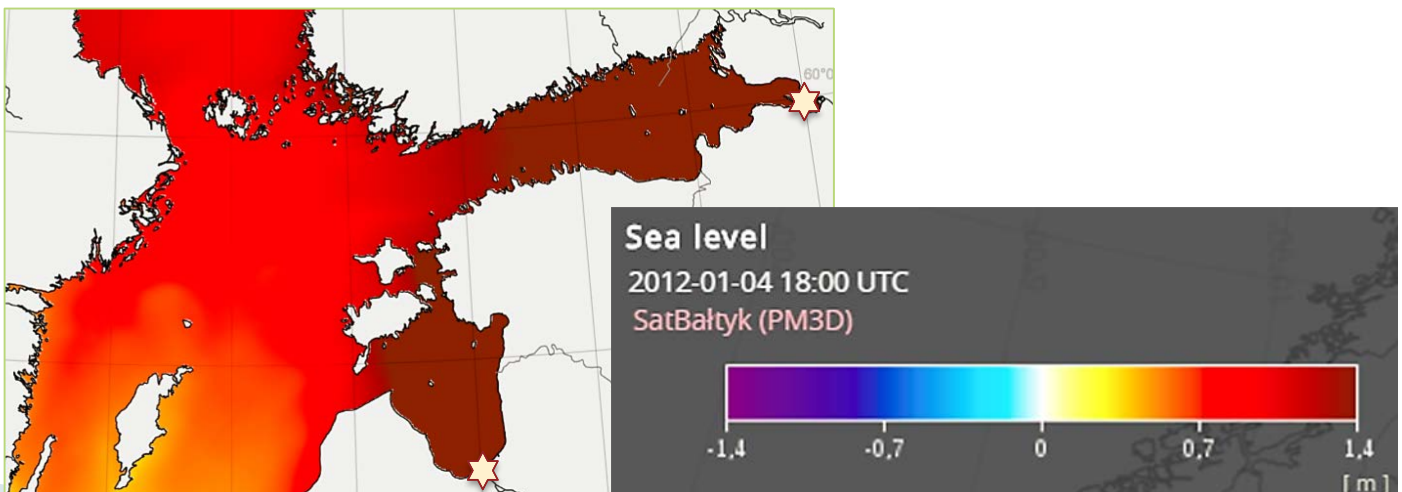
Sea level changes

4 – 7 January 2012







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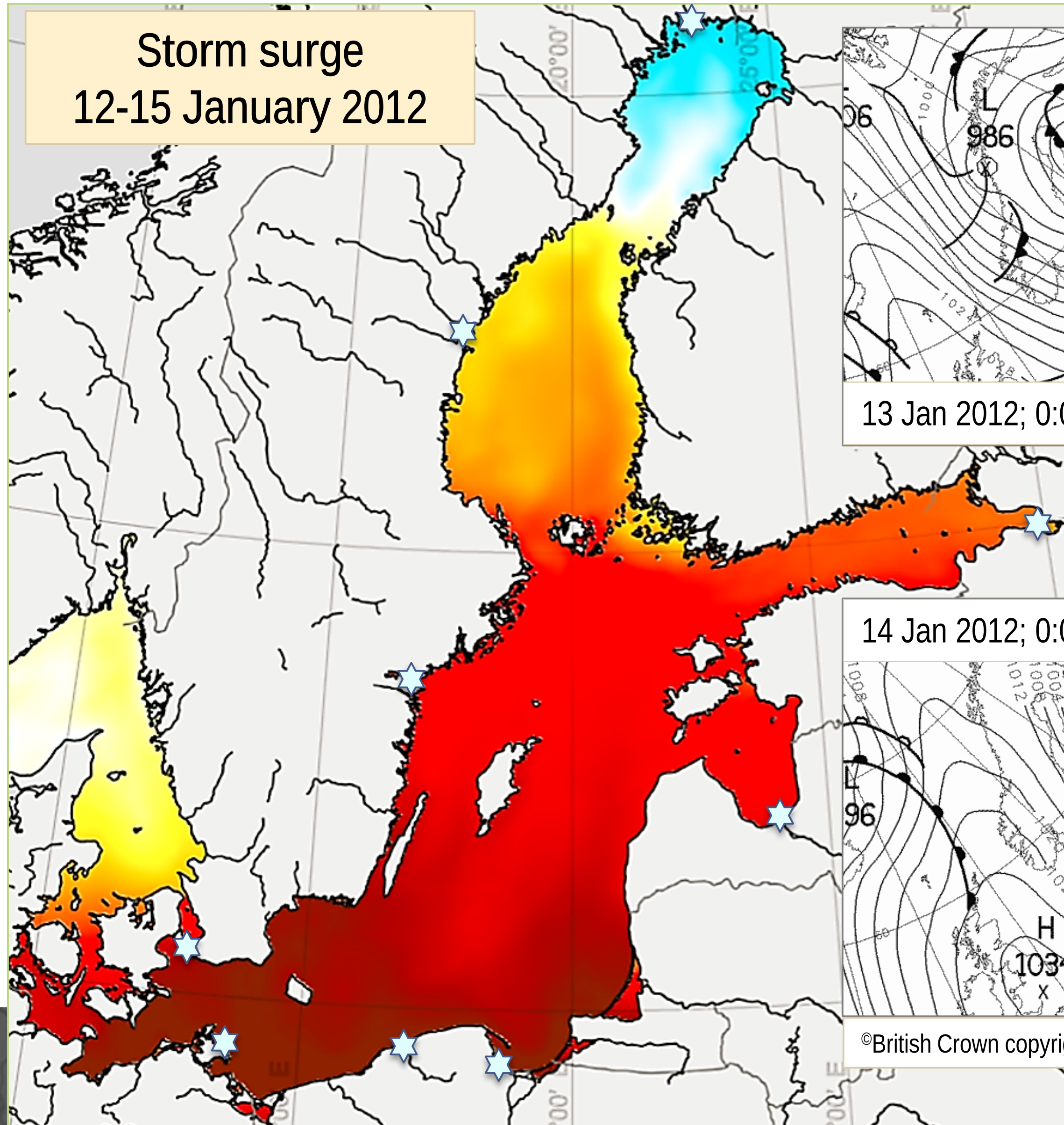
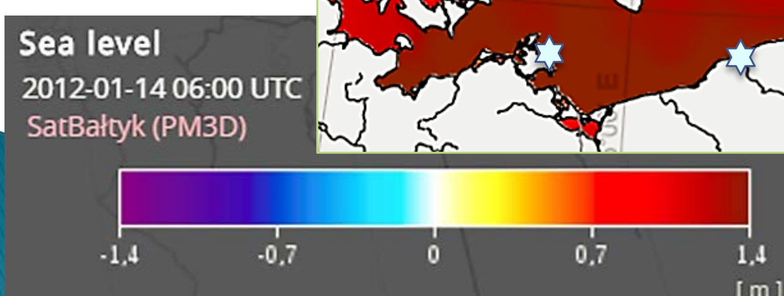
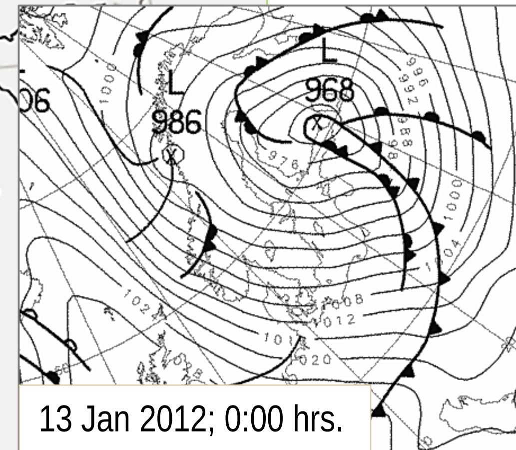
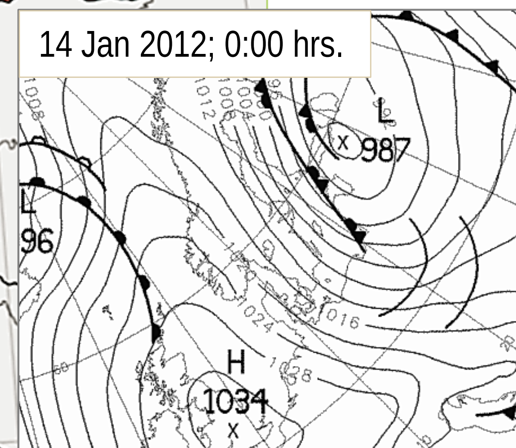
Storm surge
12-15 January 2012









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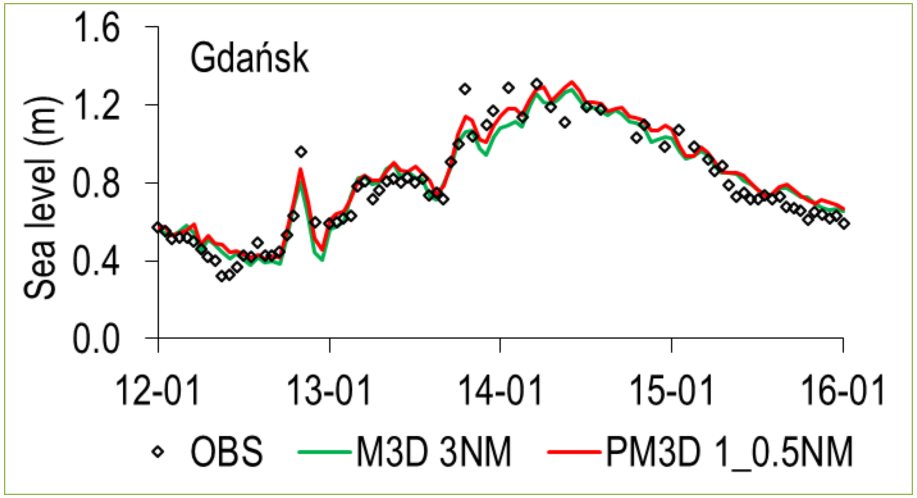
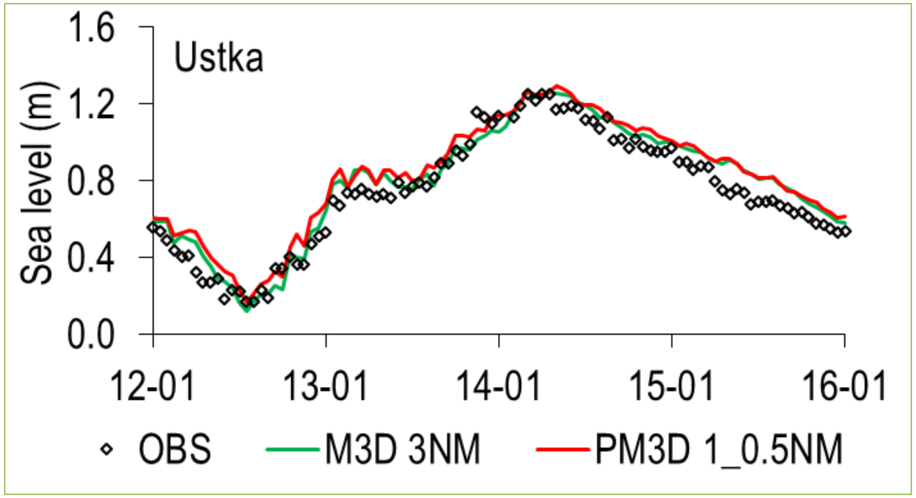
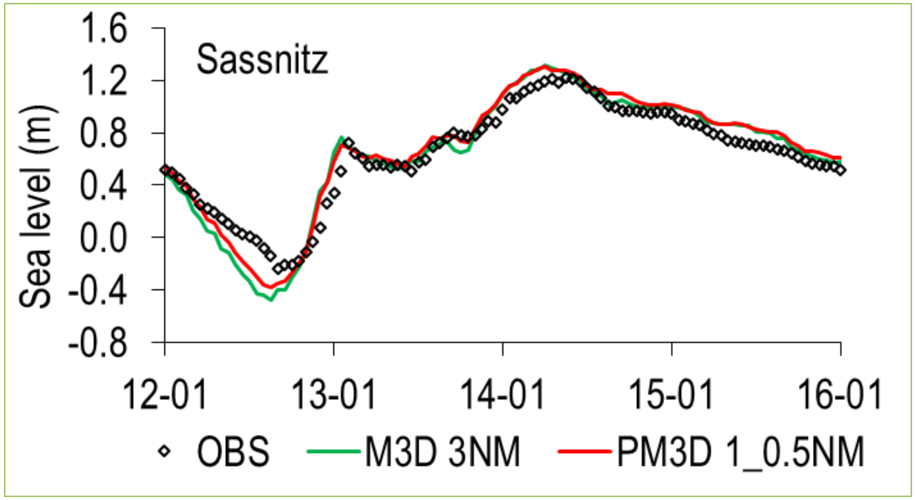
Sea level changes

12 – 15 January 2012







Sea level changes

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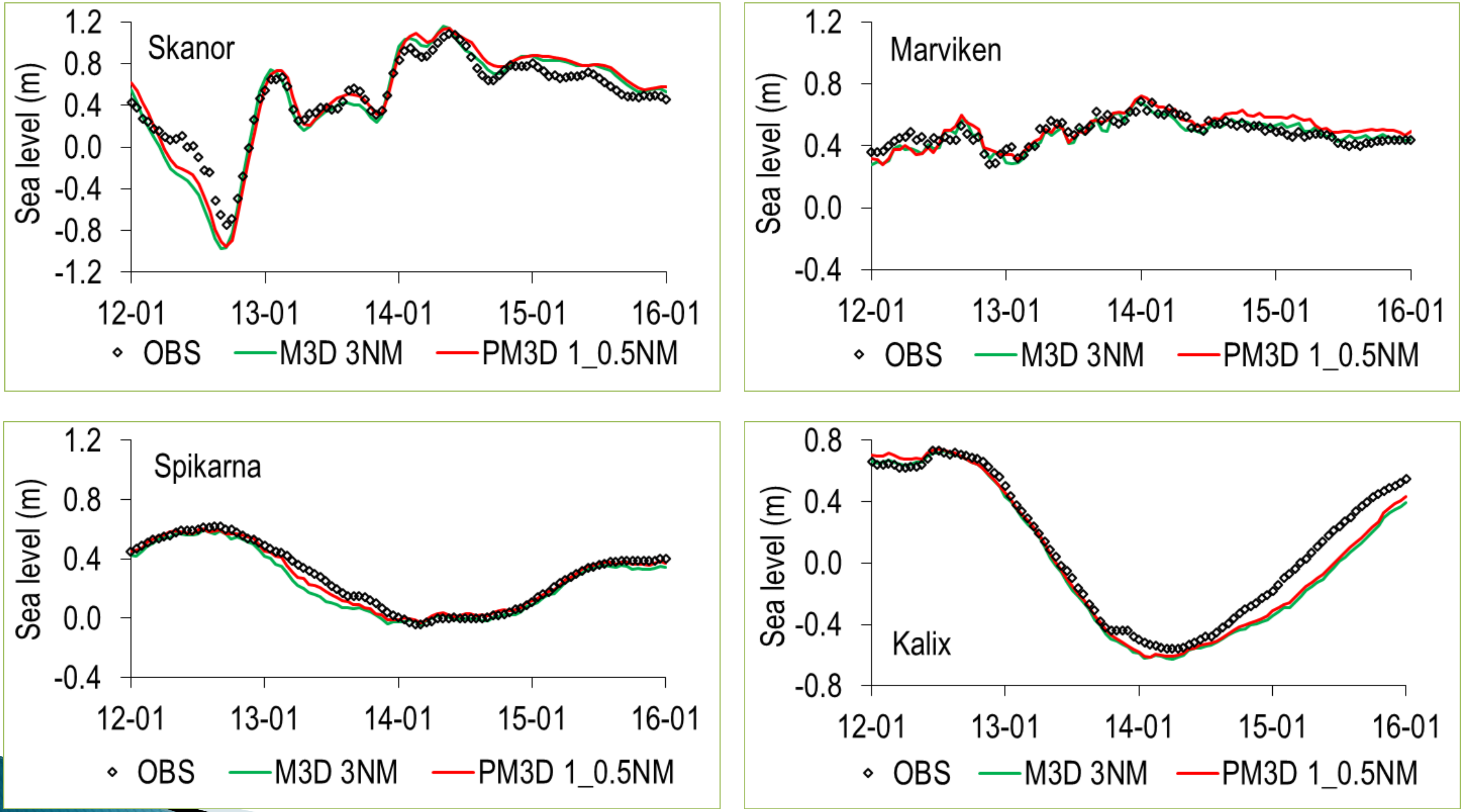

Sea level changes

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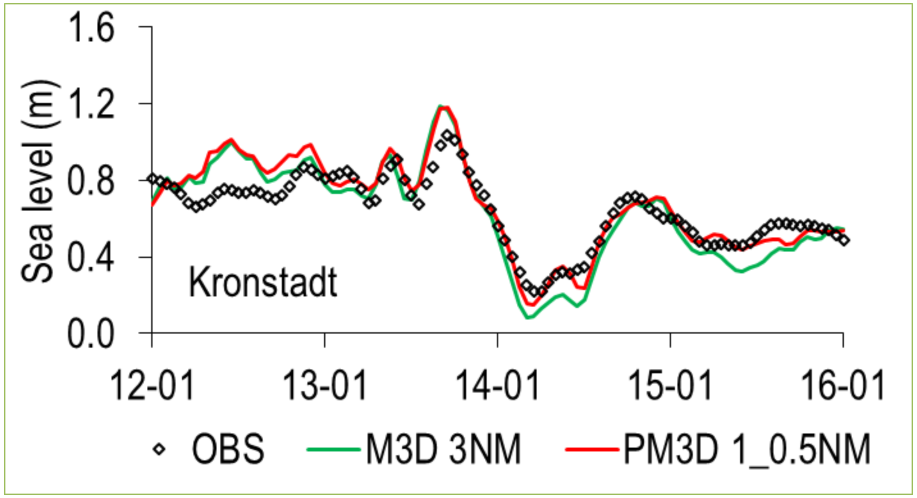

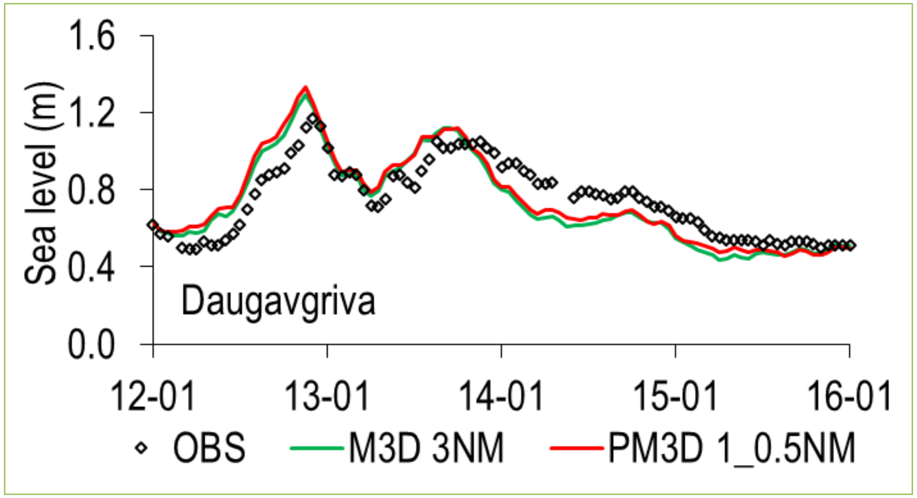

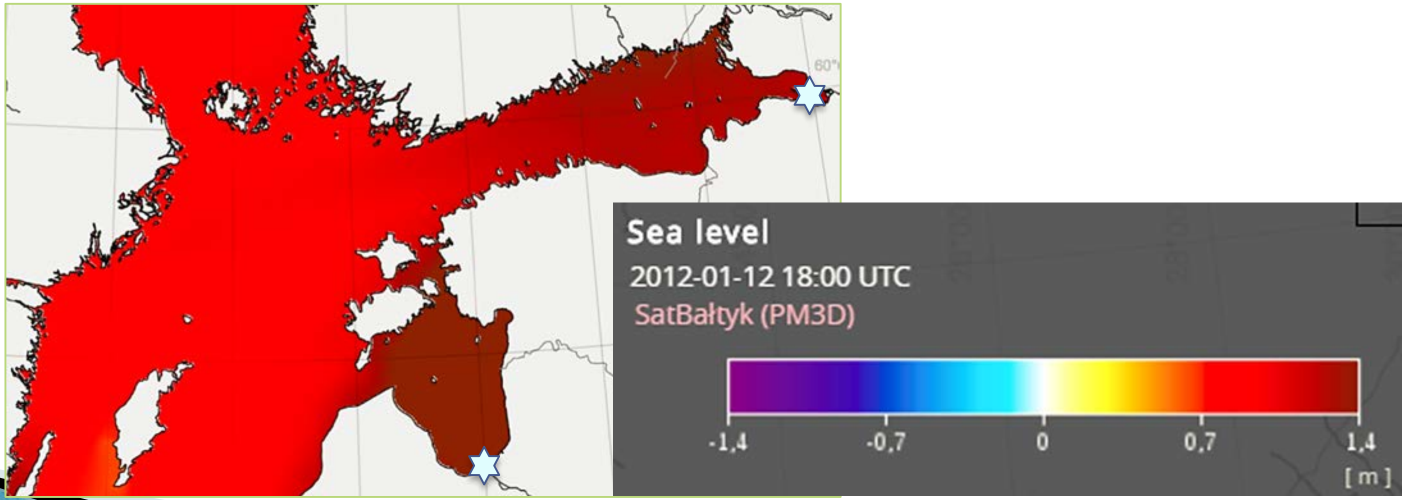

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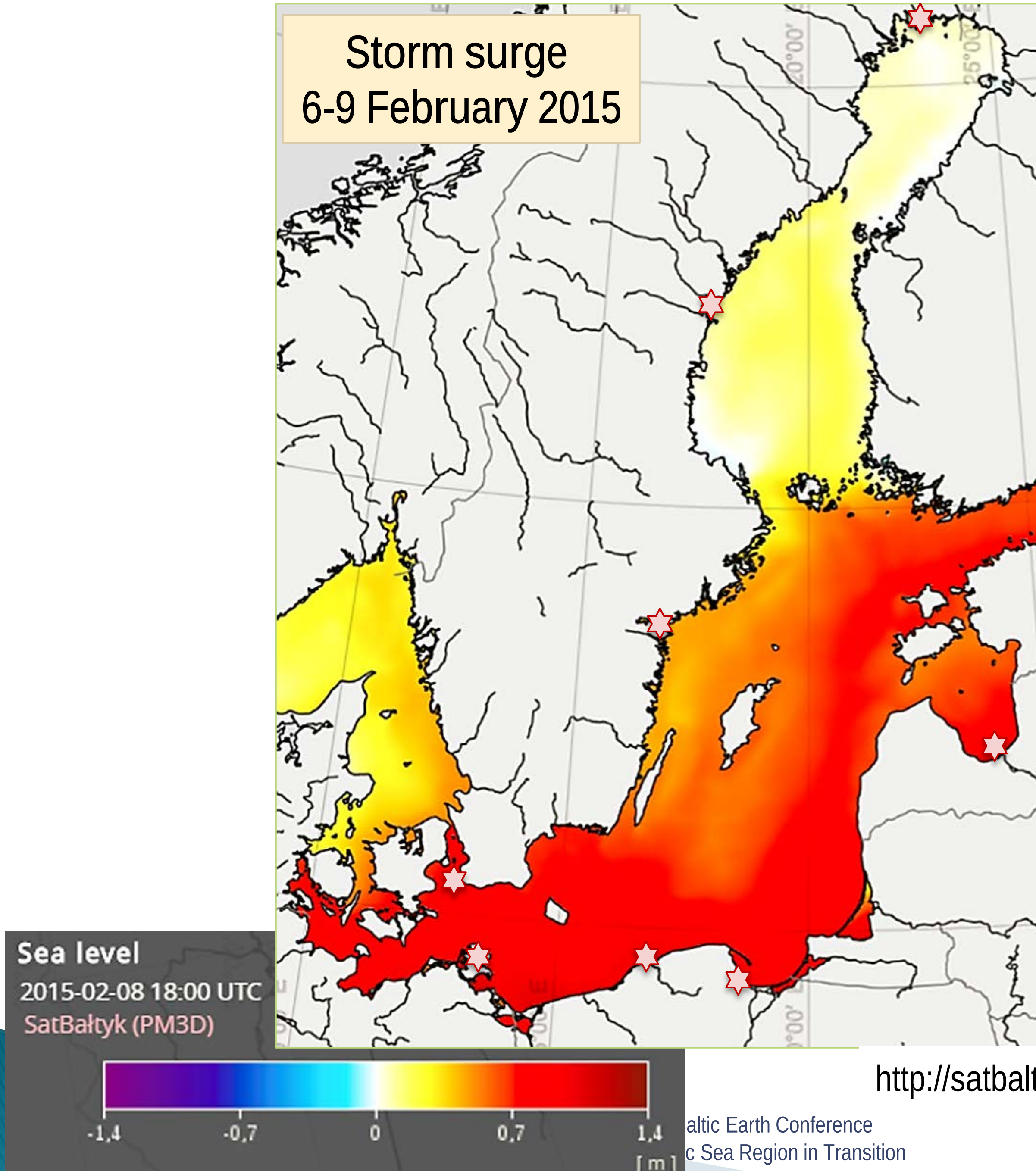
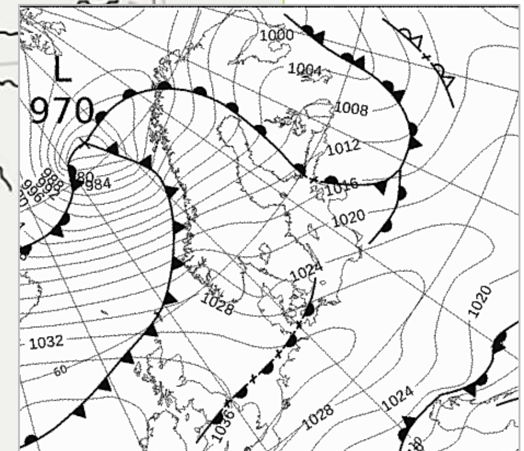
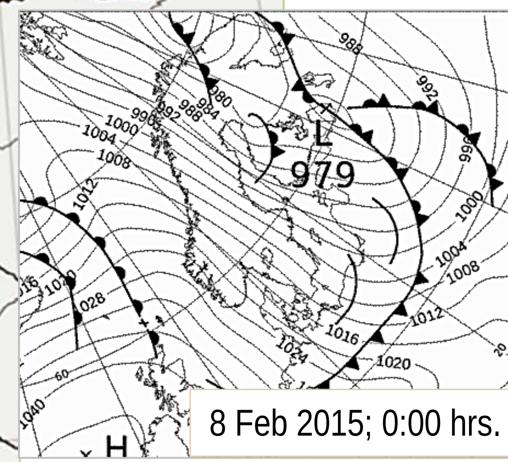
Storm surge
6-9 February 2015







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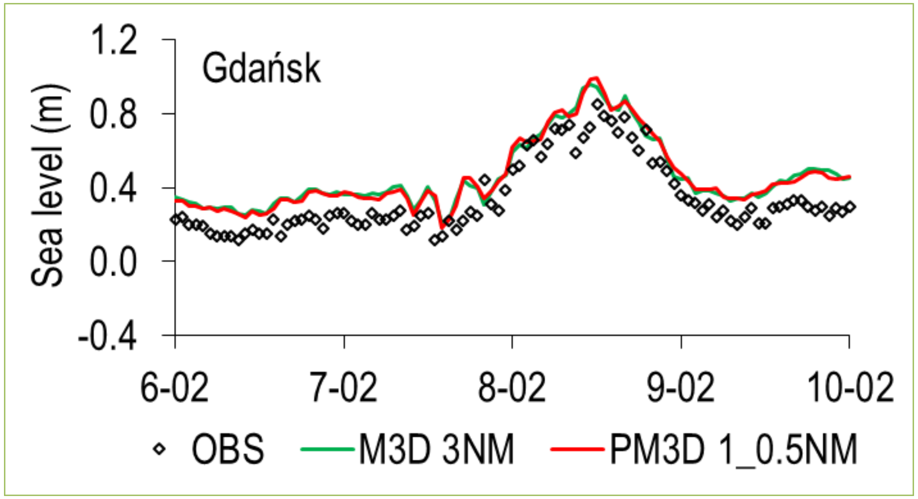
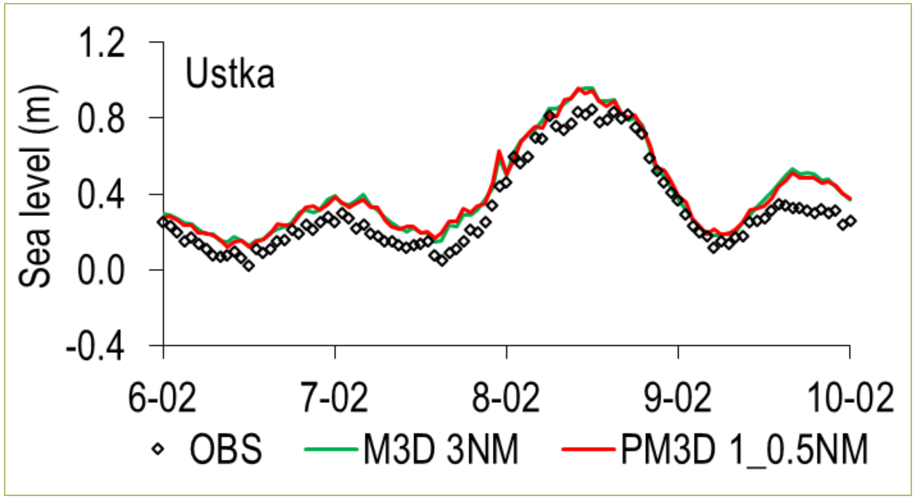
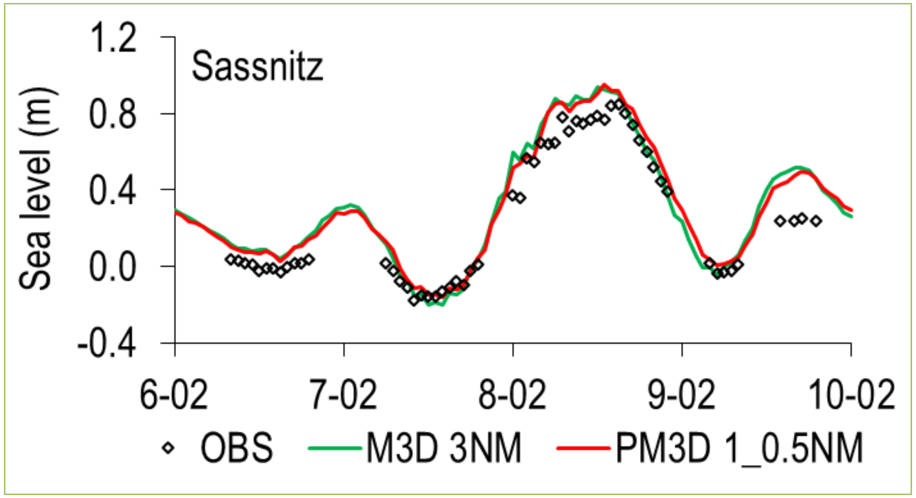
Sea level changes

6 – 9 February 2015







Sea level changes

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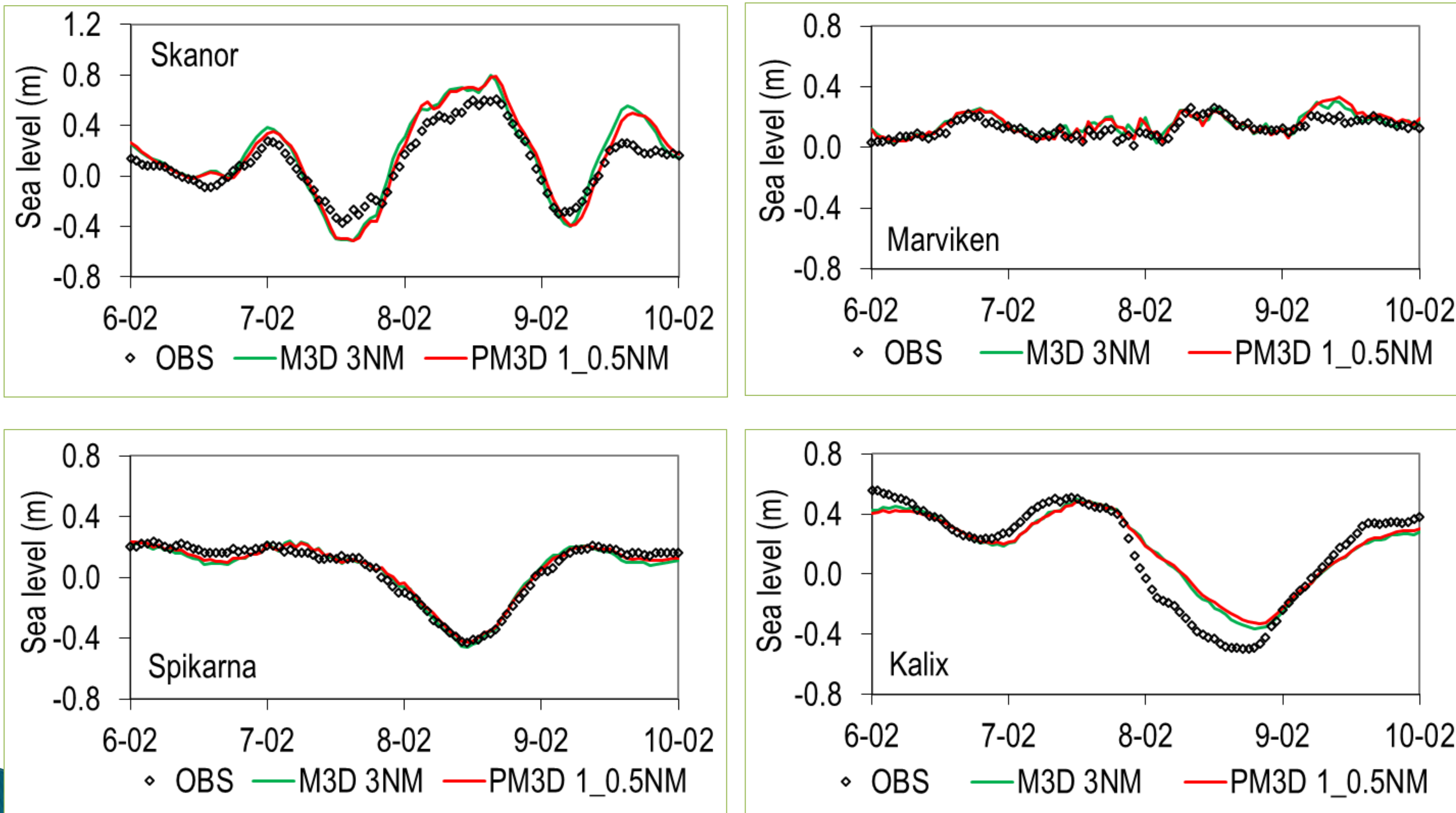

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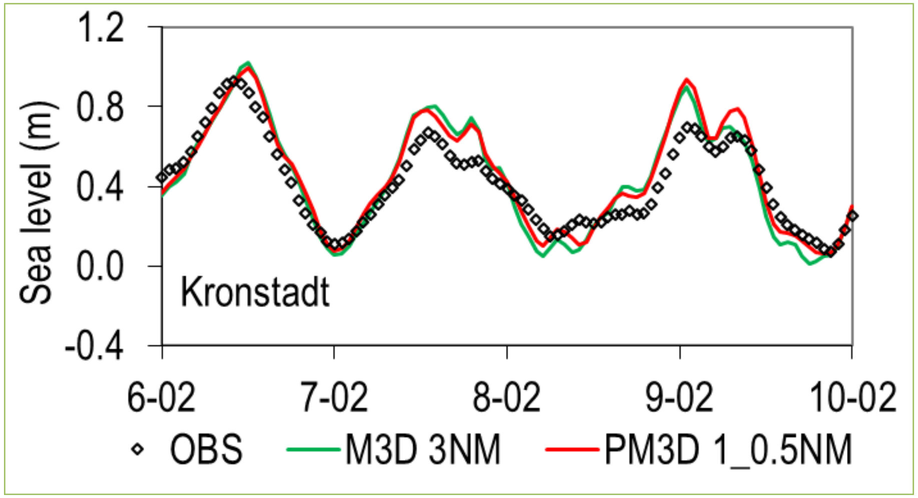

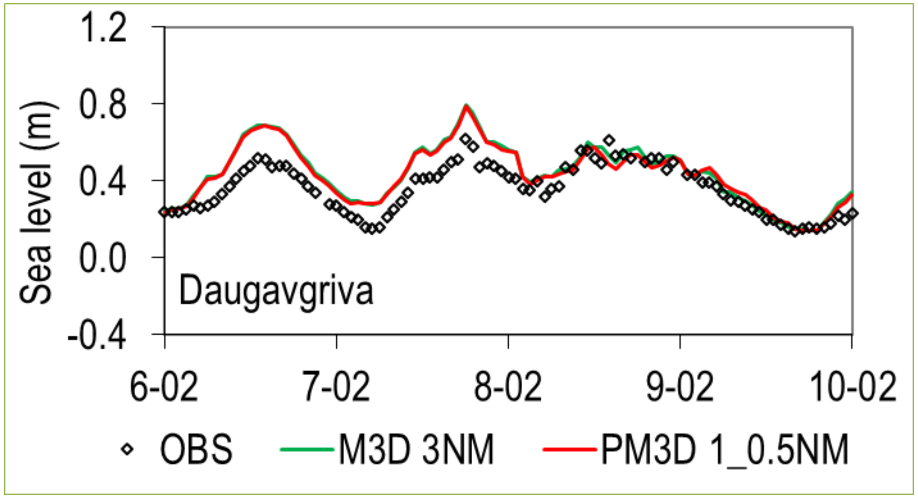

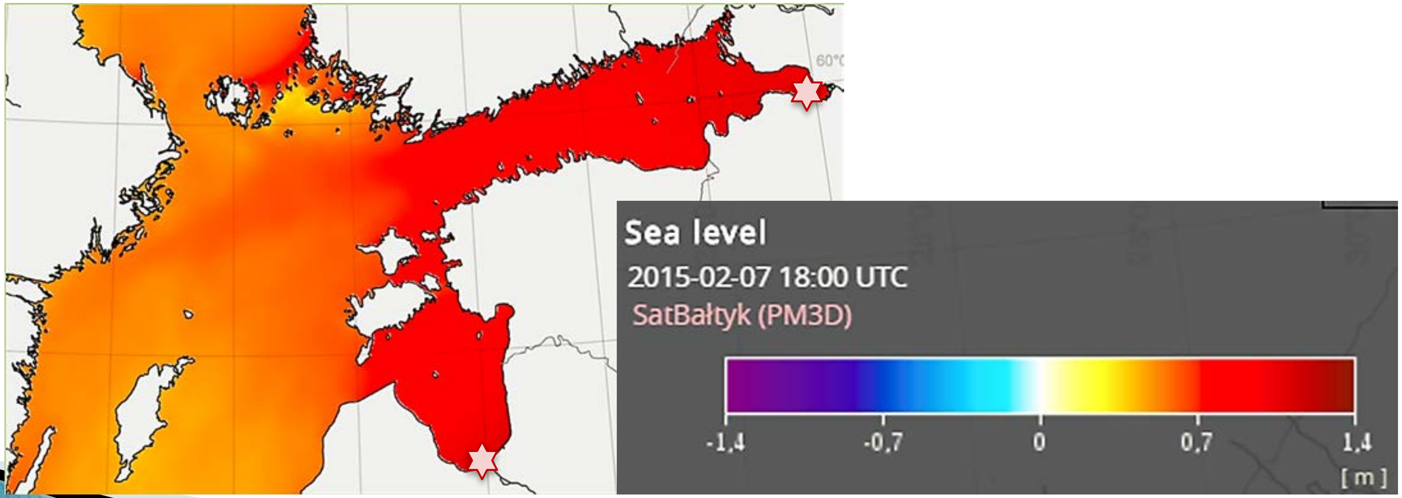

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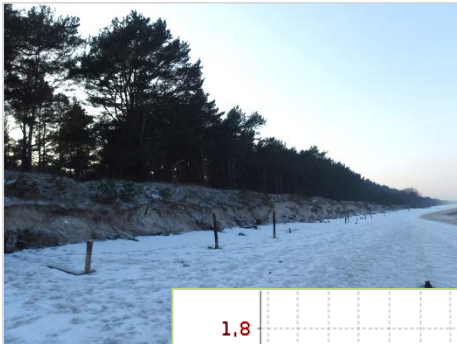
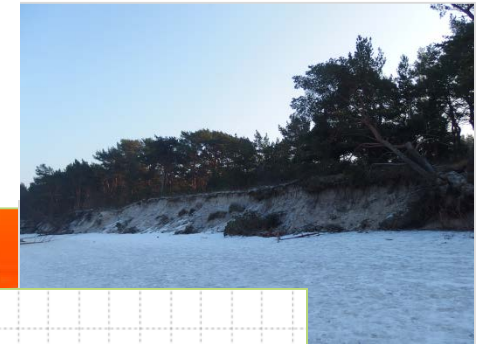
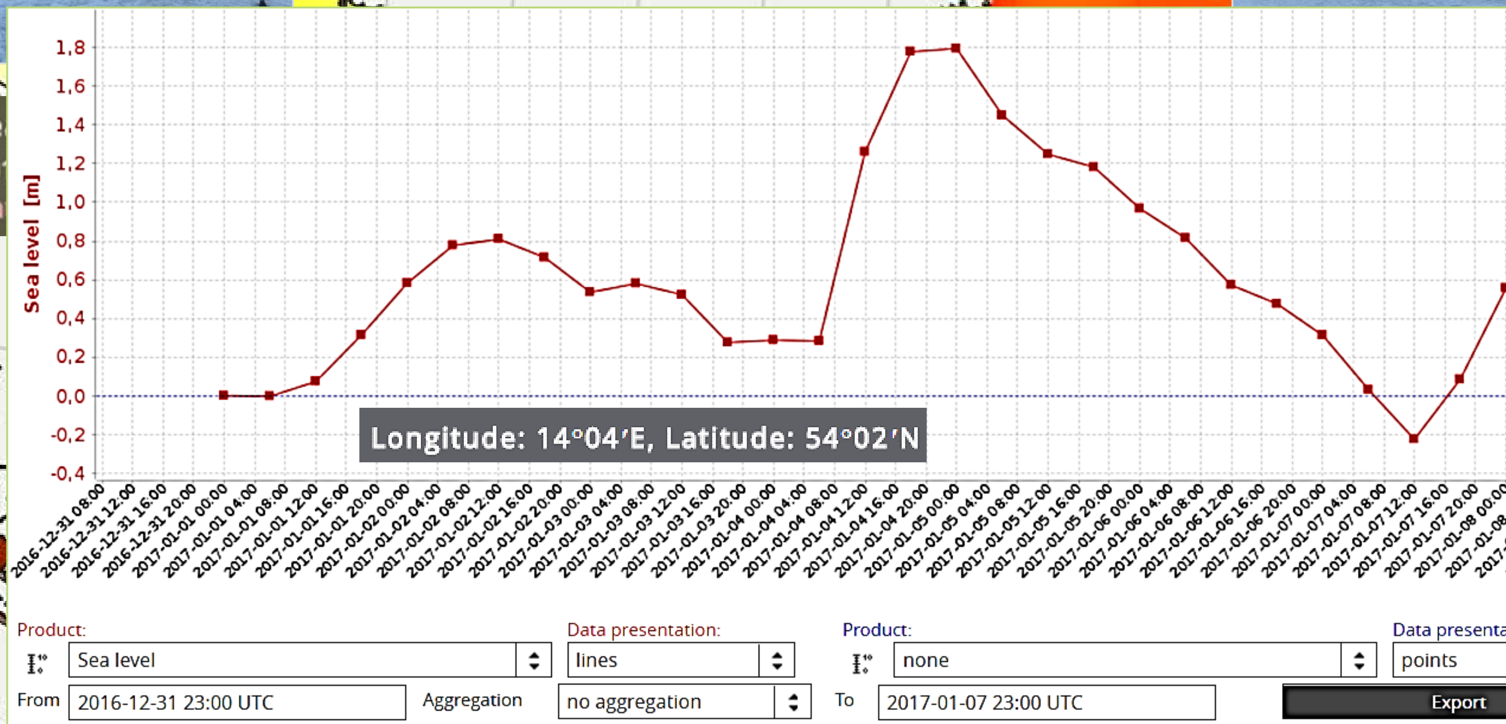
Main achievements

- The 1 NM numerical grid used for the region covering the entire Baltic Sea and the Skagerrak as well as the 0.5 NM resolution applied to the southern Baltic in the PM3D resulted in a better description of the coastline and the area's bathymetry. As a result, the model quality improved, as indicated by the lowest variability, the highest correlation and the highest percentage of water level simulations within ±0.15 m difference from the readings. The most significant advance in the PM3D performance was achieved for the southern Baltic coast.
- Evaluation of the PM3D performance during the Baltic storm surges that occurred in 2010-2015 showed a good representation of events characterized by rapid water level fluctuations. The model generated relatively good simulations, properly predicting the timing and extent of extreme values with errors usually not exceeding 0.15 m.
- As the PM3D involves parallel calculations, the computation time of simulations was reduced significantly, thus allowing to apply the high-resolution grid to the operational version of the model.
- A quick website access to daily-updated 72-h forecasts of hydrodynamic conditions within the SatBałtyk System (http://satbaltyk.iopan.gda.pl) provides potential users with an opportunity of predicting the magnitude and duration of storm surges. Therefore, the PM3D may prove of assistance in flood risk management in the coastal areas of the Baltic Sea.

Storm surge forecast produced by the PM3D – presentation in the **SatBałtyk** System







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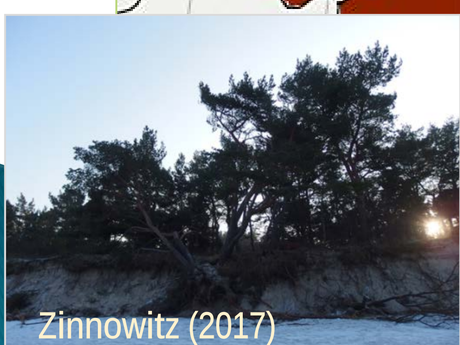

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Acknowledgments

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Water level data series were available through the Baltic Operational Oceanographic System (BOOS, www.boos.org).

Monthly mean runoffs based on data from Baltic Environment Database of the Nest Institute (http://nest.su.se/bed/).

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