# Application of data assimilation for improved operational water-level forecasting on the Northwest European Shelf and North Sea

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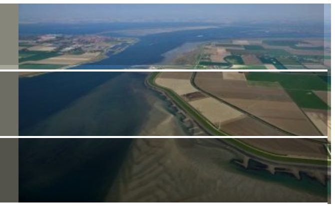
JONSMOD, May 2014

# Introduction

**The Northwest European Shelf and North Sea**

Need for accurate, real-time operational water level forecasting:

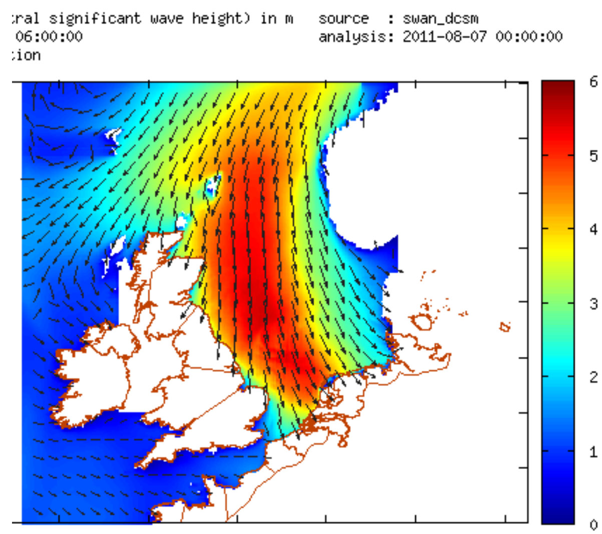
- On a daily basis, it is important for port operations and to ensure maritime safety on busy shipping routes towards the large sea ports of Rotterdam, Antwerp and IJmuiden.
- For the coastal regions of the Netherlands, it is crucial, since large areas of the land lie below sea level.
- During storm surges, detailed and timely water-level forecasts provided by an operational storm surge forecasting system are necessary to support, e.g. the decision for closure of the movable storm surge barriers in the Eastern Scheldt and the Rotterdam Waterway or potentially even activate an evacuation scenario.

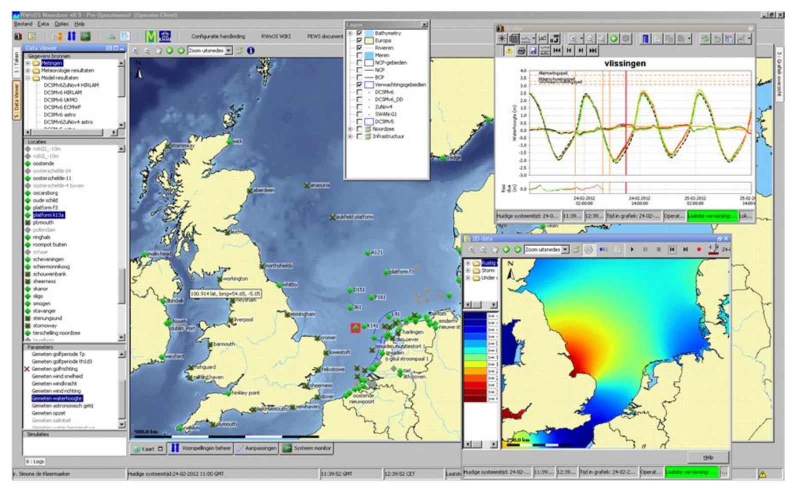



# Real-time forecasting in The Netherlands

**Developments in real-time flood forecasting for the Northwest European Shelf and North Sea**

- Deltares develops the numerical models
- Storm Surge Warning Service (SVSD), in close cooperation with the Royal Netherlands Meteorological Institute (KNMI), is responsible for operational forecasts and issuing warnings to coastal authorities in case of high water threats.
- Water-level forecasts at stations along the Dutch coast are provided every 6 h, with a 48-hour lead time.
- After the November 2006 All Saints storm it was decided that further improvements in model framework were required
- Decision to completely redesign both operational model and framework
- New generation model is part of a comprehensive development to upgrade the operational forecasting system for the North Sea

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# JONSMOD 2012

- Presentation of completely redesigned, new generation Dutch Continental Shelf Model version 6 (DCSMv6).
- Huge improvement in tide and surge representation (Dutch coastal waters and shelf wide)
  - ✓ A necessary condition in achieving this excellent representation quality is the increased model resolution.
  - ✓ Use of shelf wide observations (both in-situ and space-borne)
  - ✓ A key element in achieving the improved water-level representation is the application of a rigorous, structured and theoretically sound approach to data assimilation. We eventually used 200 control variables which reflect the need to reduce uncertainty in a large area, as spatial interactions are important and relevant phenomena are to a large extent generated elsewhere.

- We believe that this is the first application on this scale in which the tidal representation is such that astronomical correction no longer improves the accuracy of the total water-level representation and where, consequently, the straightforward direct forecasting of total water levels is better.

→ Dutch Continental Shelf Model v6 (DCSMv6) has replaced operational DCSMv5

# Focus of this presentation

**Recent advances in the Dutch operational tide-surge models**

• Improving water level representation in Dutch Estuaries and Wadden Sea aided by increased grid resolution

• A structured approach to data assimilation to reduce parameter uncertainty during model development

• Development of a steady-state Kalman filter is implemented to increase the predictive quality for the shorter lead times.

•The predictive value of the Kalman filter is determined by comparing the forecast quality for various lead-time intervals against the model without steady-state Kalman filter.


***Focus of this presentation:***

***(i) model setup and off-line data assimilation***

***(ii) real-time data assimilation***

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# Model setup

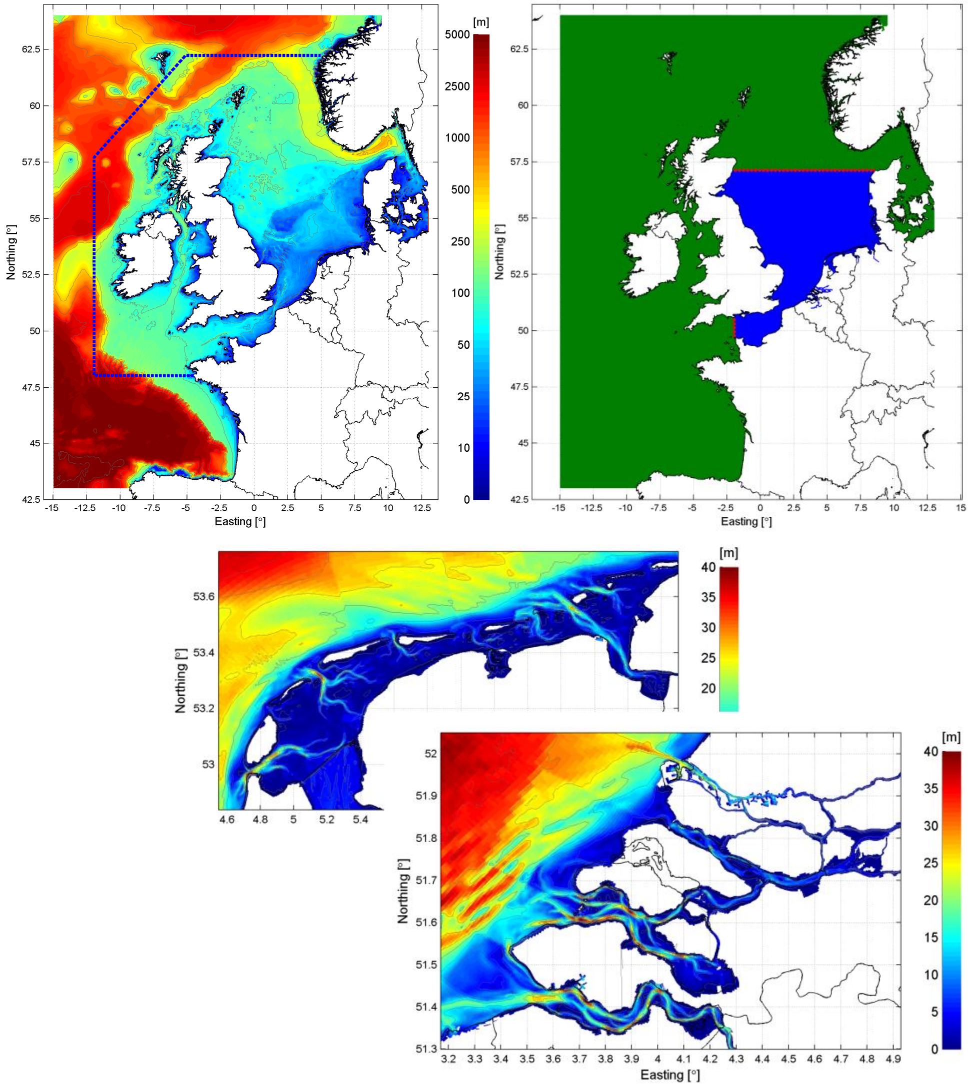
# DCSMv6-ZUNOv4 (model grid and bathymetry)

**Model setup - computational grid**

- Increased grid resolution through domain decomposition approach
- DCSMv6 (outer) domain: Uniform cell size of 1.5’ (1/40°) in east-west direction and 1.0’ (1/60°) in north-south direction (~nautical mile)
- ZUNOv4 (inner) domain: variable grid size up to 200 m – 400 m in Dutch estuaries and Wadden Sea
- Around $10^6$ active grid cells
- With a computational time step of 1 minute, a 1 day simulation takes approximately 15 minutes on 12 computational cores

**Model setup – bathymetry**

- Initially based on NOOS gridded bathymetry data set, supplemented by ETOPO2 and data from hydrographic office

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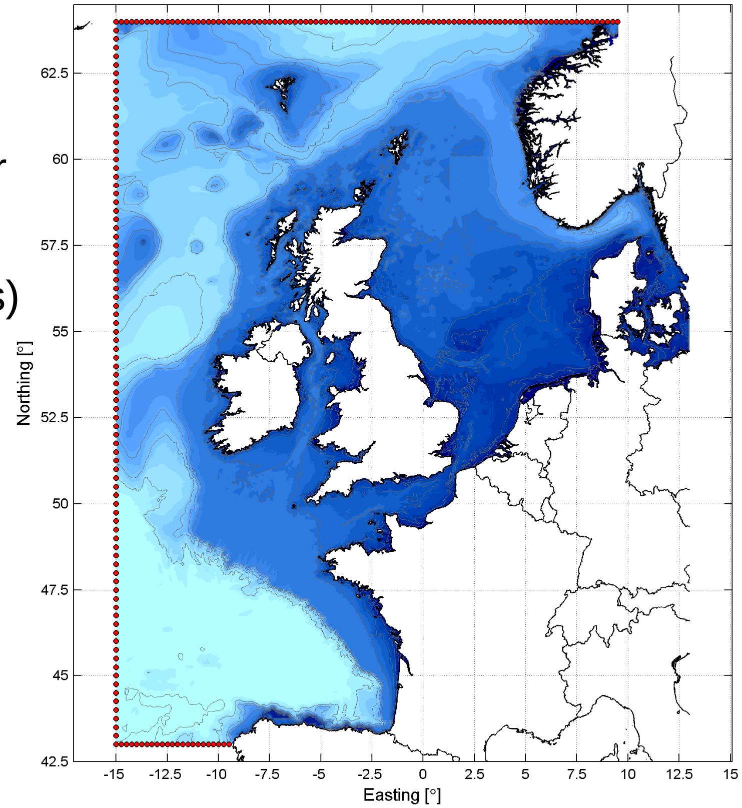
# Model setup (boundary forcing)

**Model setup - boundary forcing**

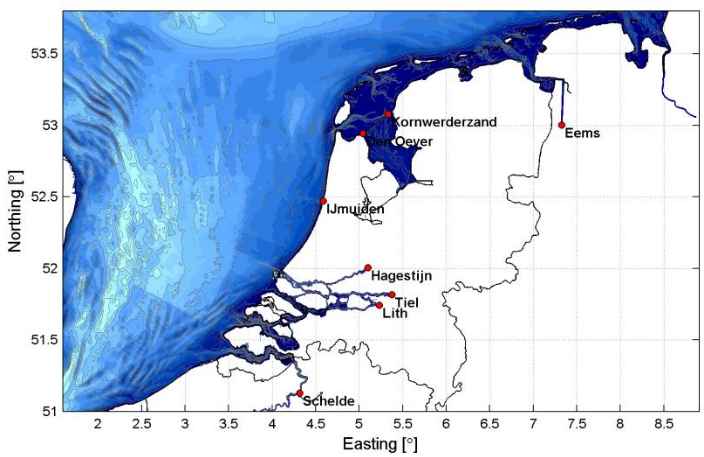
- Open boundary with 205 sections
- Distinction made between 2 components of the water level elevation:

(1) Tide, defined in frequency domain (22 constituents)

(2) Surge, as an inverse barometer correction (IBC) based on time and space varying pressure fields




**Model setup - river discharges**

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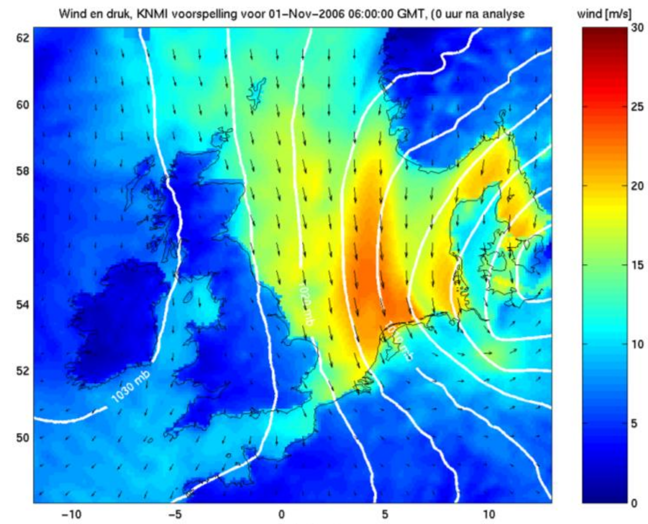
# DCSMv6-ZUNOv4 model setup (meteo forcing)

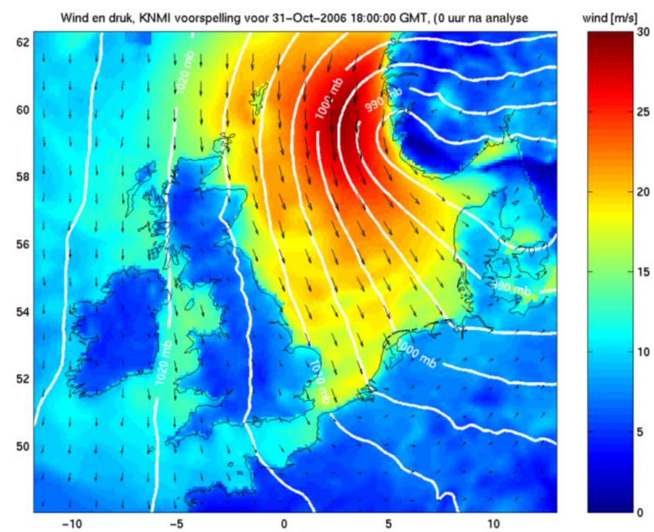
**Model setup - meteo forcing**

- Wind speed and air pressure from HIRLAM (NWP) model provided (operationally) by KNMI (Dutch MetOffice)
- Sea surface roughness is calculated using the Charnock relation (Charnock parameter 0.025)




**Model setup - miscellaneous**

- WAQUA module of SIMONA framework, for numerical modelling of 2D free surface flows
- Spatially varying manning bed roughness
- Tide Generating Forces (TGF) included
- Barrier closure included (4 storm surge barriers, 4 sluices)

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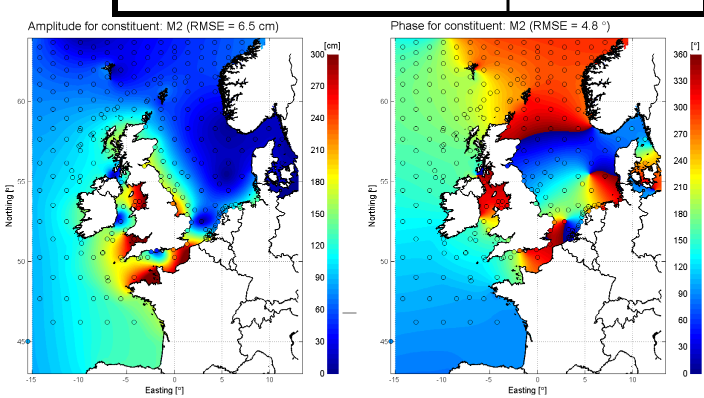
# Calibration approach

# Calibration approach

| Modeling stage | Model | Description |
|---|---|---|
| Calibration (1) | DCSMv6 | One year period (2007) – manual step-by-step approach - *assessment of tidal propagation with Satelite Altimeter data* |
| Calibration (2) | DCSMv6<br>DCSMv6 -ZUNOv4 | One year period (2007) – *data assimilation* to reduce parameter uncertainty in bottom roughness and bathymetry |
| Validation (1) | DCSMv6 -ZUNOv4 | One year period (2008) |
| Validation (2) | DCSMv6 -ZUNOv4 | Modeling of historical events (All Saints storm 2006, 'Santa Claus' storm 2013) |
| Validation (3) | DCSMv6 -ZUNOv4 | One year period (2007), assessment of *forecast accuracy* (4 runs / day with a 48 hr lead-time) |

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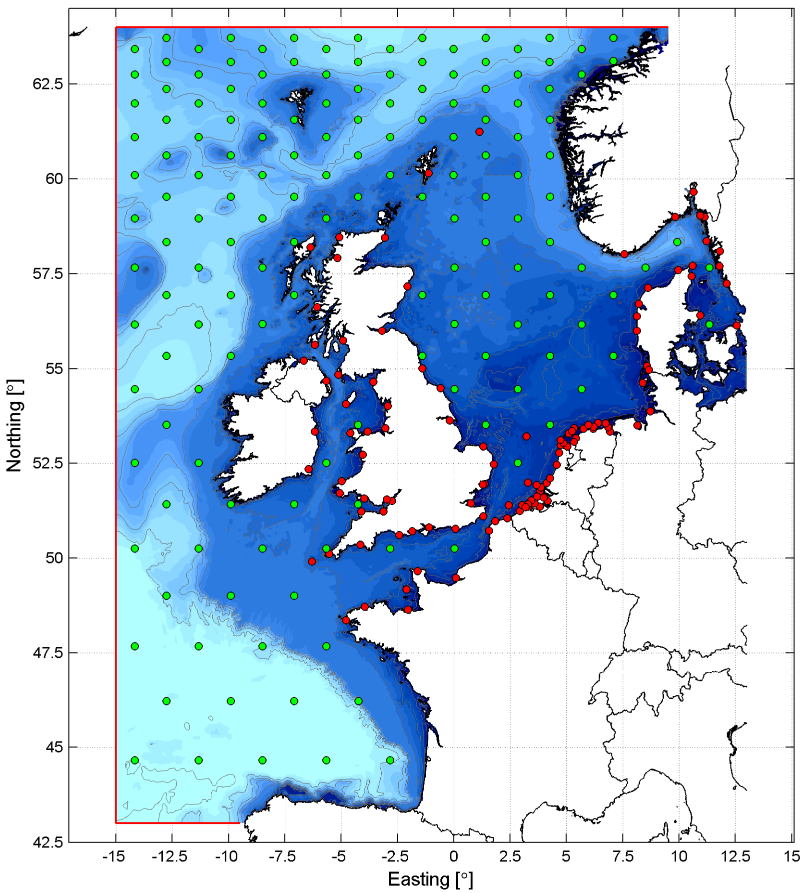
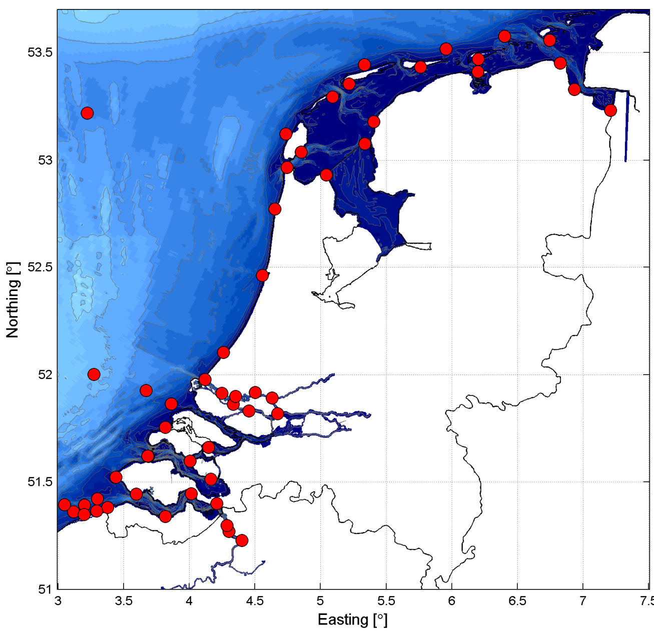
# DCSMv6-ZUNOv4 model calibration

**Calibration and validation using tide gauge data at >120 locations**




Green dots: radar altimeter cross-over locations

Red dots: in-situ tide-gauge locations

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# Doesn't Use Derivatives (OpenDA-DUD)

- Open Source Data Assimilation toolbox OpenDA used for uncertainty reduction
- DUD: a derivative-free algorithm for nonlinear least squares (Ralston and Jennrich 1978)
- Minimizes quadratic cost function by adjusting model parameters (bias ignored, since hardly related to uncertainty in control parameters)
- DUD should be initialized with one unperturbed run and *n* sensitivity run, where n is the number of control parameters

OpenDA

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# DCSMv6-ZUNOv4 Model Development

**OpenDA-DUD experiment setup and parameters**

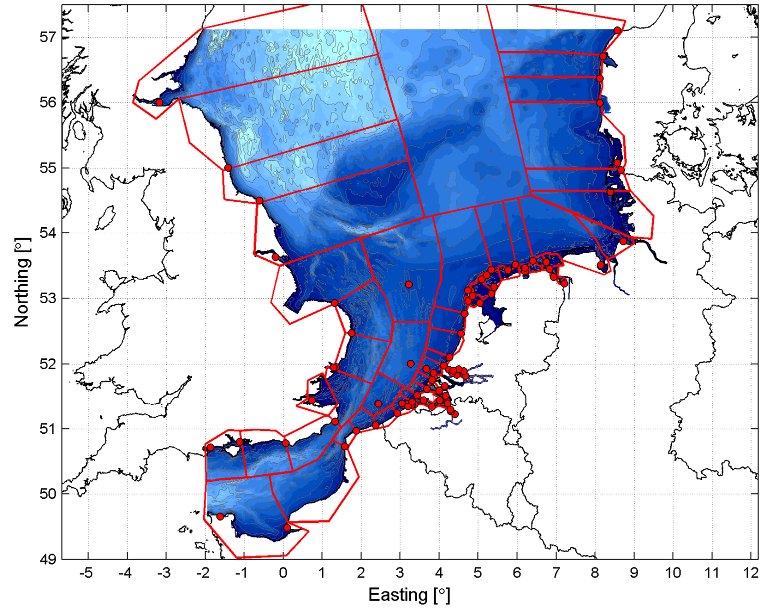
- Tidal error introduced during the tidal propagation
- Parameters related to prescription at the open boundary excluded from the optimization problem
- Reduction of uncertainty in bottom friction coefficient and bathymetry

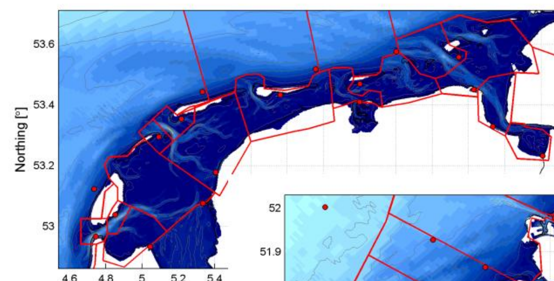
•Control paramters defined between measurement locations

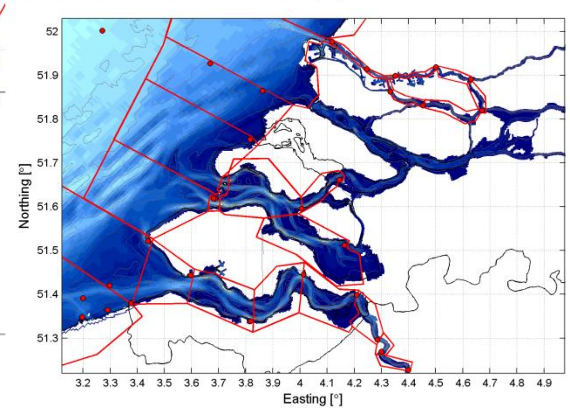
•Multiple optimization runs, with increasing length and number of parameters

•Final experiment: 146 control parameters, 6 months, ~120 observations

- Long period to account for non-stationarity of tidal amplitudes and phases
- Large area to account for spatial interaction

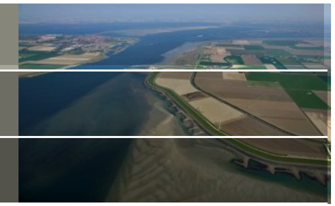


# Validation

# DCSMv6-ZUNOv4 (shelf-wide)



**Goodness-of-Fit (in cm) for final calibration results (all stations)**

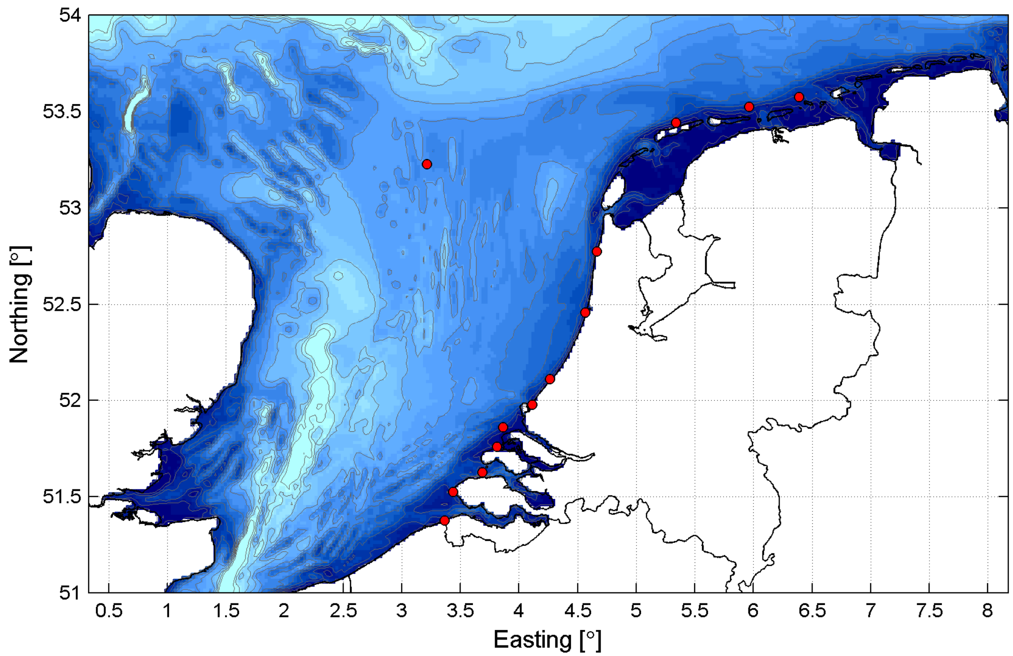
| | RMSE tide | RMSE surge | RMSE full | RMSE high waters | RMSE low waters |
|---|---|---|---|---|---|
| North Sea | 5.9 | 6.2 | 8.3 | 7.7 | 8.3 |
| English Channel | 6.5 | 4.9 | 7.6 | 7.2 | 7.9 |
| Irish Sea and Severn Est. | 10.4 | 6.5 | 11.5 | 10.8 | 13.8 |
| Skagerrak and Kattegat | | | 7.4 | 7.1 | 7.2 |
| Western Scheldt | 6.2 | 6.8 | 9.2 | 9.6 | 9.7 |
| Eastern Scheldt | 3.8 | 5.3 | 6.5 | 6.1 | 7.0 |
| Wadden Sea | 4.4 | 6.1 | 7.5 | 6.6 | 7.5 |
| Eems-Dollard Estuary | 4.9 | 7.0 | 8.6 | 8.2 | 9.4 |
| **Total** | **7.2** | **6.1** | **8.8** | **8.1** | **9.5** |

Water level signal is split in a tide and surge
part with harmonic analysis (118 constituents)

# DCSMv6-ZUNOv4 (Dutch coastal stations)

**Goodness-of-Fit (in cm) for final calibration results (13 Dutch coastal stations)**

| | RMSE (tide) | RMSE (surge) | RMSE (total) | RMSE (high water) | RMSE (low water) |
|---|---|---|---|---|---|
| **DCSMv5** | **10.7** | **7.7** | **13.1** | **11.3** | **11.0** |
| **DCSMv6** | **4.1** | **5.9** | **7.2** | **6.6** | **7.1** |
| **DCSMv6-ZUNOv4** | **4.0** | **5.8** | **7.0** | **6.2** | **6.9** |
| | -63% | -25% | -47% | -45% | -37% |

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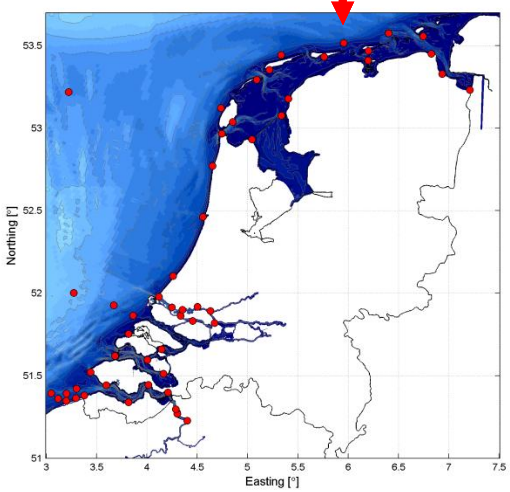
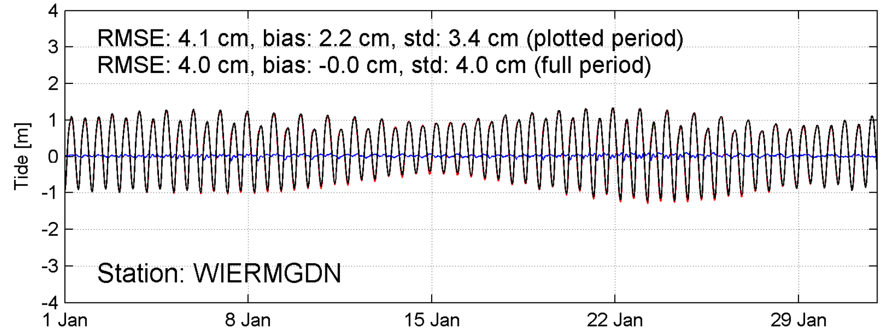
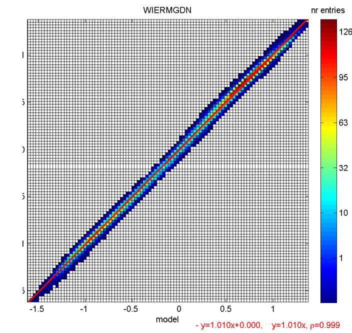
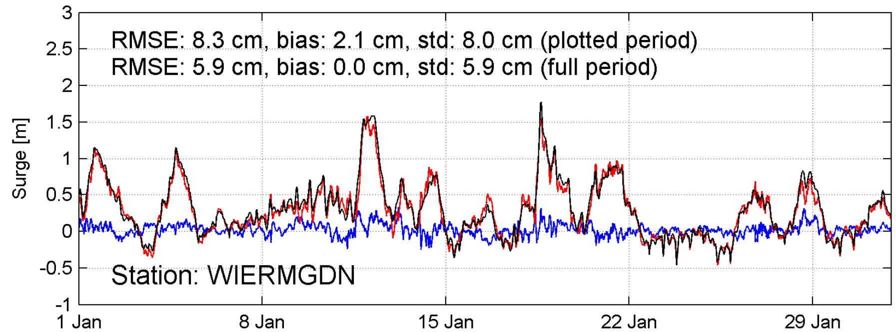
# DCSMv6-ZUNOv4 model calibration

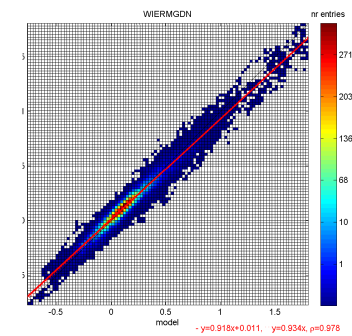
**Calibration results for tide, surge and total water level**

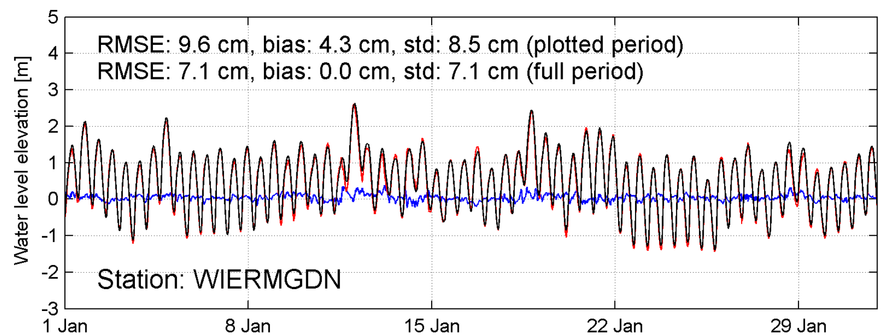


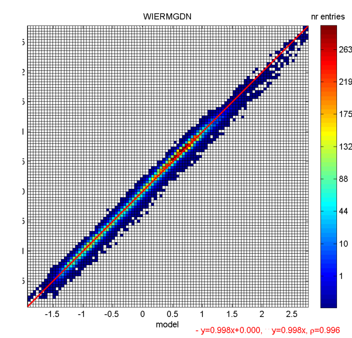




| | |
|---|---|
| Red: | Measurement |
| Black: | Computation |
| Blue: | Residual |

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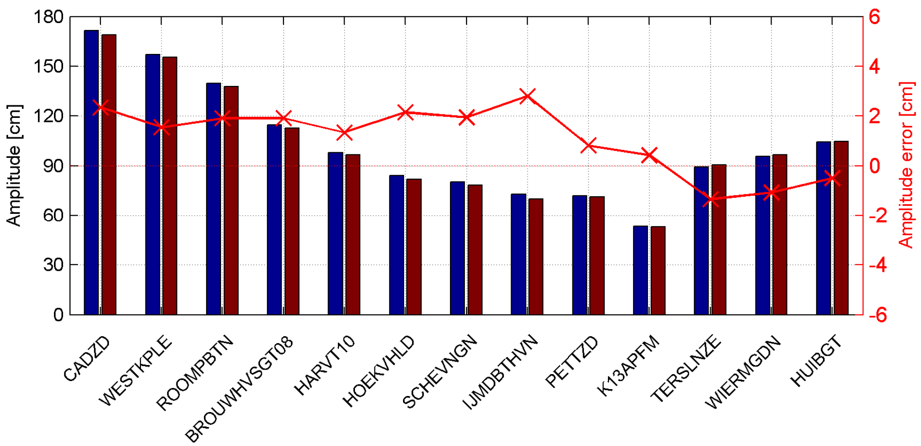
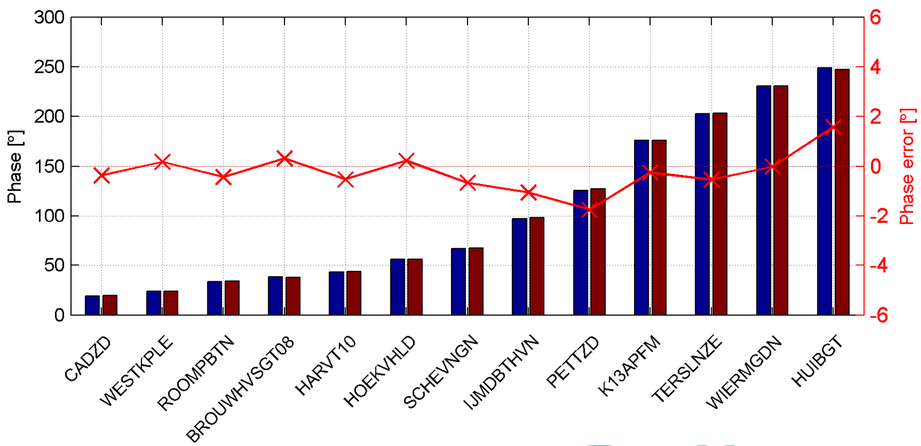
# Tide representation in the frequency domain

## Based on 13 Dutch coastal stations

| | DCSMv6-ZUNOv4 | | |
|---|---|---|---|
| | RMS(ΔA) | RMS(ΔG) | RMS(VD) |
| Q1 | 0.4 | 7.2 | 0.6 |
| O1 | 0.2 | 2.7 | 0.5 |
| P1 | 0.9 | 3.9 | 0.9 |
| K1 | 0.2 | 3.4 | 0.5 |
| N2 | 0.2 | 1.0 | 0.4 |
| **M2** | **1.7** | **0.8** | **2.1** |
| **S2** | 1.0 | 1.1 | 1.1 |
| K2 | 0.7 | 1.8 | 0.8 |
| M4 | 0.4 | 3.4 | 0.7 |
| M6 | 0.7 | 11.6 | 1.3 |




**A: amplitude in cm, G: phase in °, VD: vector difference in cm**

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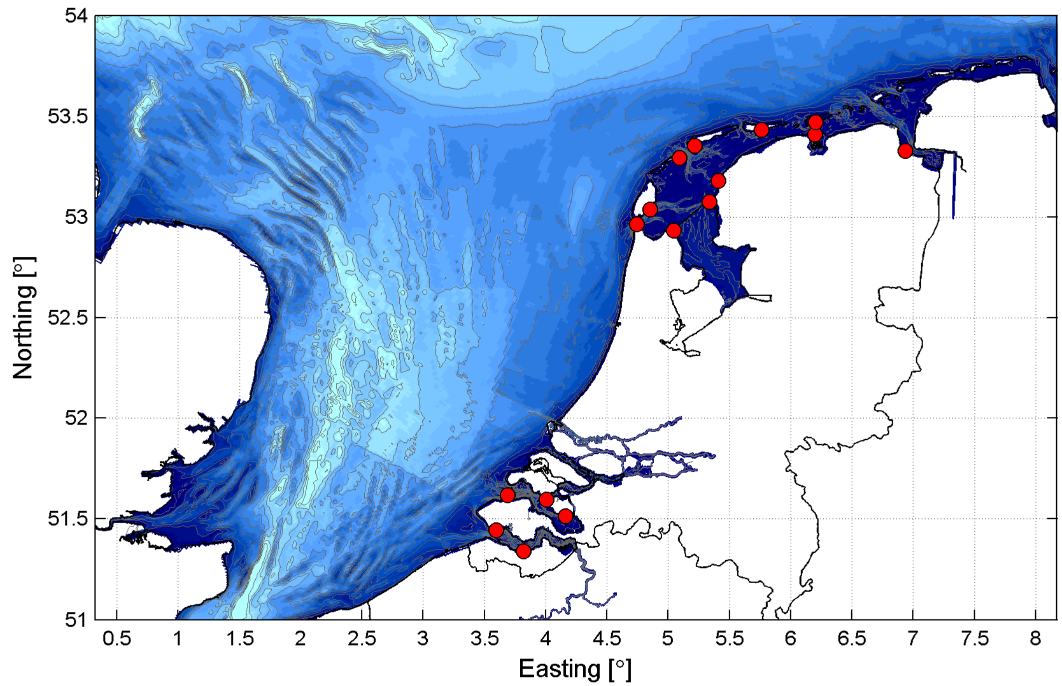
# DCSMv6-ZUNOv4 (Dutch estuaries and Wadden Sea)



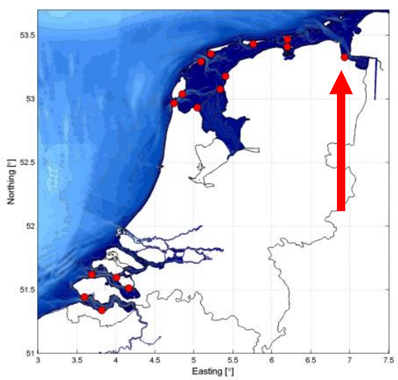

Improvement in:

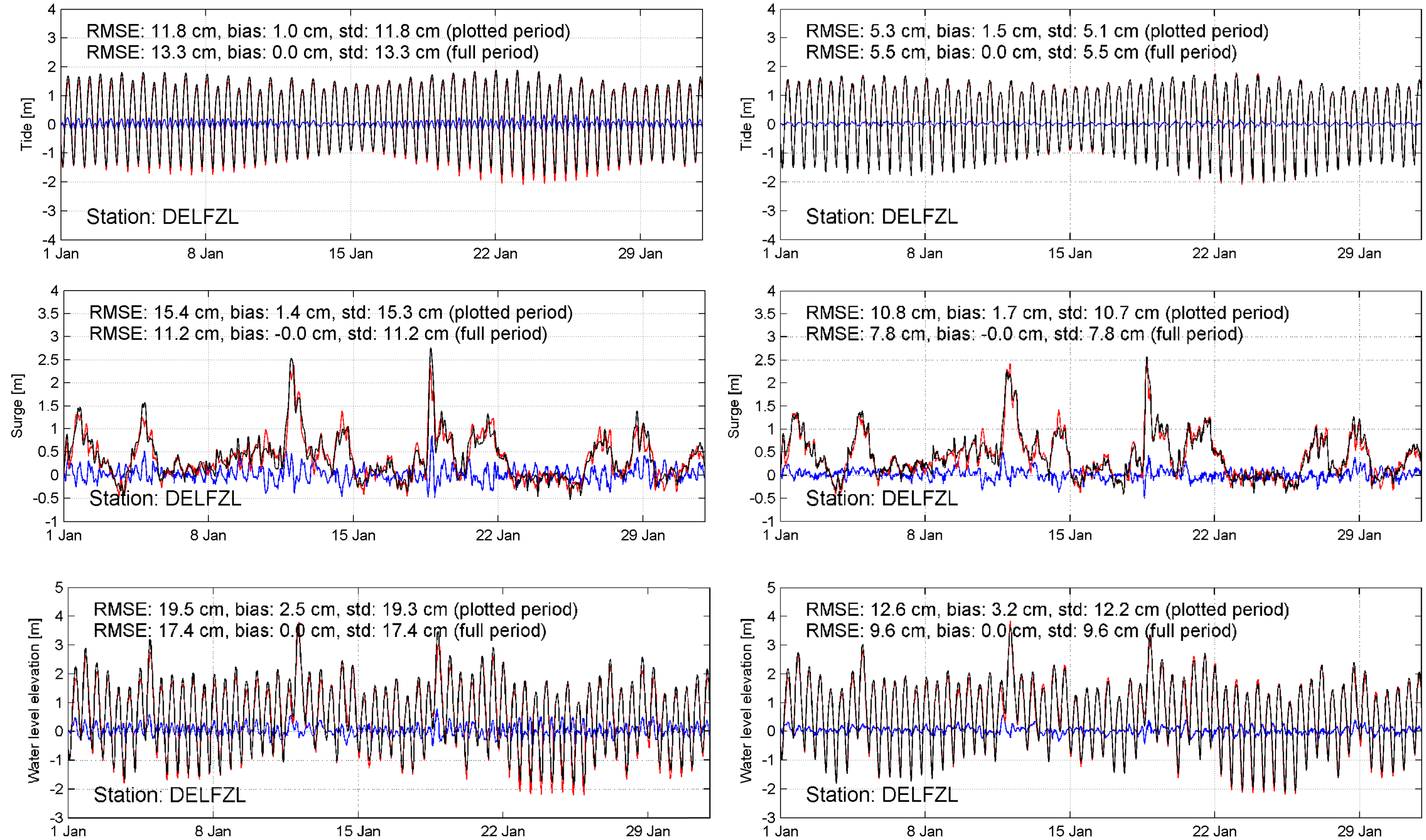
- tidal propagation
- generation of higher harminics
- non-linear tide-surge interaction

**Based on 16 stations in Dutch estuaries en Wadden Sea**

| | RMSE (tide) | RMSE (surge) | RMSE (total) | RMSE (high water) | RMSE (low water) |
|---|---|---|---|---|---|
| **DCSMv6** | 7.1 | 7.0 | 9.9 | 9.3 | 10.7 |
| **DCSMv6-ZUNOv4** | **4.5** | **6.0** | **7.5** | **6.7** | **7.6** |
| | -37% | -14% | -24% | -28% | -29% |

# DCSMv6-ZUNOv4 (Dutch estuaries and Wadden Sea)




Red: Measurement

Black: Computation

Blue: Residual

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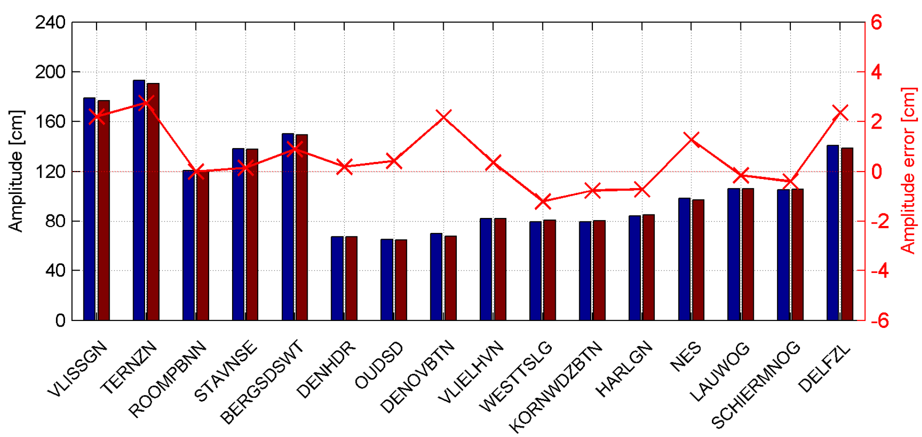
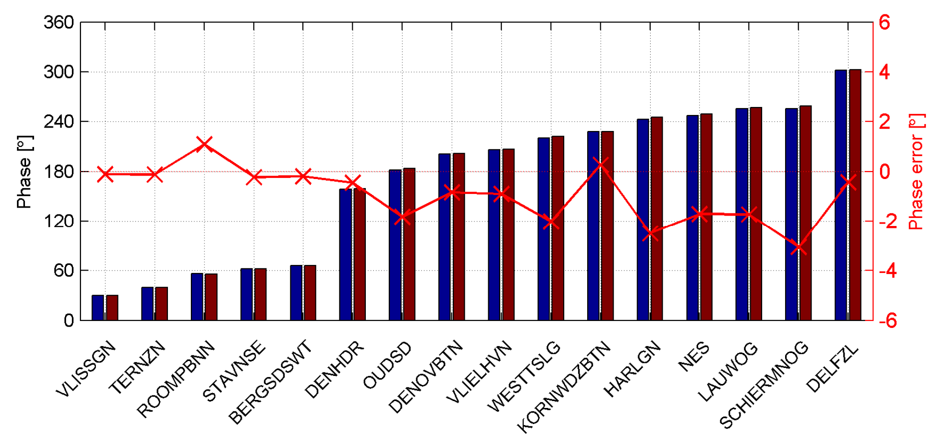
# Tide representation in the frequency domain

## Based on 16 stations in Dutch estuaries en Wadden Sea

| | DCSMv6-ZUNOv4 | | |
|---|---|---|---|
| | RMS(ΔA) | RMS(ΔG) | RMS(VD) |
| Q1 | 0.4 | 8.0 | 0.6 (0.6) |
| O1 | 0.3 | 2.4 | 0.5 (0.6) |
| P1 | 1.0 | 3.4 | 1.0 (0.9) |
| K1 | 0.1 | 2.4 | 0.3 (0.4) |
| N2 | 0.3 | 1.4 | 0.5 (0.7) |
| **M2** | **1.3** | **1.4** | **2.7 (4.1)** |
| **S2** | 0.8 | 1.2 | 1.0 (1.4) |
| K2 | 0.7 | 1.5 | 0.7 (0.8) |
| **M4** | **0.9** | **6.6** | **1.4 (5.2)** |
| M6 | 0.6 | 9.8 | 1.1 (2.0) |

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**H: amplitude in cm, G: phase in °, VD: vector difference in cm**

# Kalman filtering (setup)

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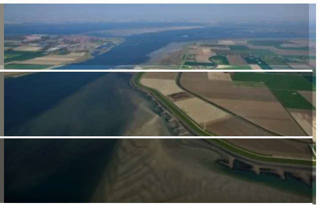
# Kalman filter setup



- Kalman filter used to do state updating
- Difference between model and observation is translated to additional wind speed, with an characteristic time scale (6 hr). This ensures a smooth transition to the predictive mode and avoids inconsistency between wind forcing and initial condition at the start of forecast.
- Both Ensembe Kalman filter and Steady State Kalman filter are available in open source data assimilation tool box OpenDA
- Ensemble Kalman filter with 100 members
- On a dual-hexacore machine, a 15-day simulation takes 17 days → for an operational system, this is not acceptable
- We have good experience with steady state Kalman filtering
  - Compute a steady state Kalman gain off-line once (average over a week)
  - Use the Kalman gain operationally with a steady-state Kalman filter

OpenDA
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# Selection of assimilation stations

- Only limited sensitivity to parameters (length and time scales) (right order of magnitude is sufficient), but very important to choose the right assimilation locations

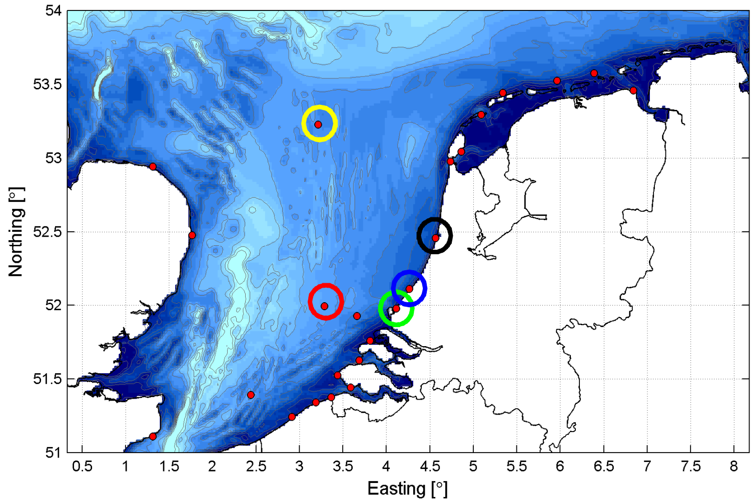
- Selection of the assimilations stations are based on:
  1. Continued, real-time availability of observing stations
  2. Insight in the physical system and model quality
  3. Use of a technique for observation impact analysis

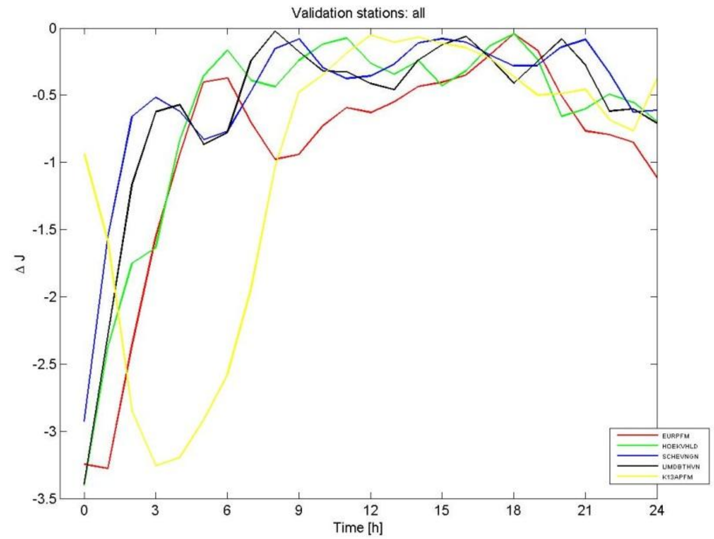
- In the past, not all observations helped improve forecast quality.

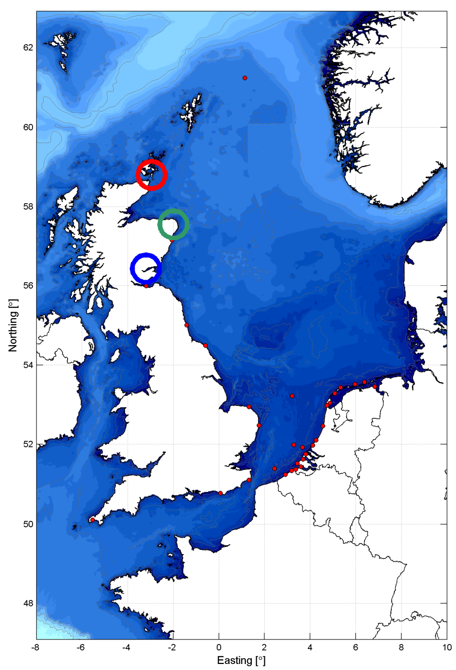
- Impact of observation on forecast quality can be obtained using data denial experiments →requires a lot of experiments, time

- Ensemble based observation sensitivity: technique to estimate sensitivity of forecast accuracy to assimilated observation, using time series of observations and model residuals.

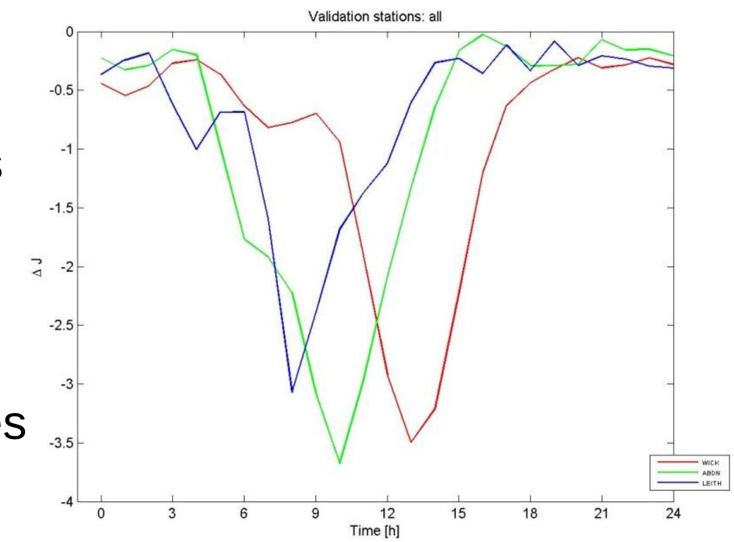
# Selection of assimilation stations



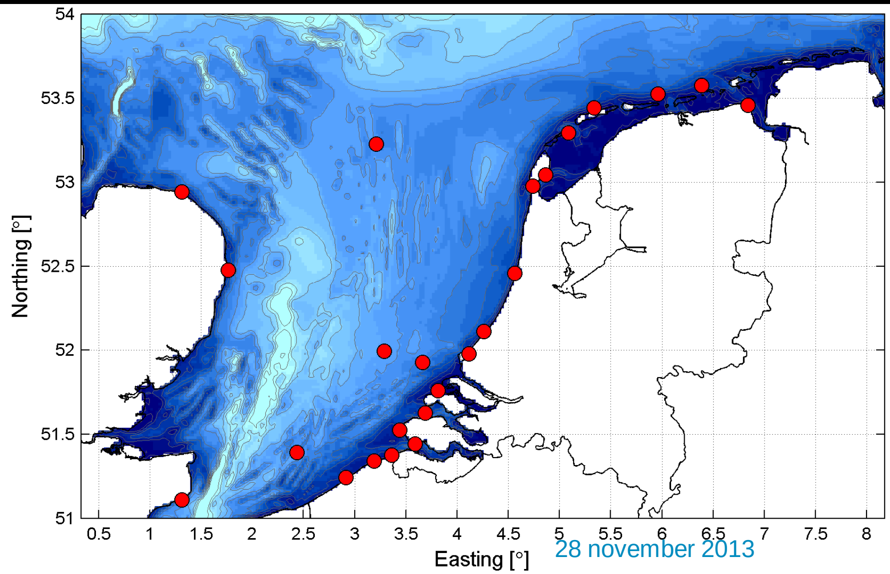



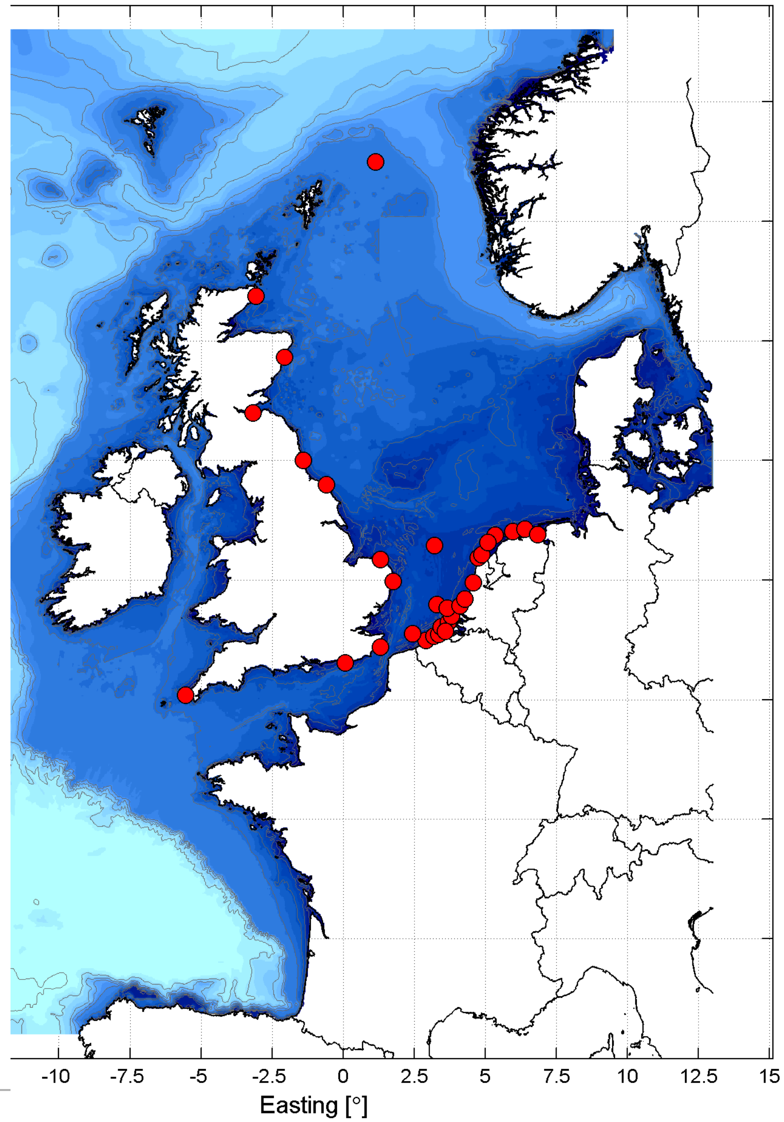

- Hardly any negative impact →initial choice of stations was good
- Assimilating nearby stations gives immediate impact on the forecast accuracy.
- Assimilating further away (upstream) stations improves the accuracy of longer forecast lead times.



# Kalman filter locations

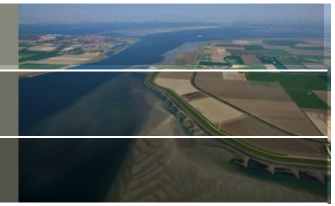
| | | |
|---|---|---|
| NORTHCMRT | CADZD | HUIBGT |
| WICK | WESTKPLE | NEWLN |
| ABDN | EURPFM | NEWHVN |
| LEITH | BROUWHVSGT08 | DOVR |
| NORTHSS | LICHTELGRE | VLISSGN |
| WHITBY | HOEKVHLD | ROOMPBTN |
| CROMR | SCHEVNGN | DENHDR |
| LOWST | IJMDBTHVN | OUDSD |
| Oostende | K13APFM | VLIELHVN |
| Westhinder | TERSLNZE | EEMSHVN |
| Zeebrugge | WIERMGDN | |



# Kalman filtering (results - hindcast)

# Kalman filter DCSMv6-ZUNOv4



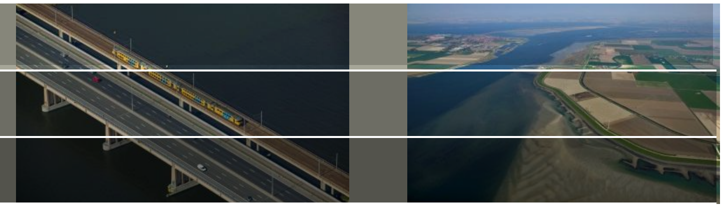
### Based on 13 stations along Dutch coast

| | RMSE (getij) | RMSE (opzet) | RMSE (volledig) | RMSE (hoogwater) | RMSE (laagwater) |
|---|---|---|---|---|---|
| **DCSMv6-ZUNOv4** | 4.0 | 5.8 | 7.0 | 6.2 | 6.9 |
| **DCSMv6-ZUNOv4-Kf** | **1.9** | **2.5** | **3.1** | **2.9** | **3.0** |

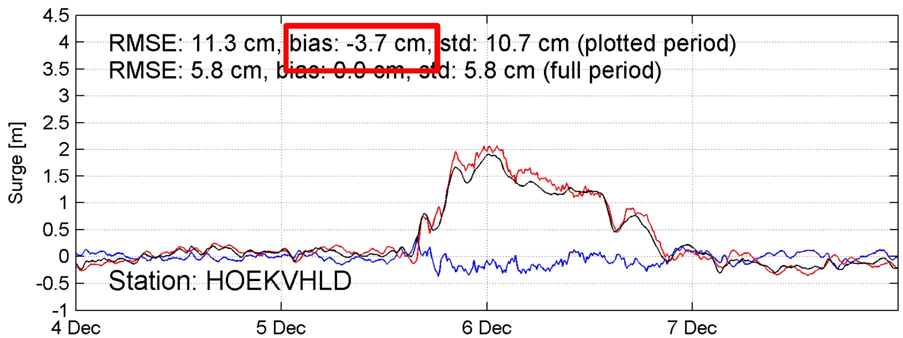
### Based on 16 stations in Dutch estuaries en Wadden Sea

| | RMSE (getij) | RMSE (opzet) | RMSE (volledig) | RMSE (hoogwater) | RMSE (laagwater) |
|---|---|---|---|---|---|
| **DCSMv6-ZUNOv4** | 4.5 | 6.0 | 7.5 | 6.7 | 7.6 |
| **DCSMv6-ZUNOv4-Kf** | **3.1** | **3.6** | **4.7** | **4.0** | **4.7** |

# Hoek van Holland

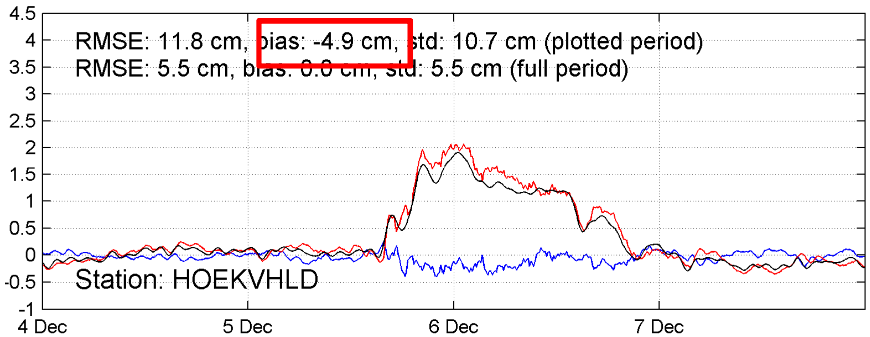


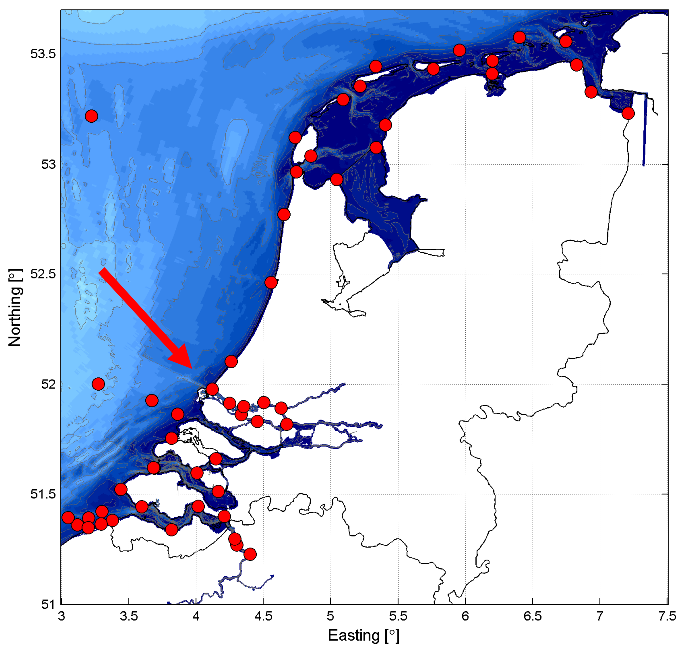
## DCSMv6



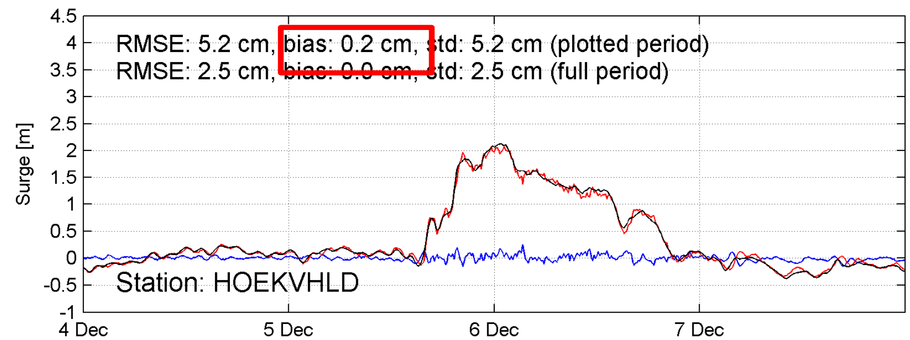

## DCSMv6-ZUNOv4

without Kf



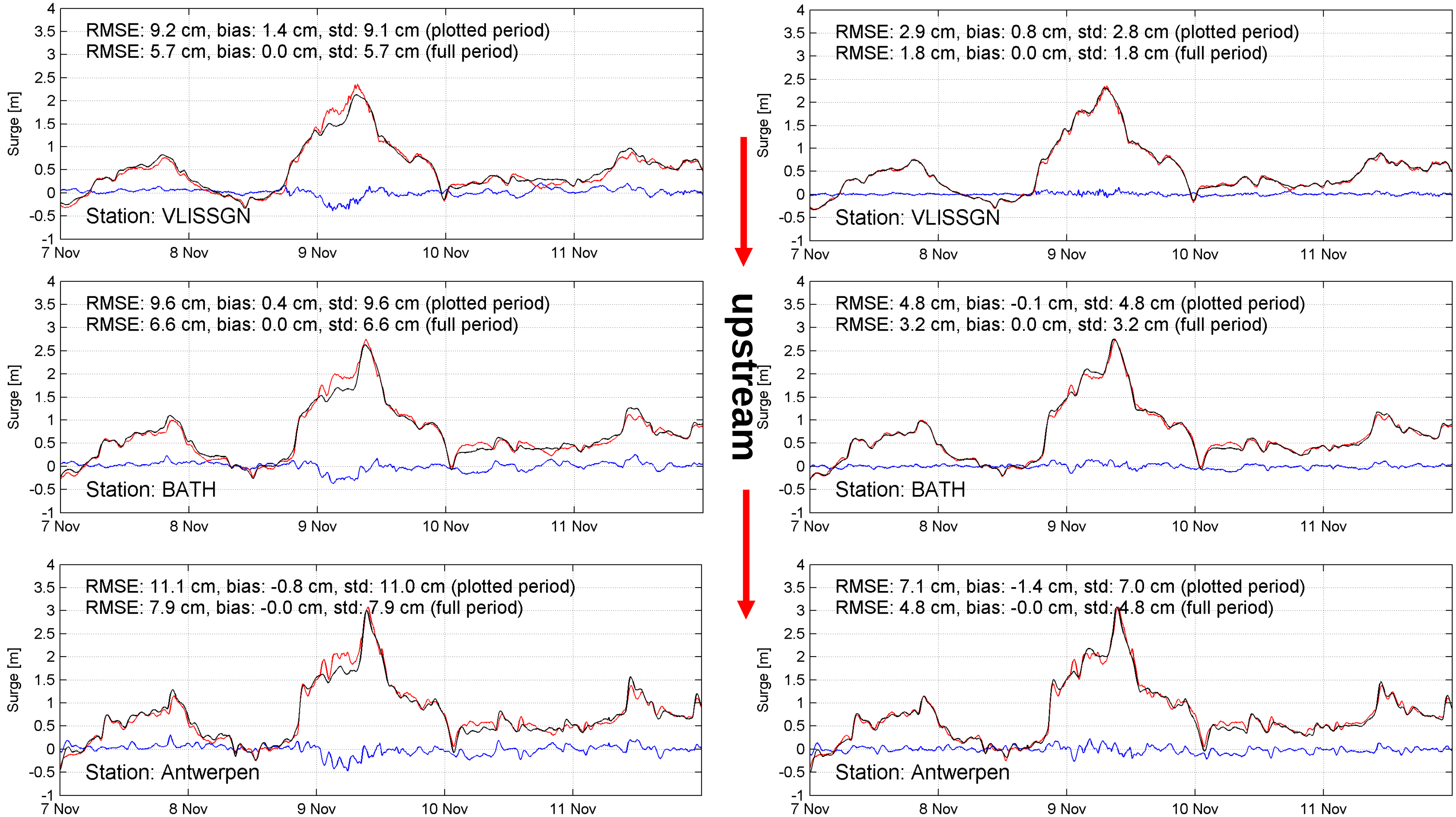




with Kf



# Kalman filter DCSMv6-ZUNOv4

**without Kalman filter** | **with Kalman filter**

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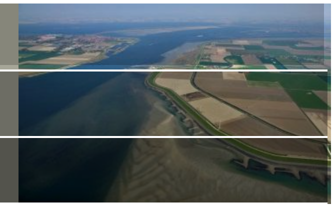
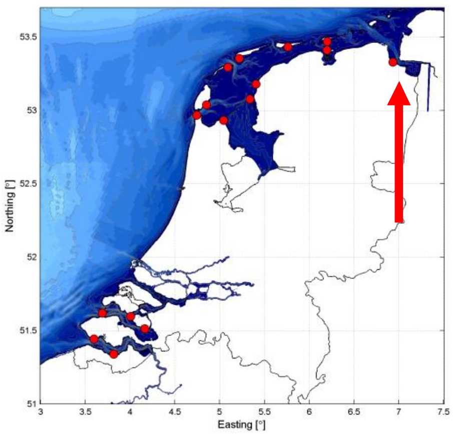
# Delfzijl



## 'Santa Claus' storm

**(December 5/6, 2013)**

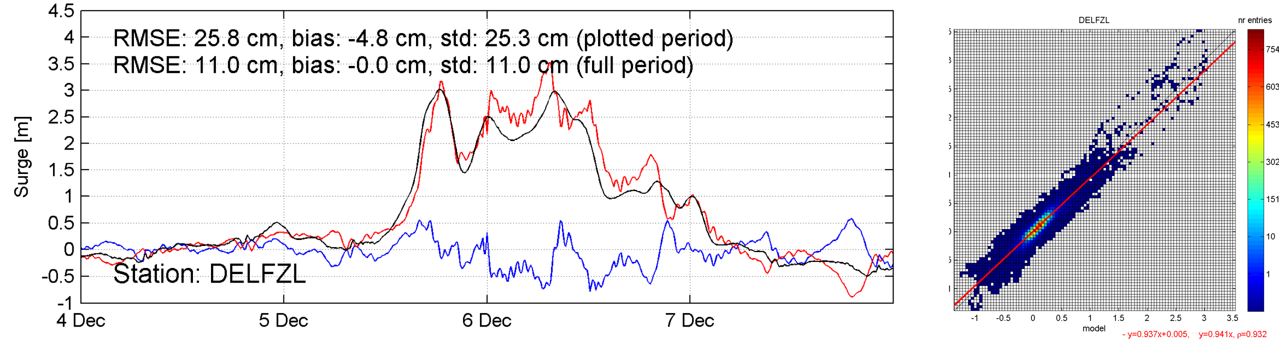



Red: Measurement

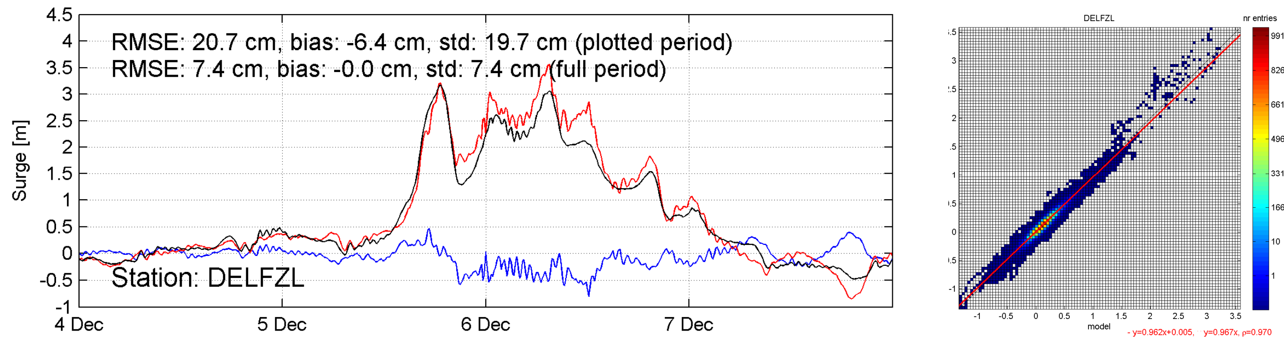
Black: Computation

Blue: Residual

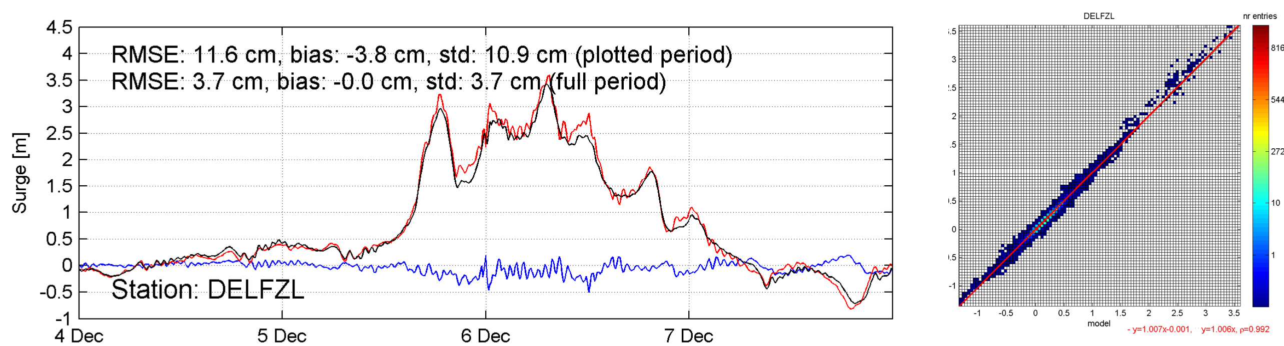
**DCSMv6**




**DCSMv6-ZUNOv4**




**with Kf**



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# Kalman filtering (results - forecast)

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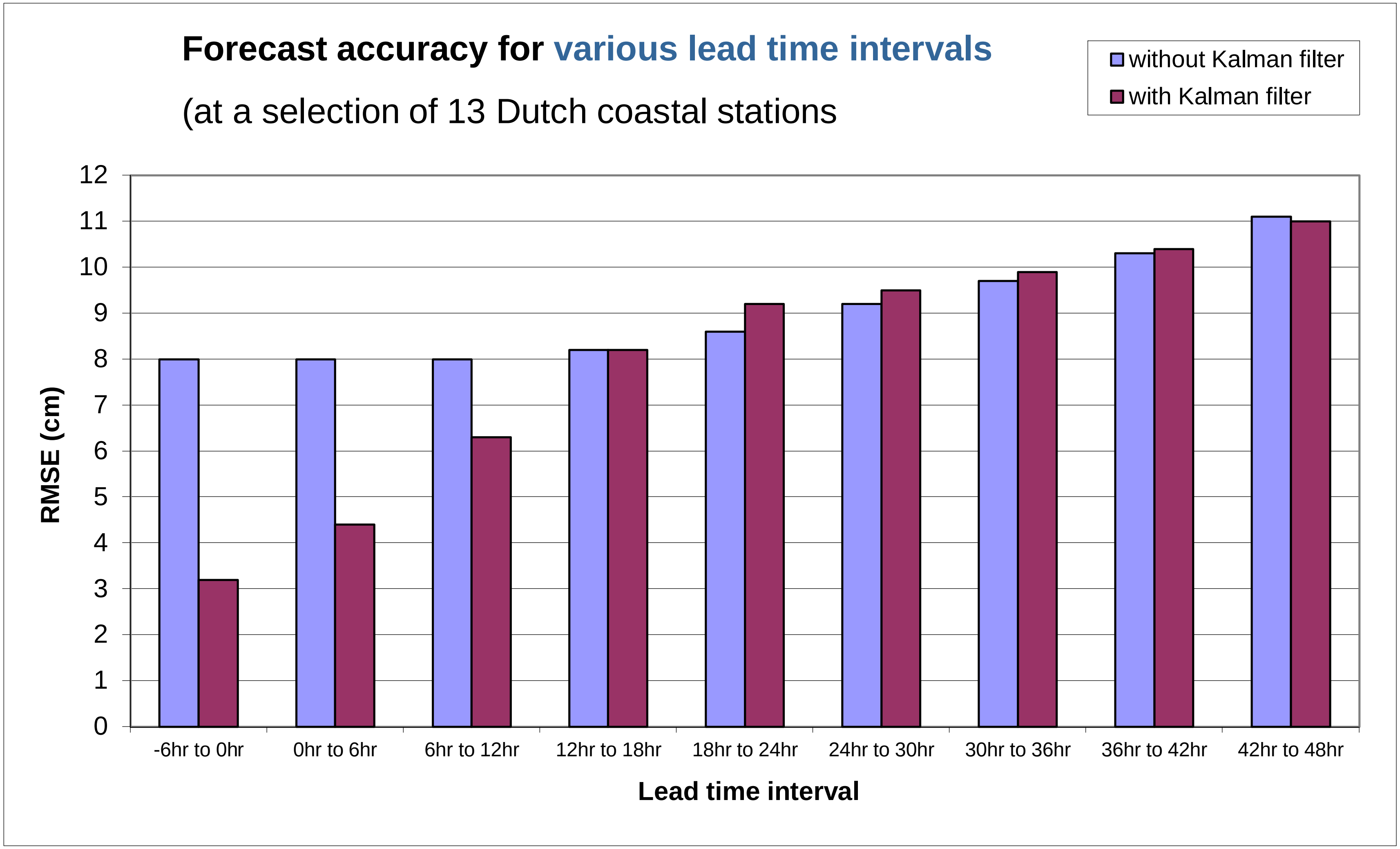
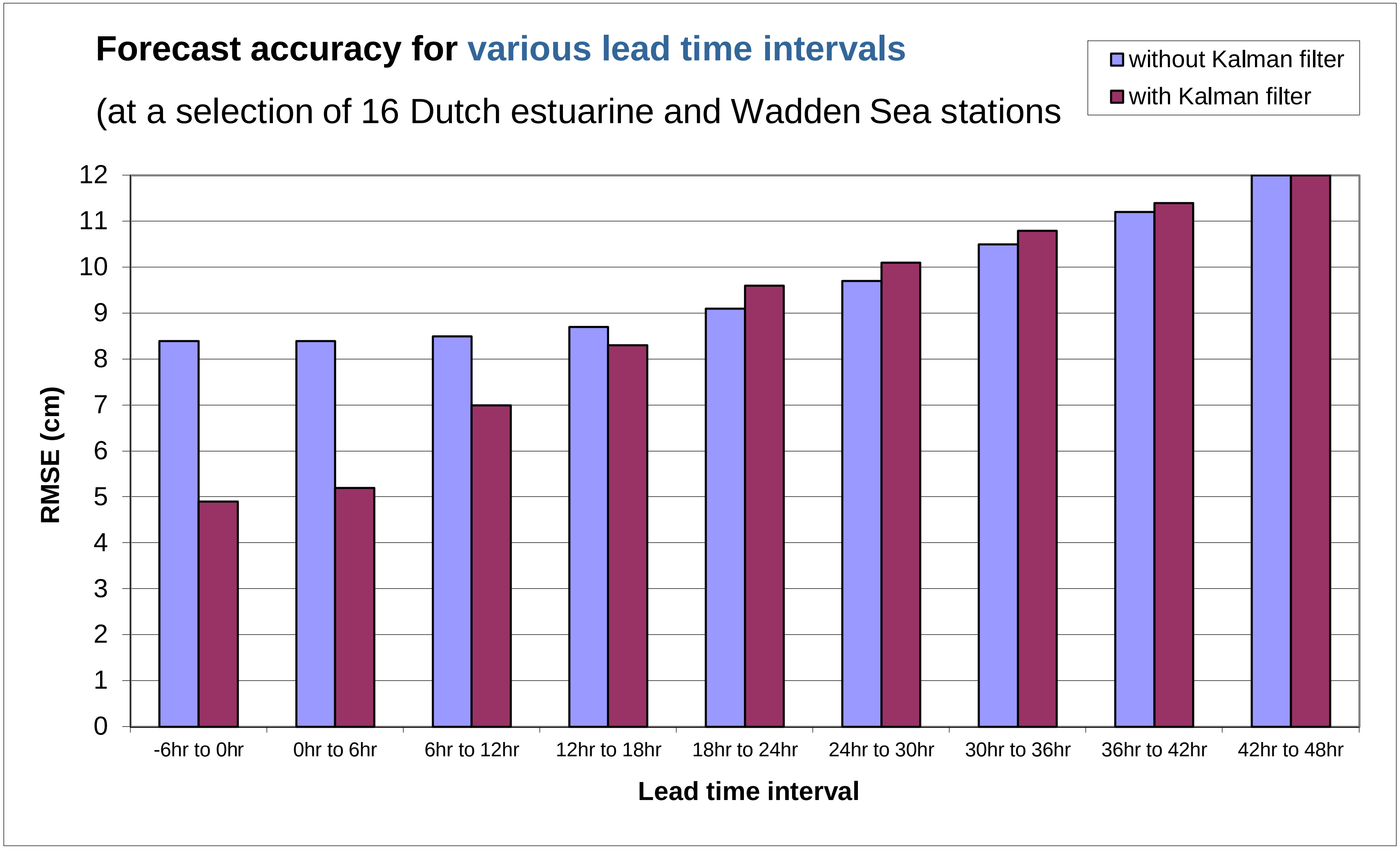
# Forecast accuracy DCSMv6-ZUNOv4




(based on collection of ~1500 historical forecasts)

# Forecast accuracy DCSMv6-ZUNOv4




(based on collection of ~1500 historical forecasts)



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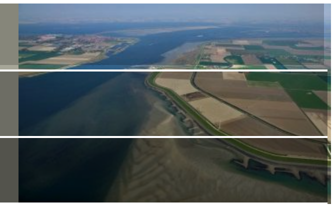
# Conclusions

# Conclusions



**Refined tide-surge model for the Northwest European Shelf**

- To better match local spatial scales in the Dutch estuaries and Wadden Sea) a domain decomposition approach was used to refine the Dutch Continental Shelf model
- A rigorous, well-structured approach to data assimilation was used to reduce uncertainty in bottom friction and bathymetry
- Year-long simulations show excellent agreement with shelf-wide measurements
- When considering Dutch coastal stations, an excellent RMSE of 7.0 cm is found (4.0 cm for the tide). This implies an improvement of 47% (63 % for the tide) compared to the previous generation model.
- When considering Dutch estuarine and Wadden Sea stations, an excellent RMSE of 7.5 cm is found (4.5 cm for the tide). This implies an improvement of 24% (37 % for the tide) compared to the unrefined model.

# Conclusions

**Steady state Kalman filter**

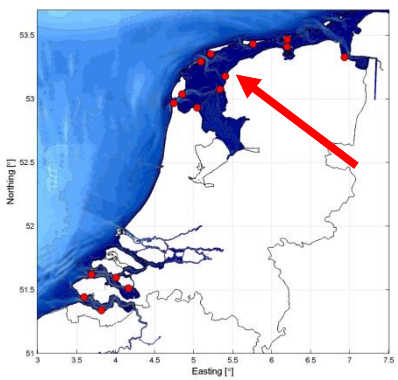
• A steady state Kalman filter is implemented to improve forecast accuracy for the shorter lead-times, with an acceptable computational burden

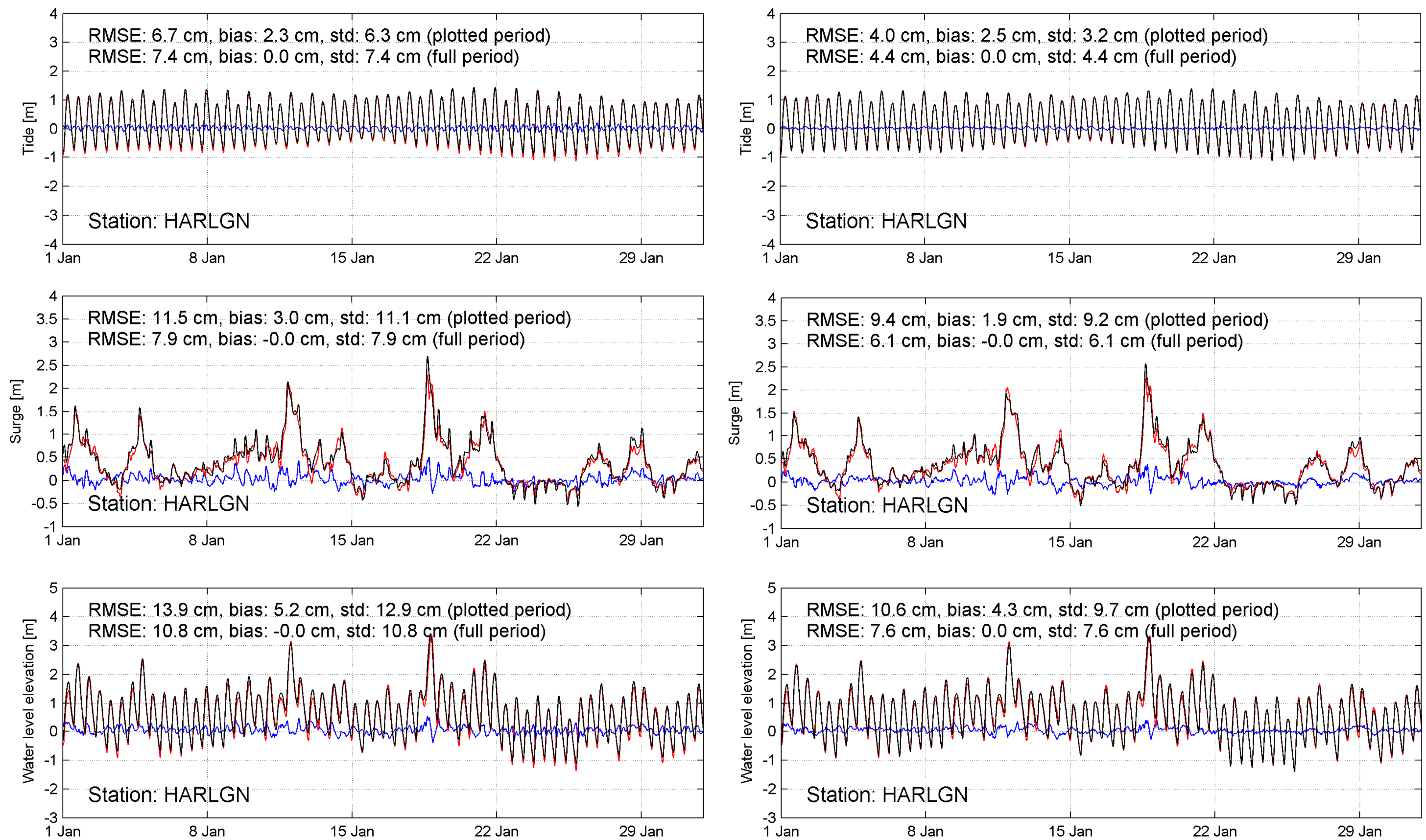
• Year-long hindcast simulations show large improvement in water level representation, both at the Kalman filter locations and further upstream.

• Crucially, the Kalman filter successfully improves forecast accuracy up to 12 - 18 hours. For longer lead times the accuracy converges to that of the model without Kalman Filter.

Thank you!

# DCSMv6-ZUNOv4 (Dutch estuaries and Wadden Sea)




Red: Measurement

Black: Computation

Blue: Residual

Deltares