A bias-kalman-filter for operational storm-surge forecasting

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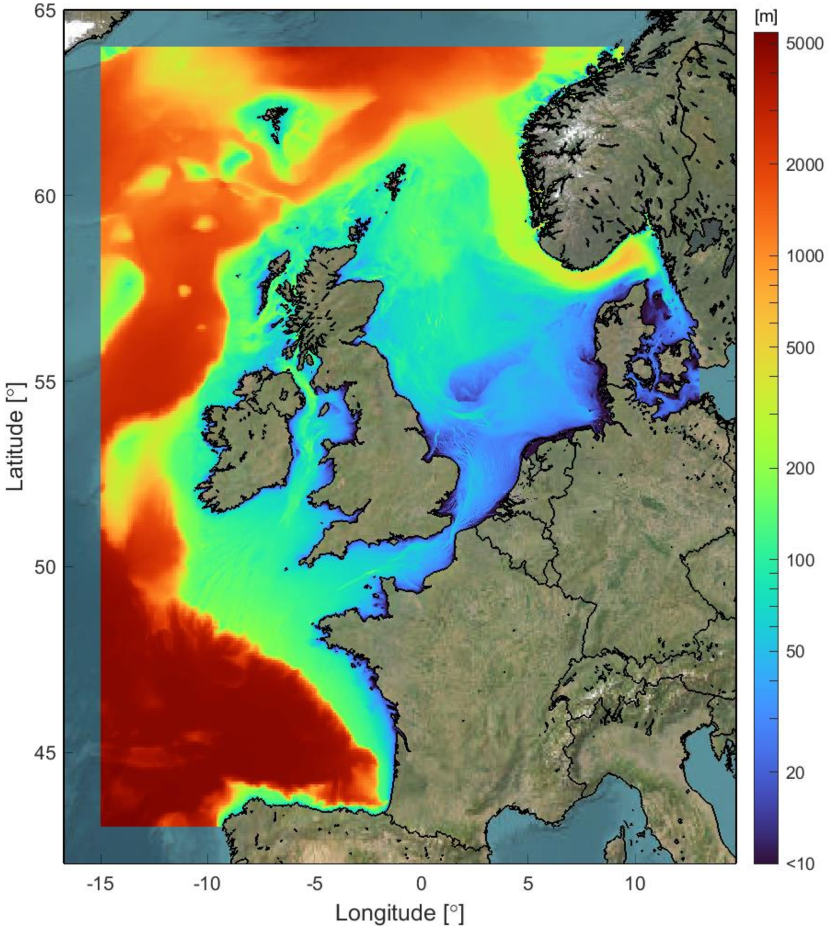
Dutch Continental Shelf Model
Delft3D-Flexible Mesh



Shallow-water tide-surge model

$$\frac{\partial h}{\partial t}+\nabla(Hu)=0$$

$$\frac{\partial u}{\partial t}+\frac{1}{H}\left(\nabla\cdot(Huu)-u\nabla(Hu)\right)+f\times u$$

$$=-g\nabla(h-\boxed{h_{tide}})-\boxed{\frac{\nabla p_{atm}}{\rho}+\frac{\tau_{atm}}{\rho H}}$$

Forcing:
- Tide
- Air-pressure and wind

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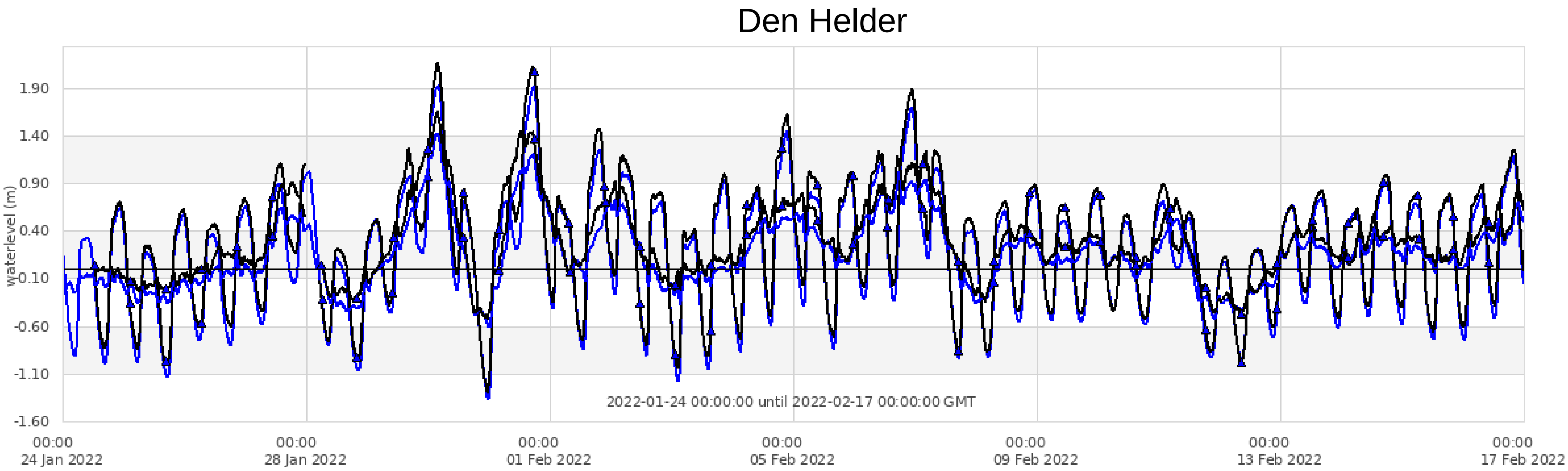
Bias in operational storm-surge forecasts in 2022



Model
Measurement

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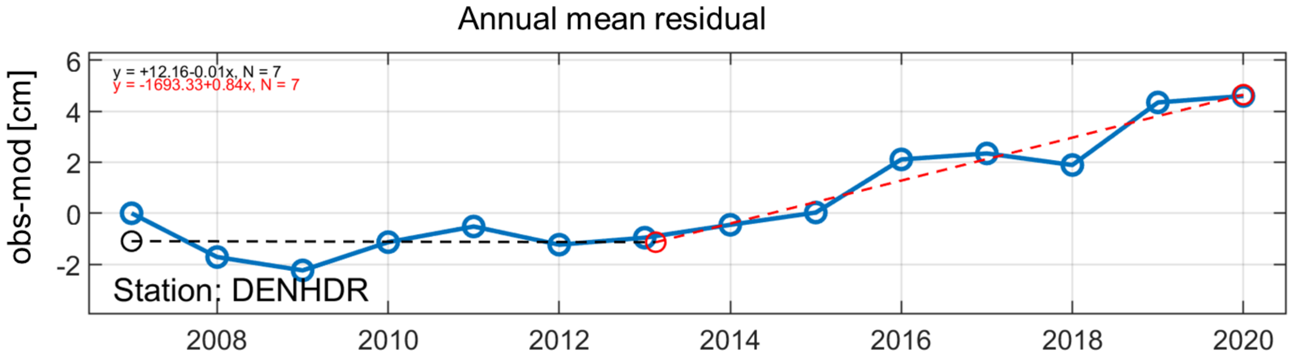
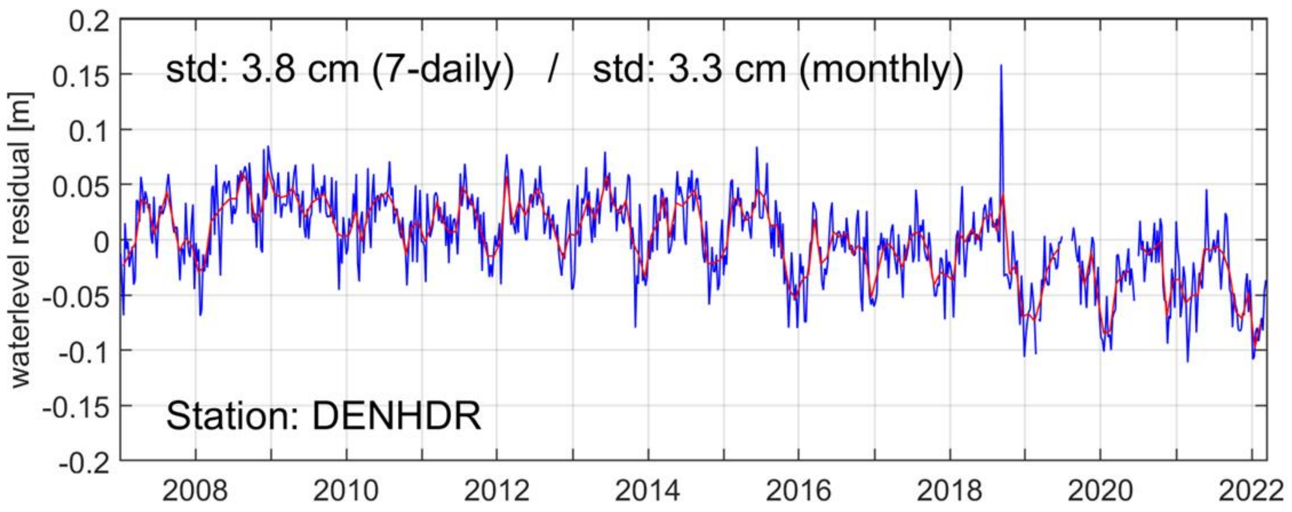
Possible causes

- Vertical referencing
  - Local subsidence / tide gauge benchmark
  - Issues in national vertical reference systems
  - Connection between countries
- Uncertainty in boundary conditions
  - Sea level rise
  - Seasonal variations
  - Long period ocean variations
- Model physics
  - 3D effects (density, temperature, salinity)



Running mean (7 and 30 days)



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Ensemble Kalman filter – add 'bias-force' to model

EnKF

Time update

$$\xi_{k+1}^f(i) = M\left(\xi_k^a(i)\right)$$

$$\hat{x}_k^f = \frac{1}{N}\sum_{i=1}^{N} \xi_k(i)$$

$$P_k^f = \frac{1}{N-1}\sum_{i=1}^{N}\left(\xi_k^f(i) - \hat{x}_k^f\right)\left(\xi_k^f(i) - \hat{x}_k^f\right)'$$

OpenDA

Measurement update

$$K_k = P_k^f H'\left[H P_k^f H' + R\right]^{-1}$$

$$\xi_k^a(i) = \xi_k^f(i) + K_k\left(z_k - H\xi_k^f(i) - v_k(i)\right)$$

Model

Shallow water equations:

$$x = \begin{bmatrix} h \\ u \\ h_{bias} \end{bmatrix}$$

$$\frac{\partial h}{\partial t} + \nabla(Hu) = 0$$

$$\frac{\partial u}{\partial t} + \frac{1}{H}\left(\nabla\cdot(Huu) - u\nabla(Hu)\right) + f\times u$$

$$= -g\nabla\left(h - h_{tide} - h_{bias}\right) - \frac{\nabla p_{atm}}{\rho} + \frac{\tau_{atm}}{\rho H}$$

Add term in pressure gradient, that will be balanced by sea-level if changes are slow enough.

Asher et al 2019, "Low frequency water level correction in storm surge models using data assimilation", Ocean modelling, https://doi.org/10.1016/j.ocemod.2019.101483

Noise model

Specifications:

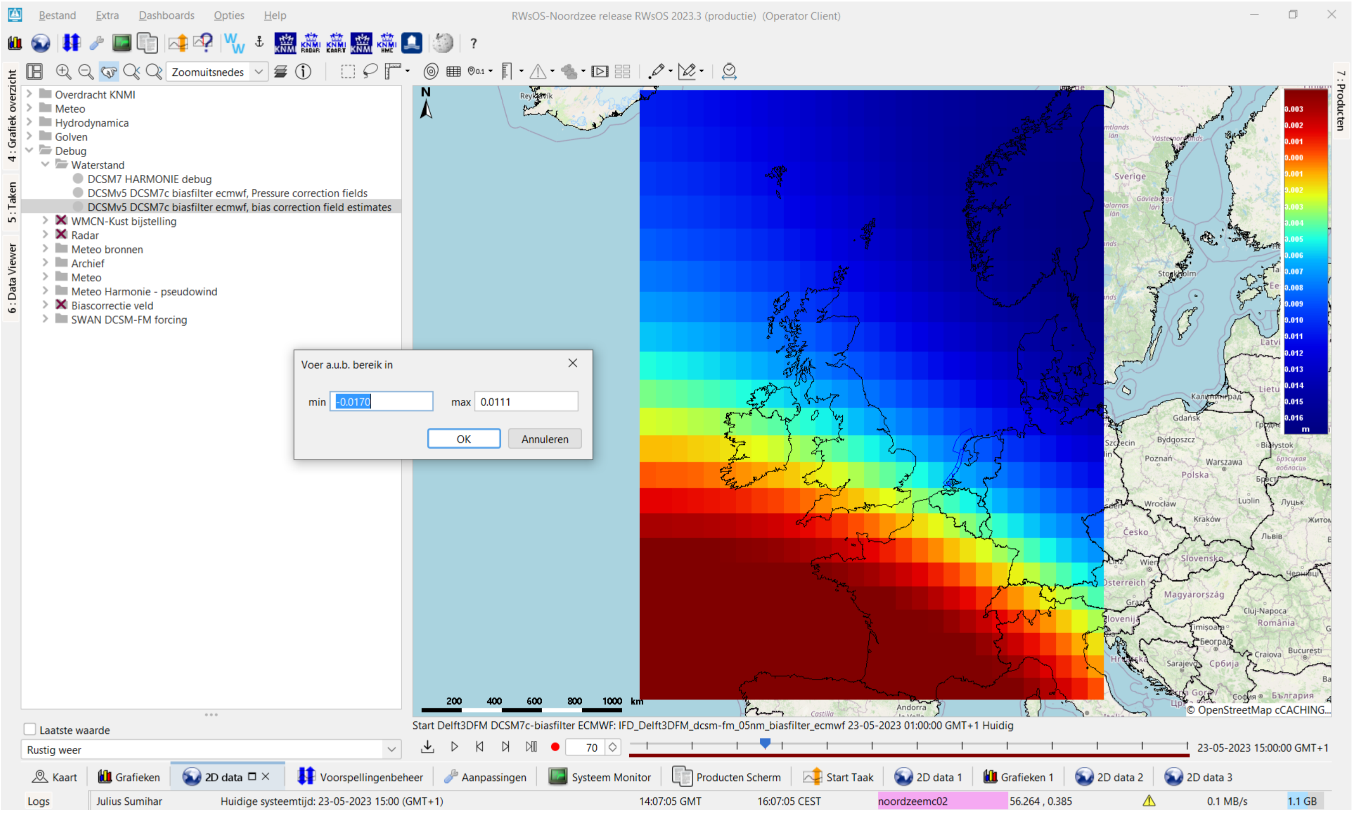
First-order autoregressive AR(1)

$$h_{bias,k+1}(x,y) = \alpha\, h_{bias,k}(x,y) + w_k(x,y)$$

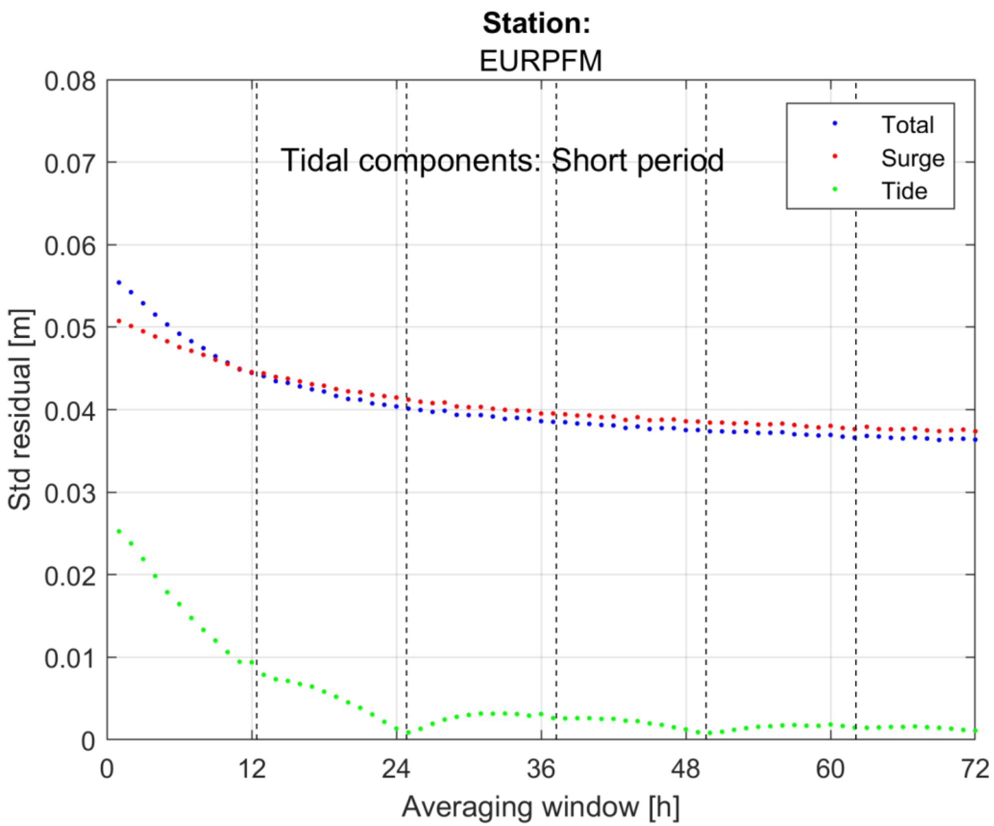
Time correlation scale: 750 hours

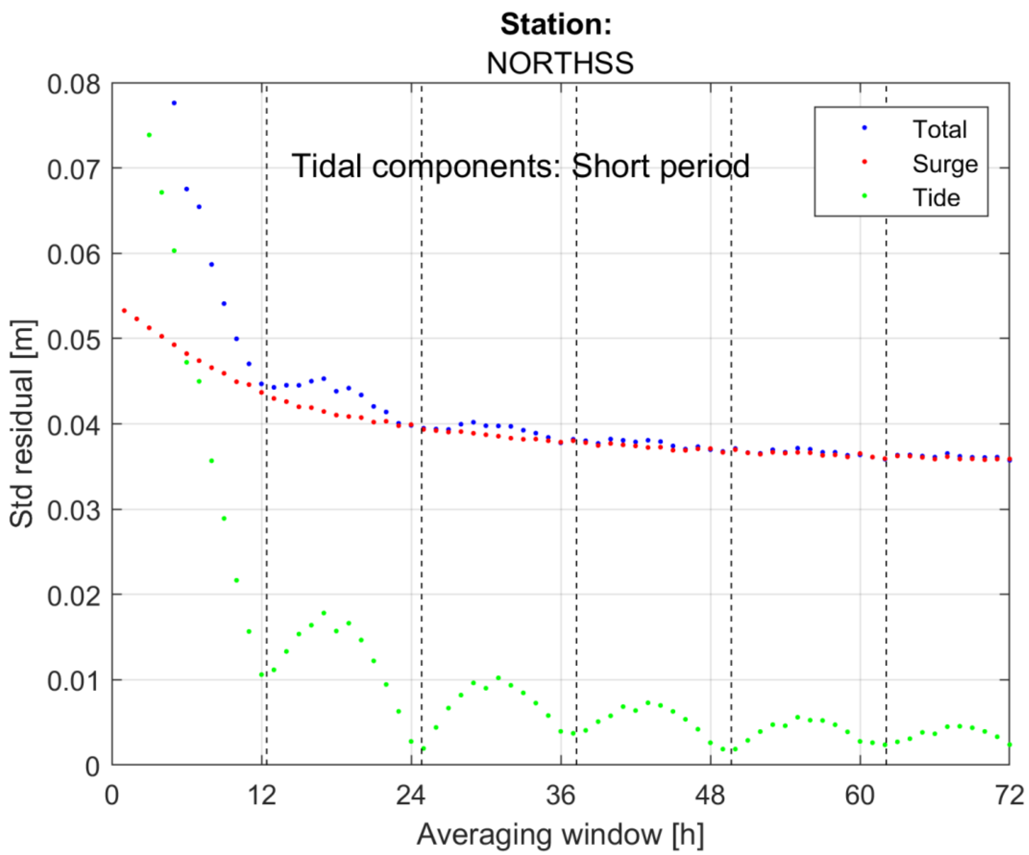
Horizontal correlation scale: 1500 km

$$w_k \sim N(0, Q)$$



Temporal averaging of measurements





24hour average eliminates most tidal errors

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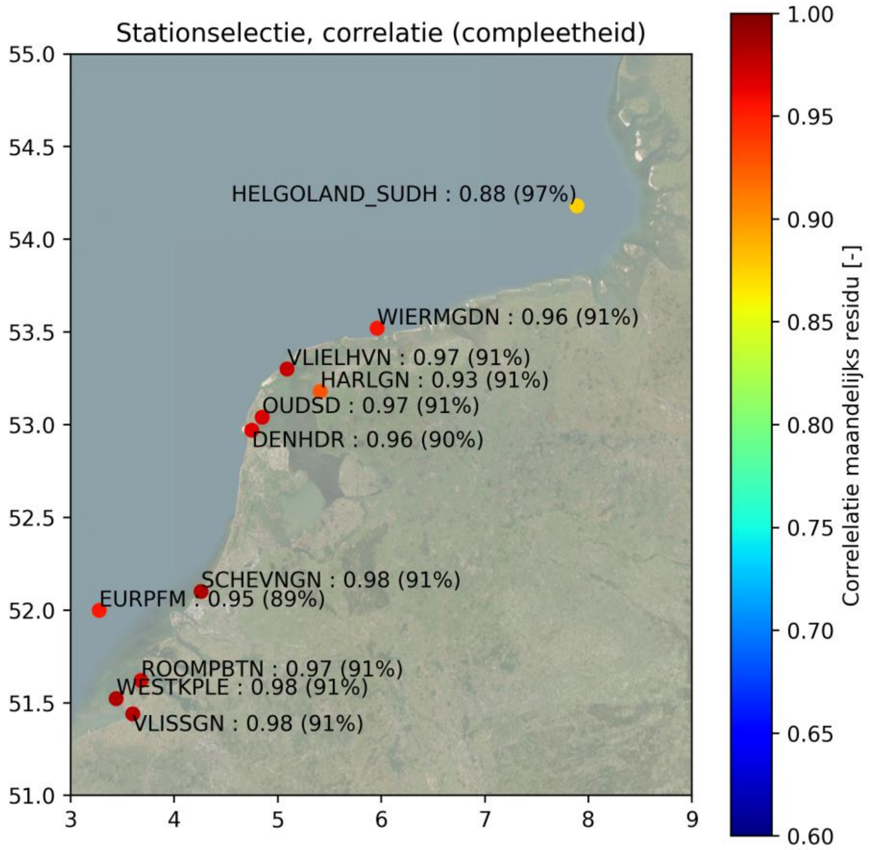
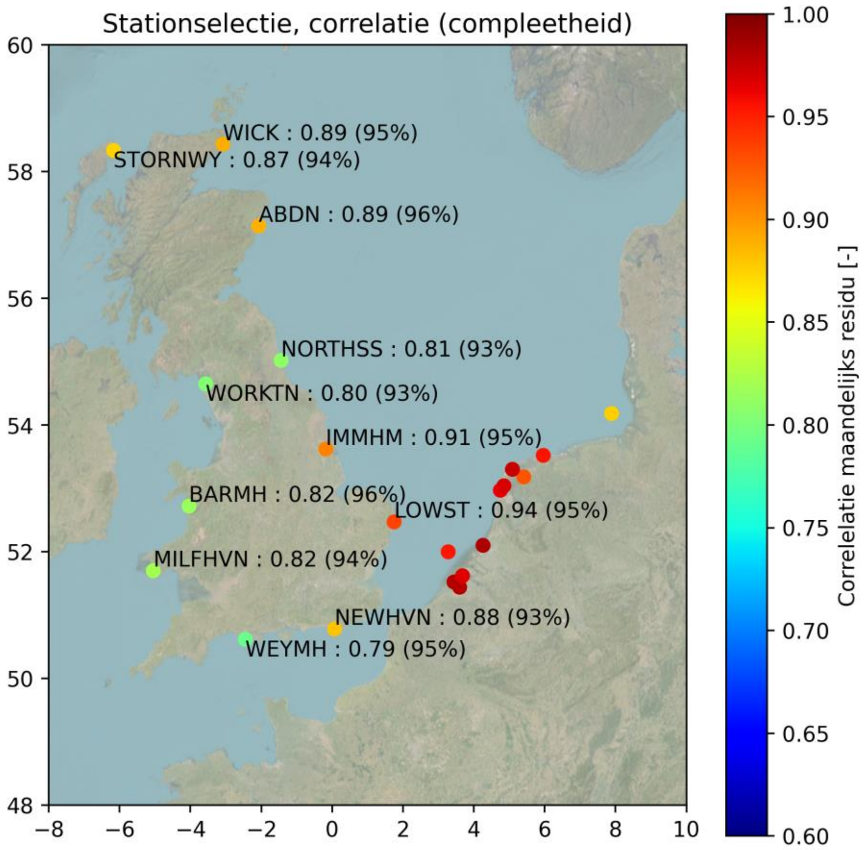
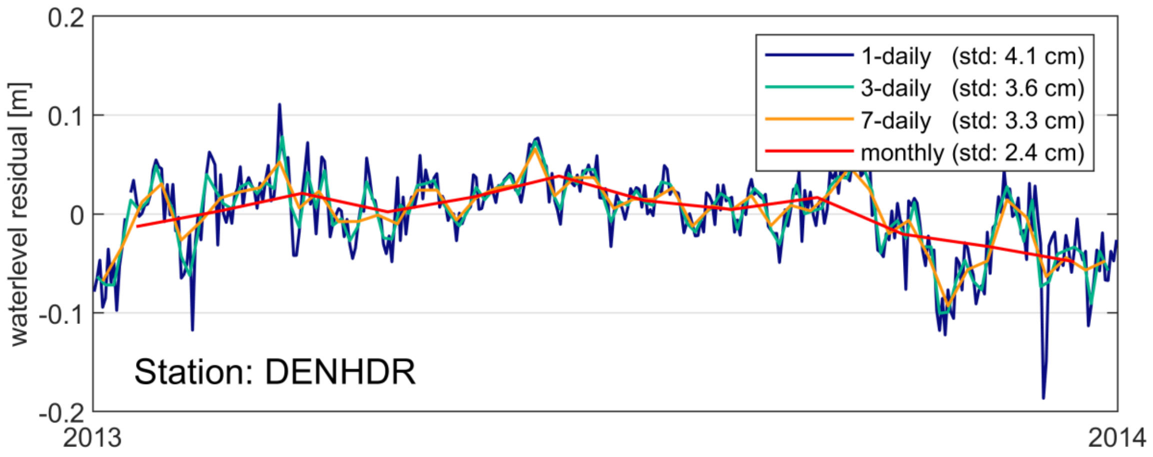
The bias kalman filter assimilates daily waterlevels at 22 stations in the North Sea



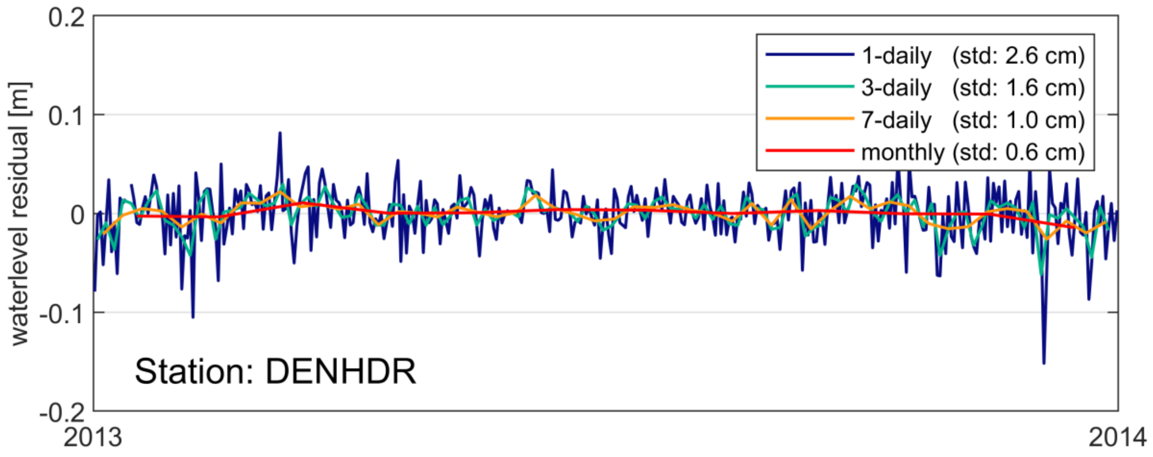


First results: example time-series of residuals from a hindcast

Simulation 2013 without bias Kalman filter

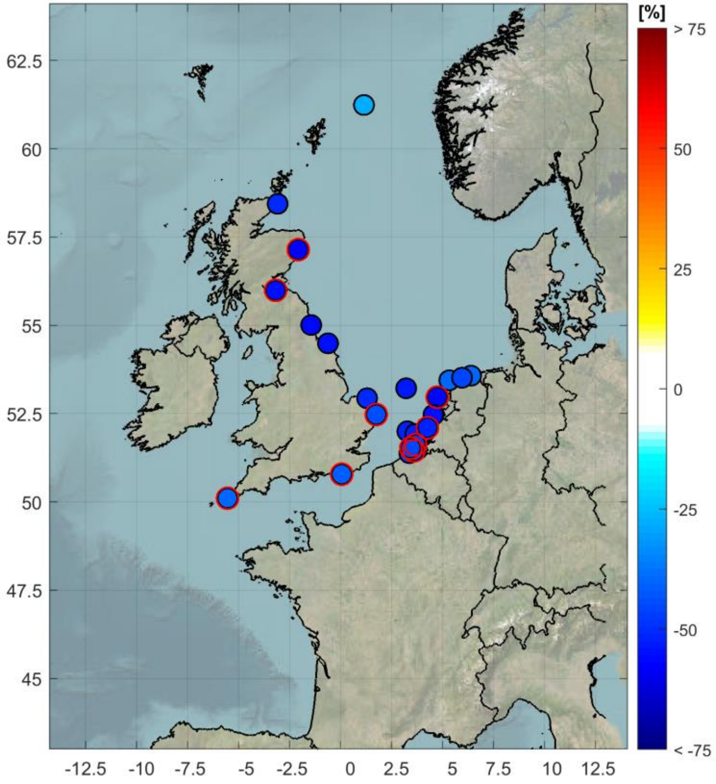


Simulation 2013 with bias Kalman filter

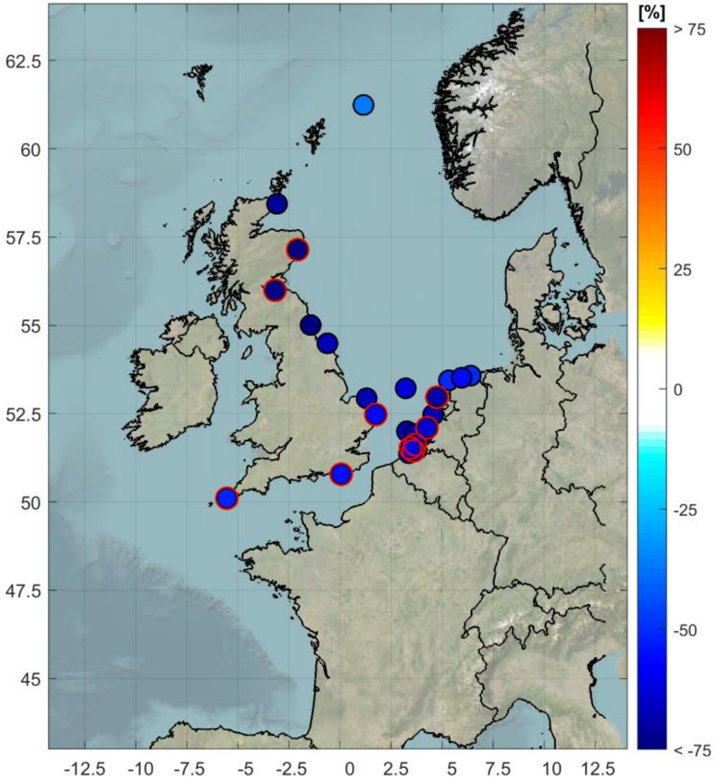


Impact on low-frequency residuals

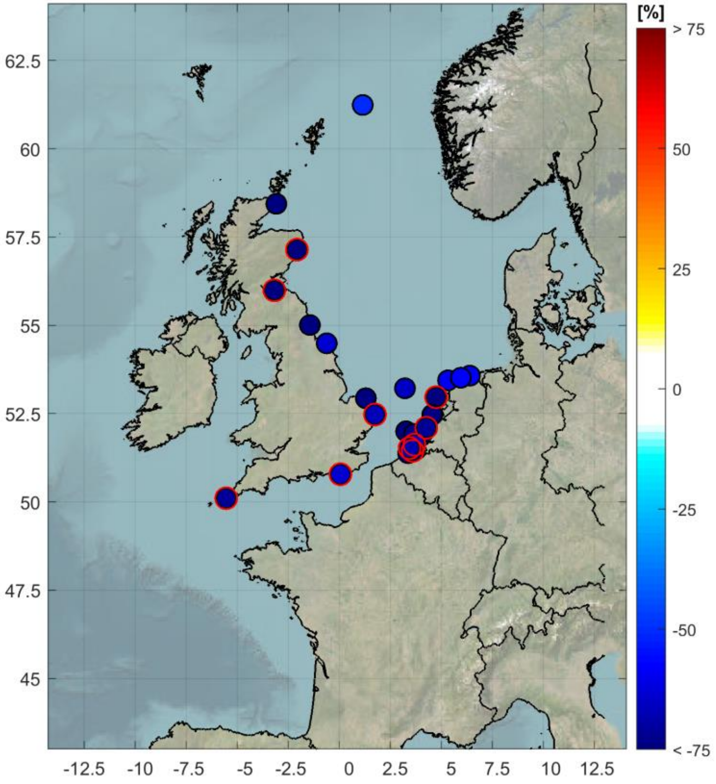
Change in std 3-day averaged residual rel. to reference simulation [%]



Change in std 7-day averaged residual rel. to reference simulation [%]



Change in std monthly residual rel. to reference simulation [%]



RMSE change of low-pass filtered residuals

○ = Assimilation station

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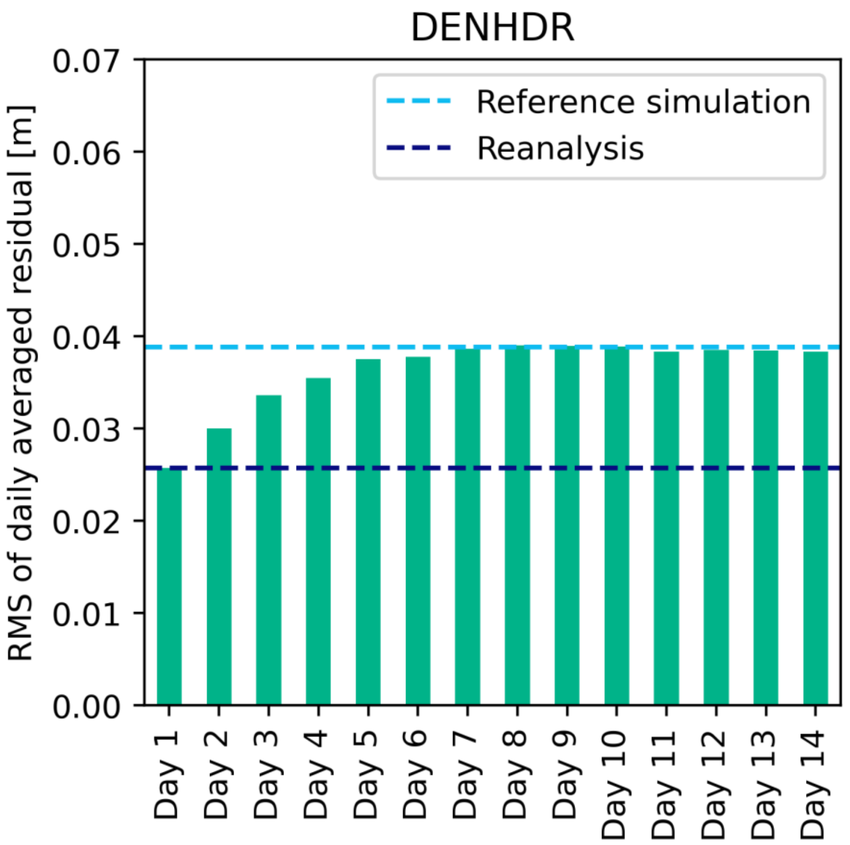
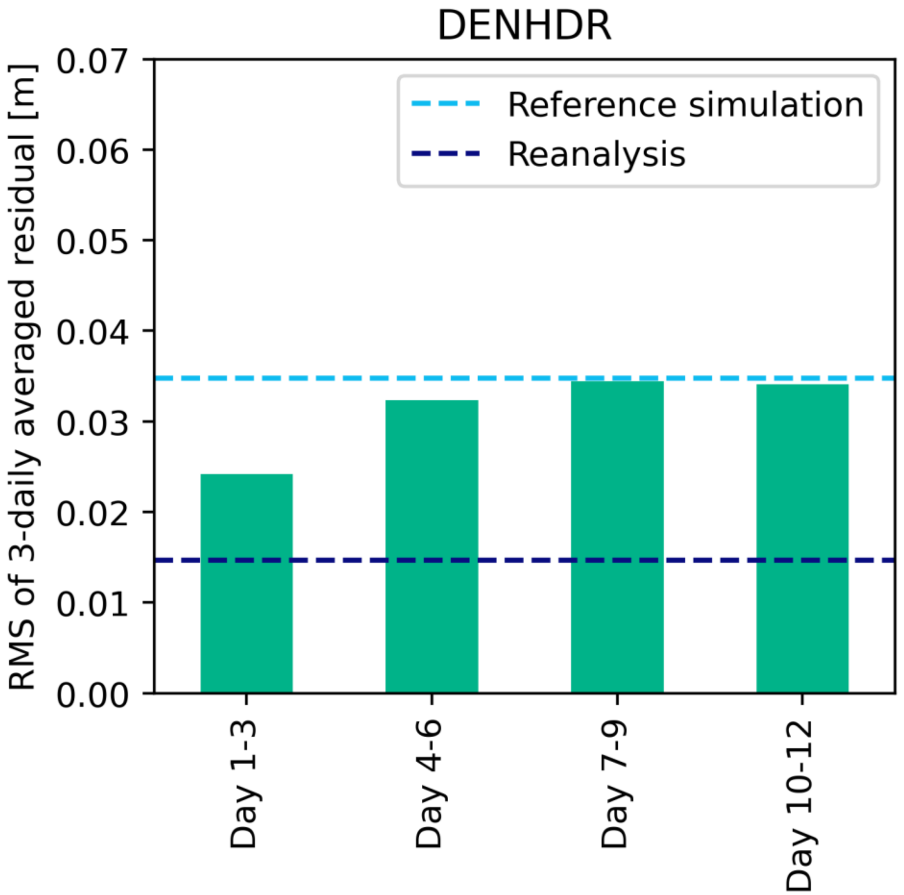
Forecast experiment with DCSM7 coarse





Reference simulation: Modelsimulation without biasKF
Reanalysis: Modelsimulation with daily assimilation of waterlevel residual

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Steady state filter vs. Ensemble Kalman Filter

EnKF

Time update

$$\xi^f_{k+1}(i) = \boldsymbol{M}\left(\xi^a_k(i)\right)$$

$$\hat{\boldsymbol{x}}^f_k = \frac{1}{N}\sum_{i=1}^{N} \xi_k(i)$$

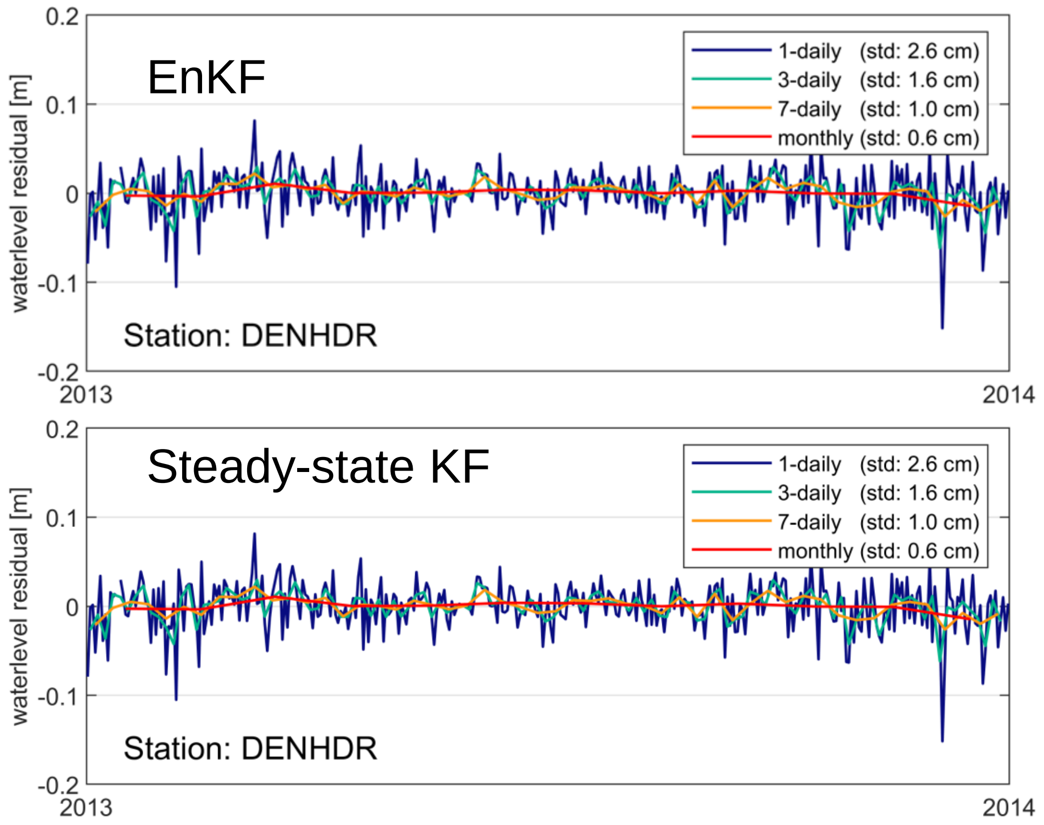
$$\boldsymbol{P}^f_k = \frac{1}{N-1}\sum_{i=1}^{N}\left(\xi^f_k(i) - \hat{\boldsymbol{x}}^f_k\right)\left(\xi^f_k(i) - \hat{\boldsymbol{x}}^f_k\right)'$$

Measurement update

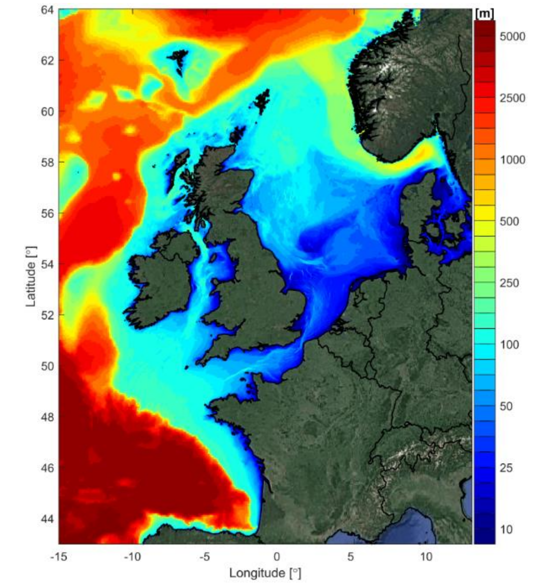
$$\boldsymbol{K}_k = \boldsymbol{P}^f_k \boldsymbol{H}'\left[\boldsymbol{H}\,\boldsymbol{P}^f_k \boldsymbol{H}' + \boldsymbol{R}\right]^{-1}$$

$$\xi^a_k(i) = \xi^f_k(i) + \boldsymbol{K}_k\left(\boldsymbol{z}_k - \boldsymbol{H}\,\xi^f_k(i) - \boldsymbol{v}_k(i)\right)$$

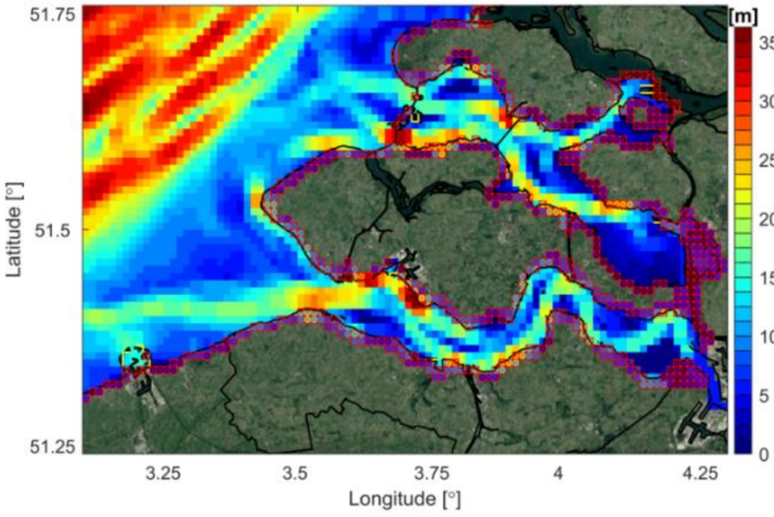
- If the Kalman Gain converges approximately to a steady value then steady-state filter is a much cheaper approximation



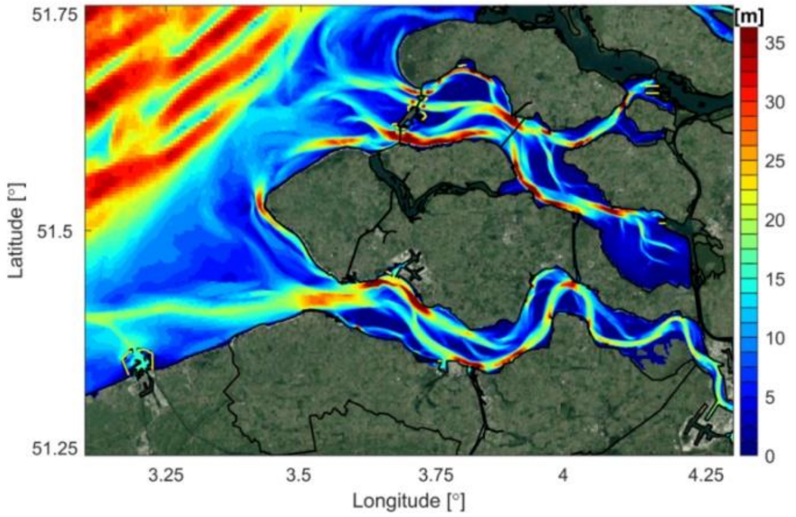
Apply estimated corrections to higher-resolution model

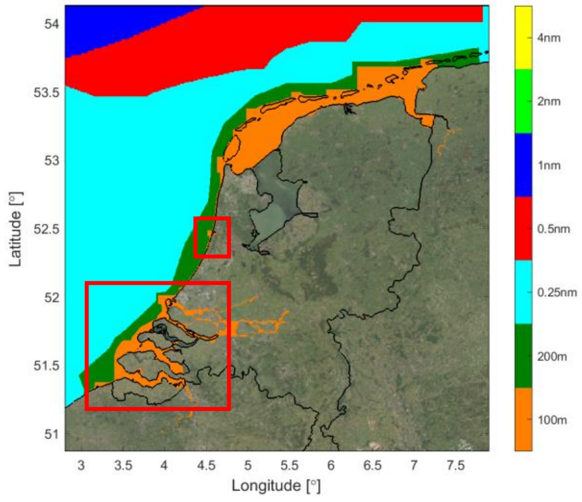


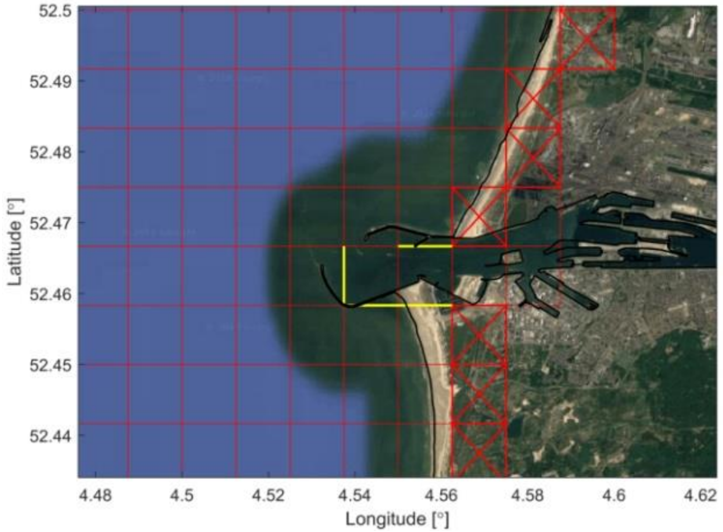
DCSM-FM 0.5 nm

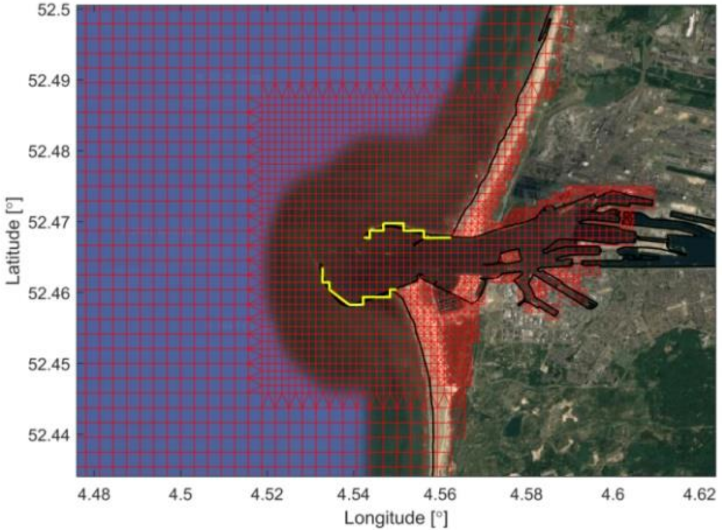


DCSM-FM 100m





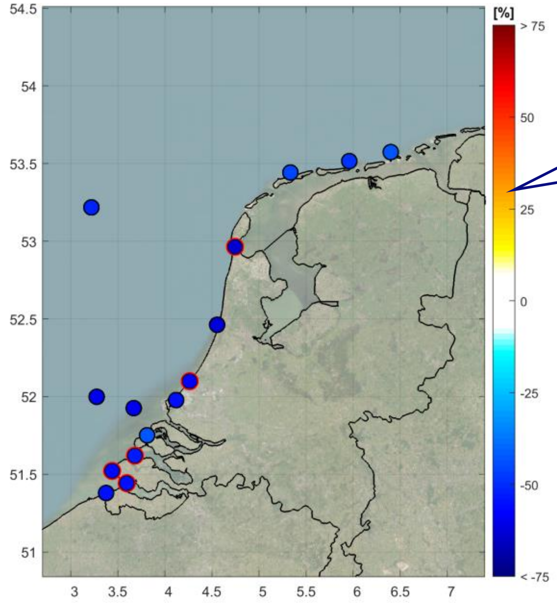




‘Bias correction field’, applied to DCSM-FM 100m

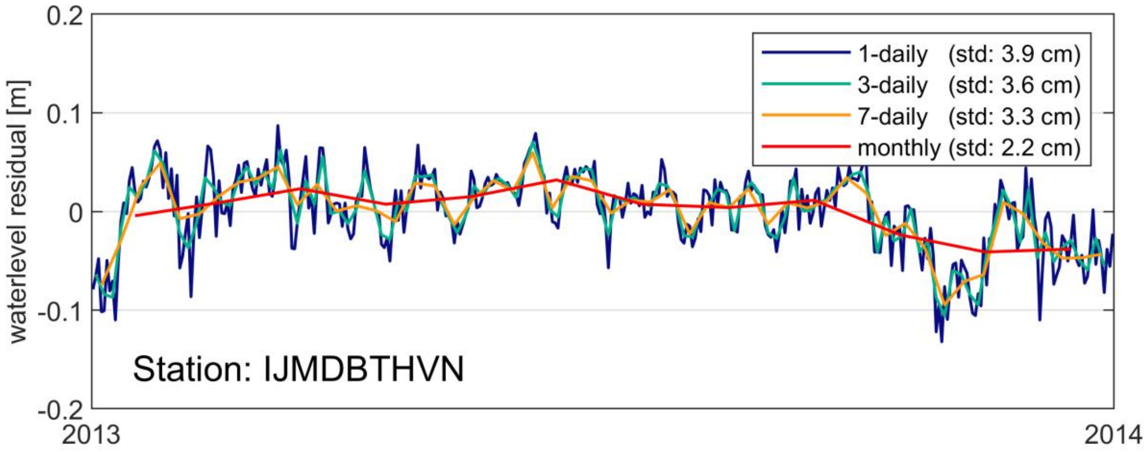
- Various model versions in operational system:
  - DCSM-FM 0.5nm
  - DCSM-FM 100m
- Estimate bias correction for coarse model and apply it to other models.

Change in std. 7-day averaged residual [%]

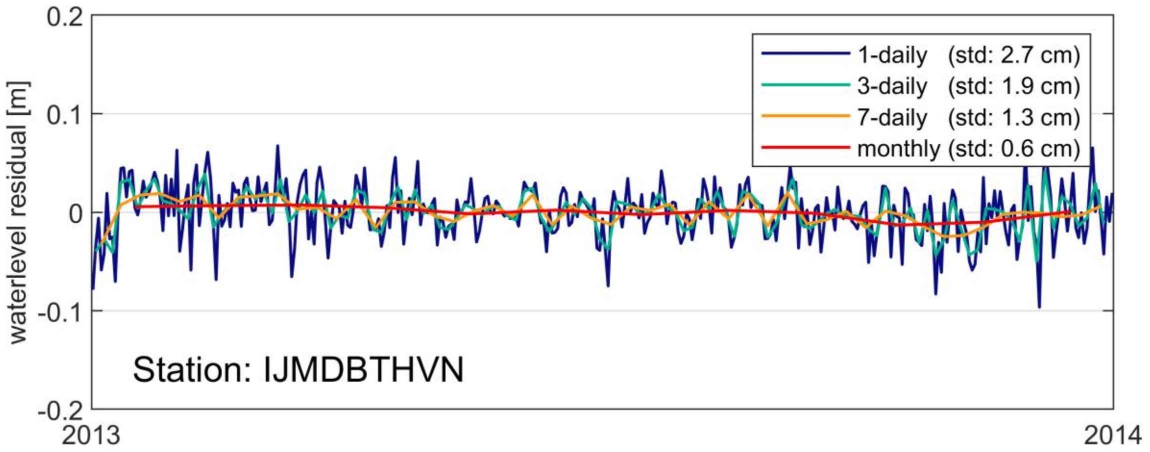


Average improvement: -56%

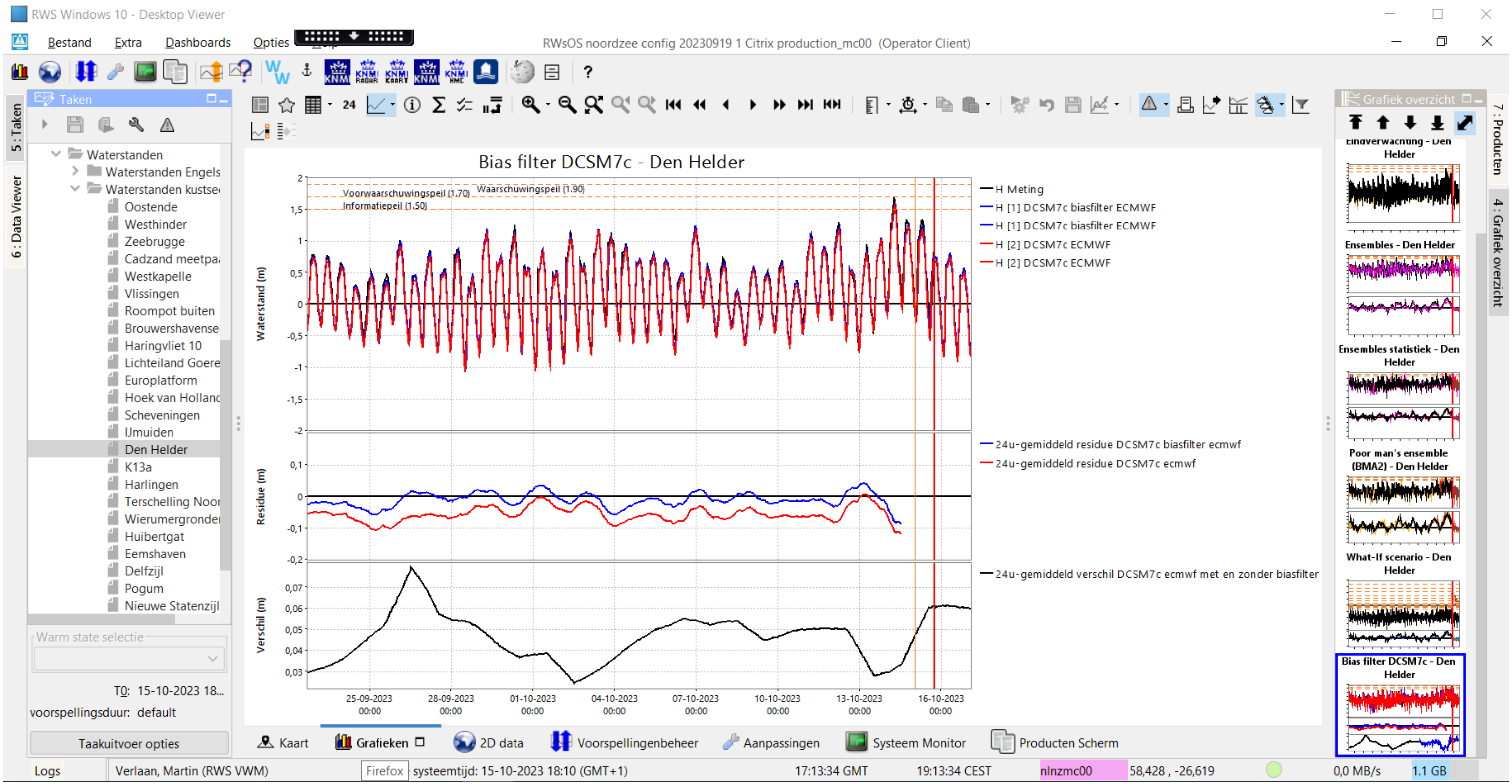
DCSM 100m without bias Kf



DCSM-FM 100m with bias correction derived from DCSM-FM 0.5nm

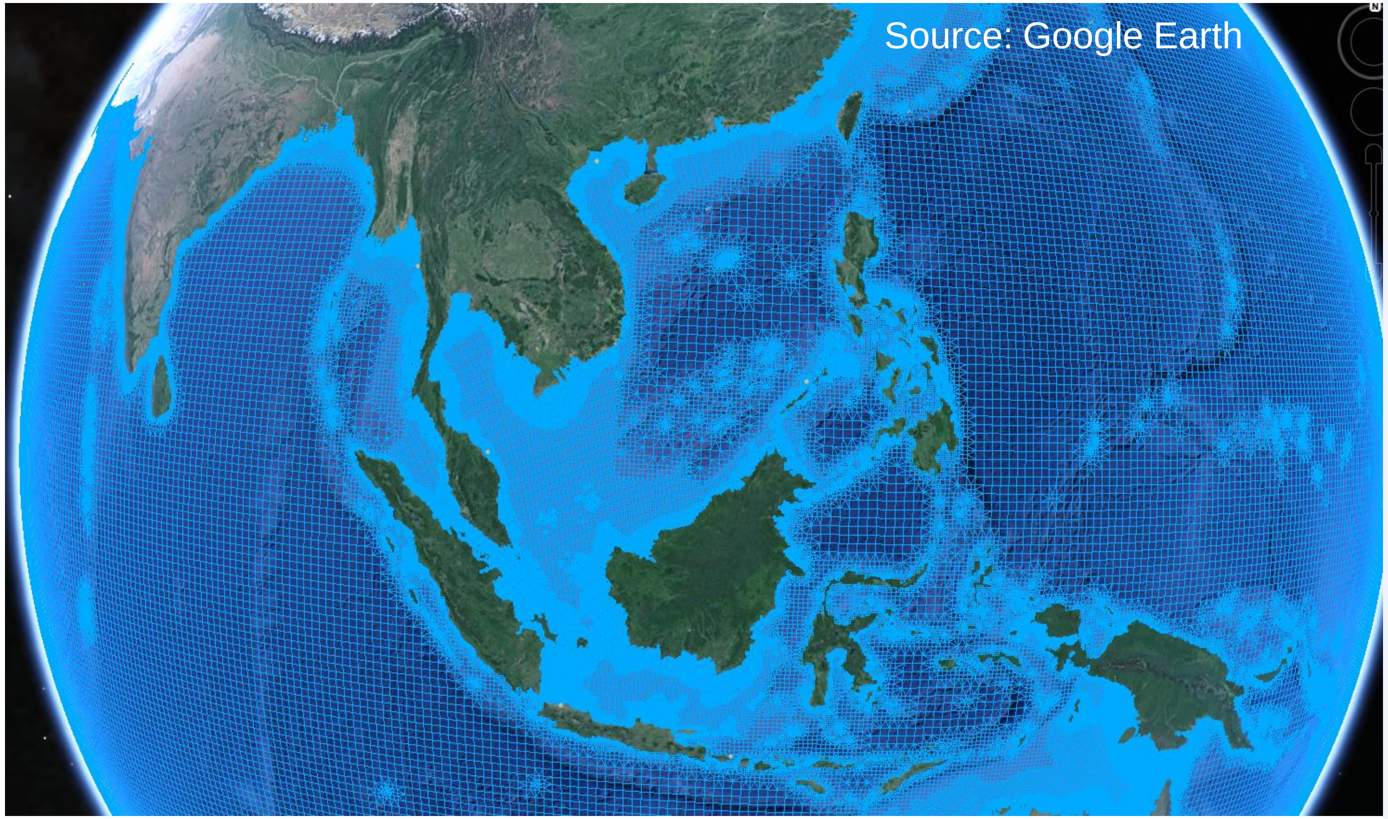


Pre-operational evaluation



Next steps

- Evaluation of pre-operational set-up for winter 2023-2024
- Connect downstream models
- Test use of satellite altimetry in global tide-surge model



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