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Enabling Delta Life

On the origins of annual modulation of M2 and M4 harmonic constituents

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JONSMOD, May 2016

Previous work

JONSMOD2012

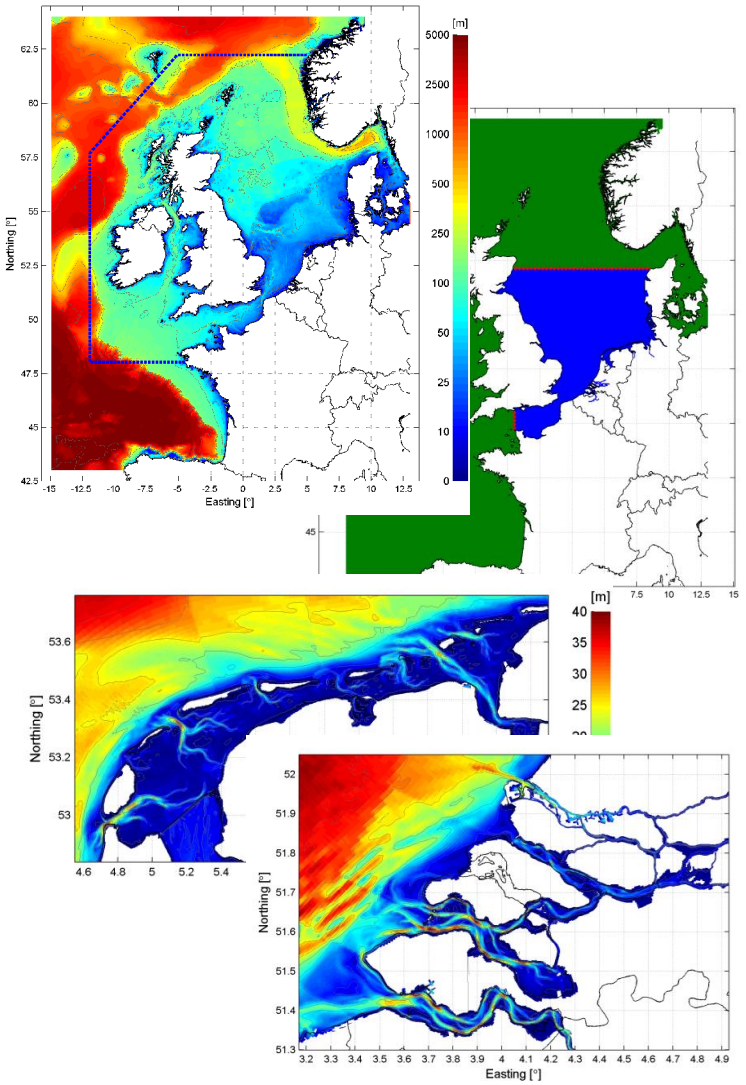
•Completely redesigned new generation Dutch Continental Shelf Model version 6 (DCSMv6)

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

JONSMOD2014

•Further improvements to water level representation in Dutch Estuaries and Wadden Sea aided by increased grid resolution (DCSMv6-ZUNOv4) through domain decomposition approach

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



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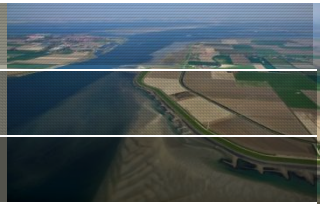
Introduction



- Several recent studies have found a seasonal modulation of the M2 tidal constituent and its overtides, such as M4.
  - Gräwe, U., et al. "Seasonal variability in M2 and M4 tidal constituents and its implications for the coastal residual sediment transport.“ (2014)
  - Müller, M., et al. "Global M2 internal tide and its seasonal variability from high resolution ocean circulation and tide modeling." (2012)
  - Müller, M., et al. "Seasonal variation of the M2 tide." (2014)
- The annual M2 modulation is hardly present in the tidal potential
  - It has to be generated by other (non-gravitational) phenomena with annual periodicity
- Precise cause of these modulations is as yet unclear:
  - Several authors have suggested seasonal variations of the thermal stratification as the cause.
  - Pugh and Woodworth (2014) mention interaction between tide and surge as primarily responsible for the modulation
- Can this be consistent with what we find in our baroclinic models?
- Subject brings together several topics of interest:
  - Continuous tide-surge model development
  - Tide prediction
  - Transport modelling for long-term WQ and ECO

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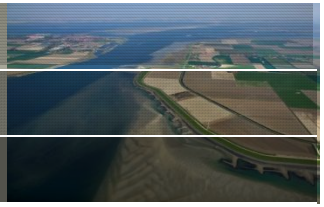
Outline of this presentation



Questions:

1) To what extent is annual modulation of M2 and M4 represented in our (barotropic) models?
2) What is the origin of these modulations?

Focus of this presentation:

(i) Analysis of model results

(ii) Analysis of tide gauge data

(iii) Barotropic experiments

(iv) Baroclinic experiments (development of 3D model)

Analysis of model results

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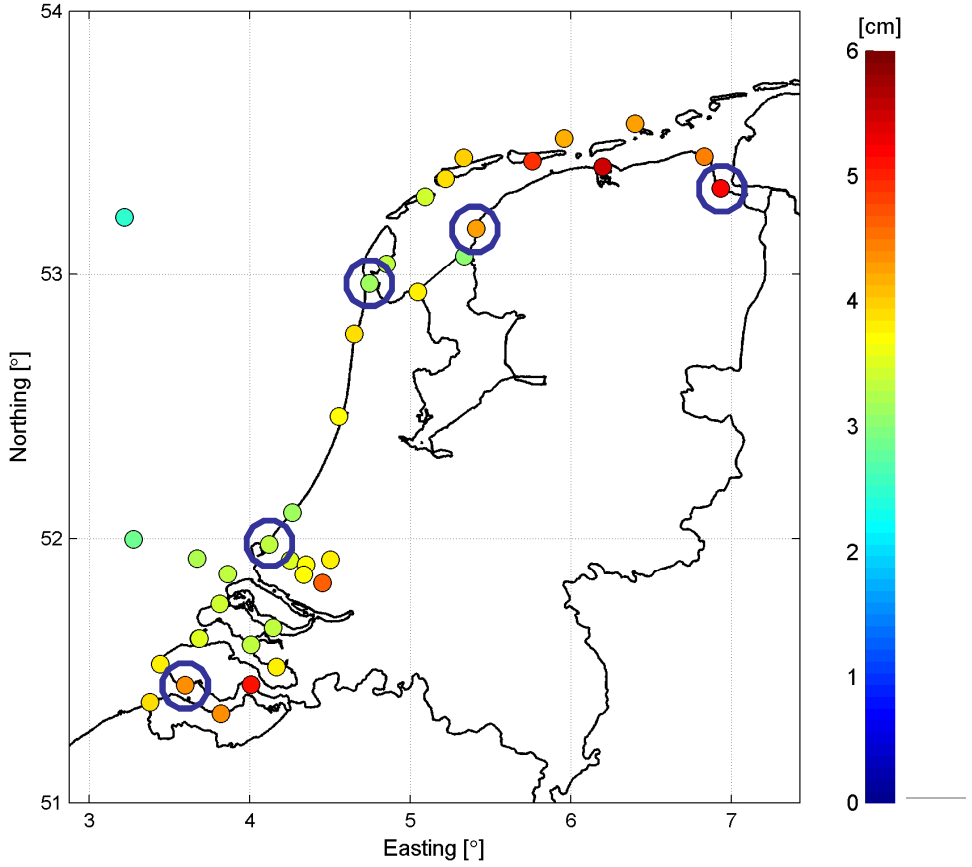
Quality of tide representation

(2007, 13 coastal stations)	RMSE (tide)	RMSE (surge)	RMSE (total)
DCSMv5	**10.7**	**7.7**	**13.1**
DCSMv6-ZUNOv4	**3.6**	**5.7**	**6.7**
	-66%	**-26%**	**-49%**



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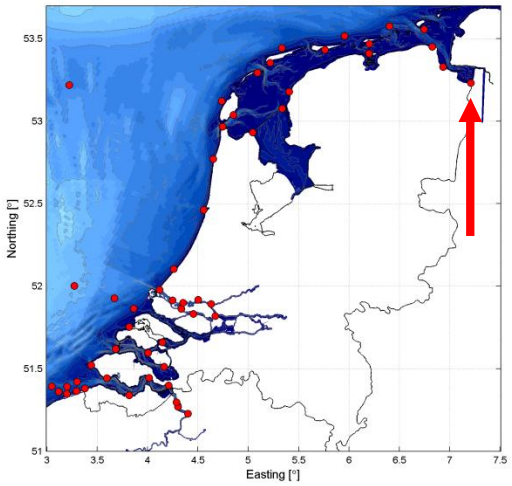
Results at Delfzijl

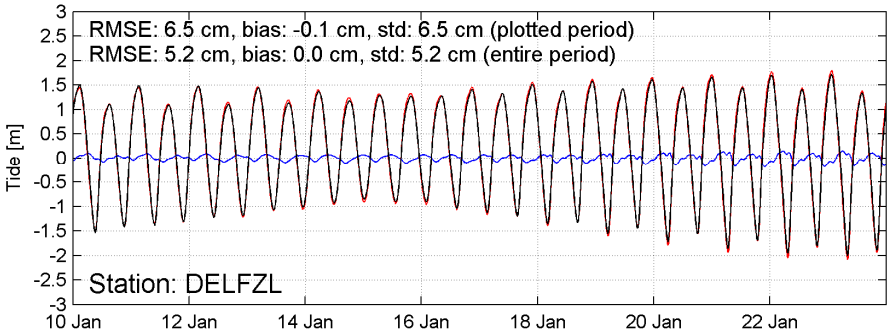


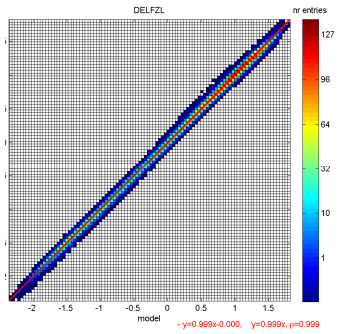
Red: Measurement

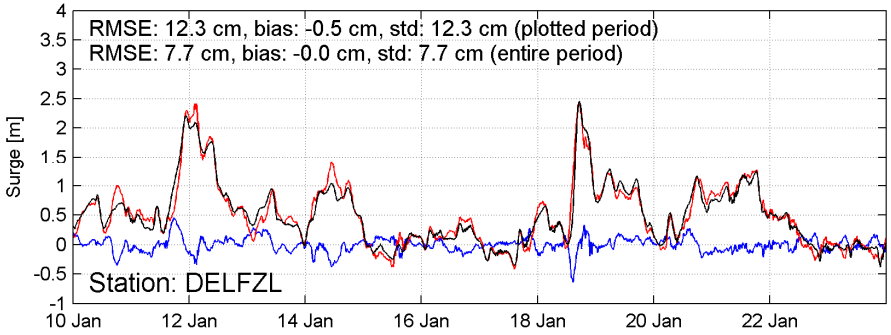
Black: Computation

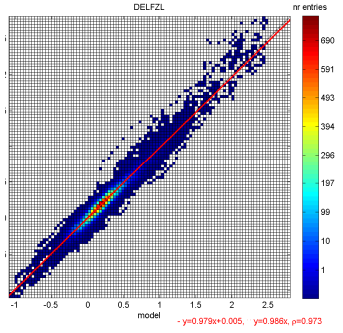
Blue: Residual

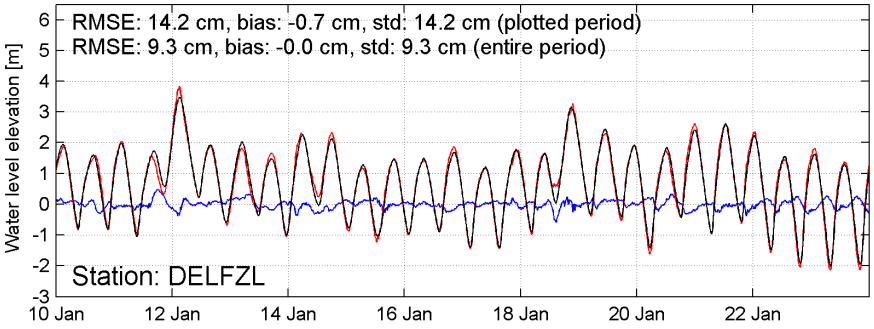
- Storm surge forecasting
- Daily operational use
- Correction of geodetic data

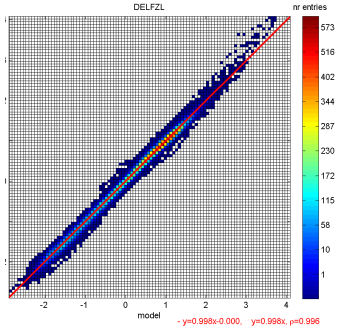












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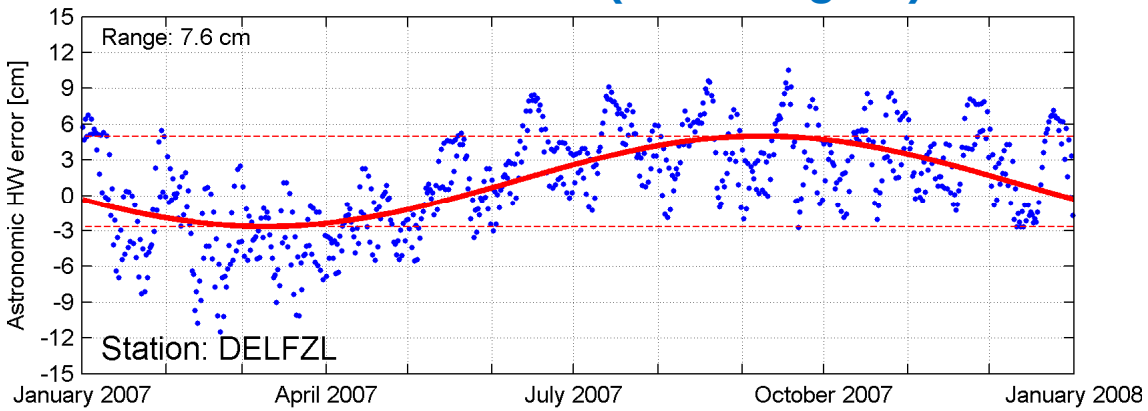
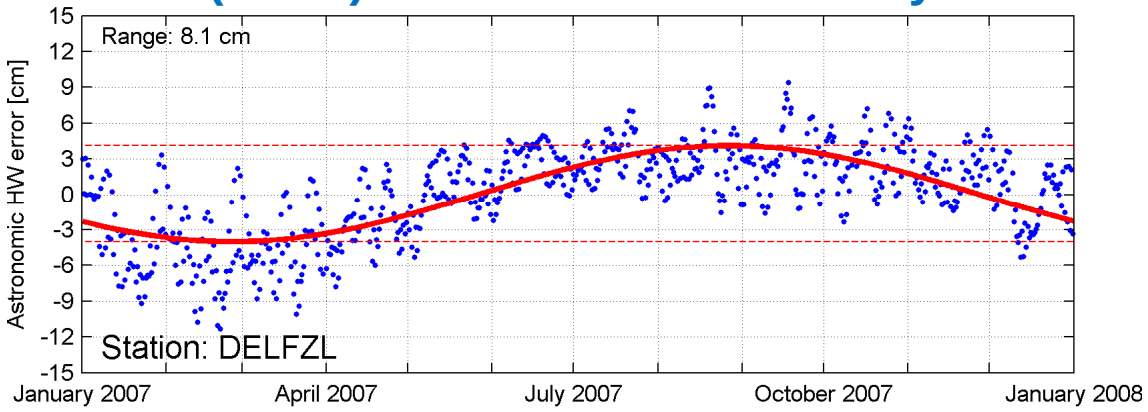
Tidal high water errors

118 constituents (including Sa)



(semi-)diurnal constituents only



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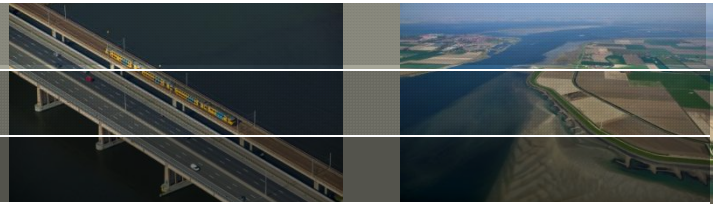
Frequency domain



Constituents with VD>1.0 cm at Delfzijl

Constituent	Amplitude (cm)	ΔA (cm)	ΔG (°)	VD (cm)
H1	5.4	-3.1	-55.0	4.5
H2	1.9	0.2	-63.6	2.1
M6	7.2	0.1	13.2	1.7
2MS6	7.1	-0.9	12.3	1.7
L2	14.3	-0.4	-6.0	1.5
T2	2.6	-0.7	25.4	1.2
S1	2.7	-1.0	-14.9	1.2
MS4	11.8	-0.9	3.5	1.1
M2	138.5	-0.3	-0.4	1.0

Two terms are used to represent the annual modulation in the M2 constituent:

Constituent name	Frequency (°/hr)	Cycles per year (1/yr)
H1 (MA2; α2)	28.9430356	704.763
M2	28.9841042	705.763
H2 (MA2; β2)	29.0251728	706.763

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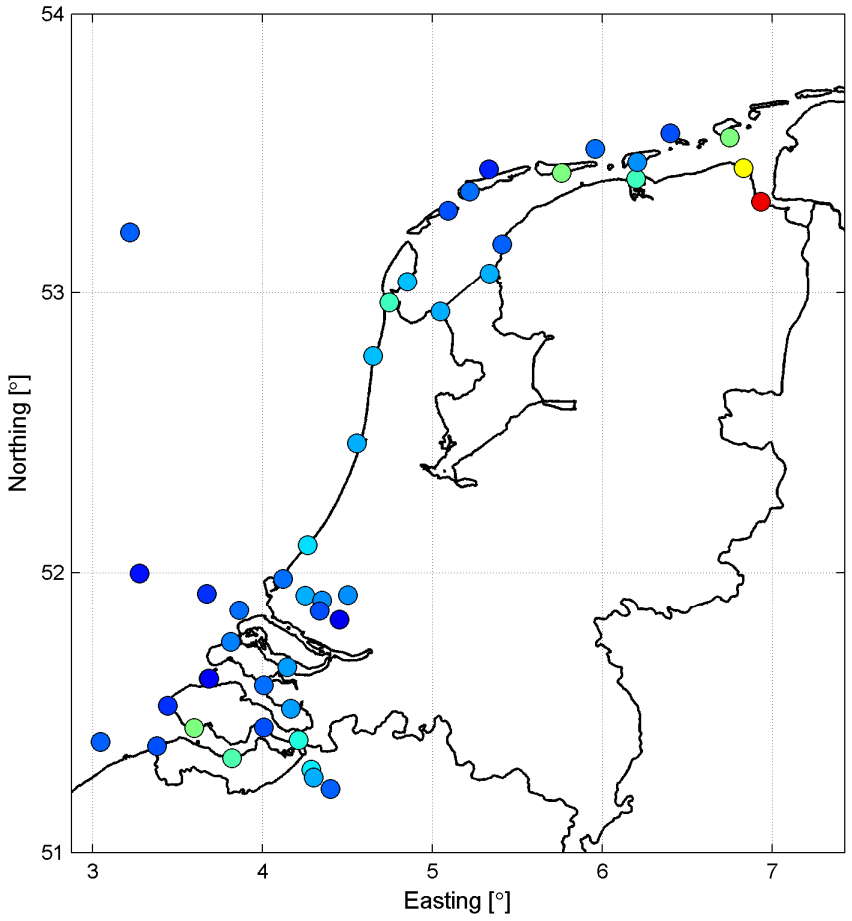
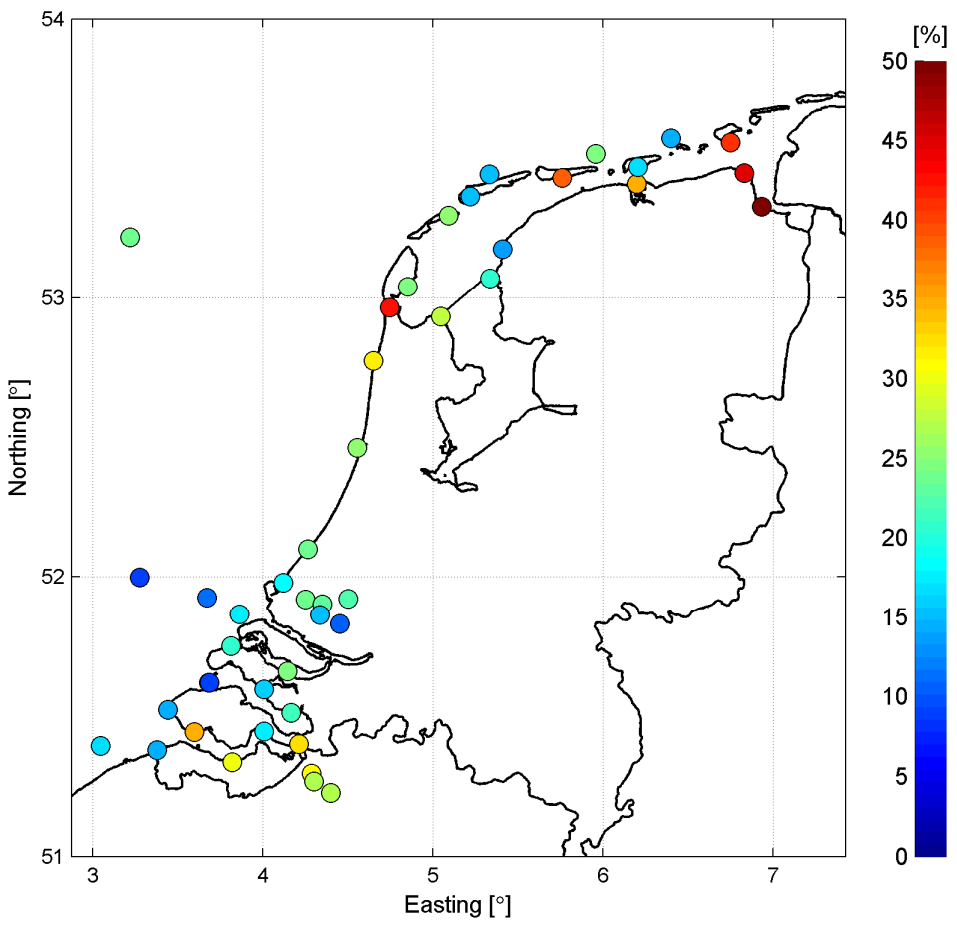
Contribution of modulation to total tide error

Contribution to total error



Contribution to (semi-)diurnal error



Contribution is around 10-20% in most stations; ~50% in Delfzijl

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Analysis of measurements

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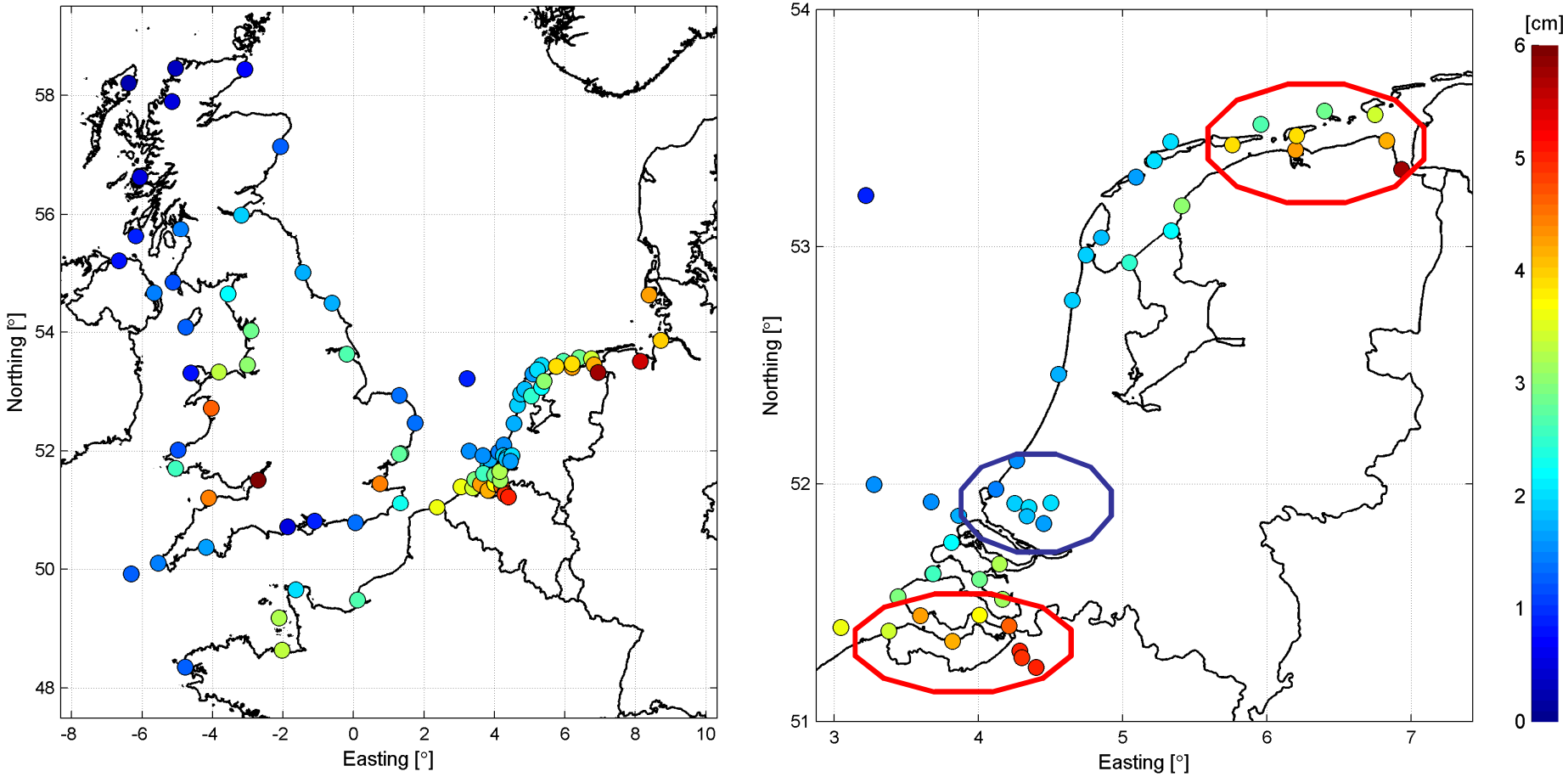
Map of modulation magnitudes

Magnitude of H1/H2



Implication for calibration of local (fluvial) models

Is there a relation with M2 magnitude?

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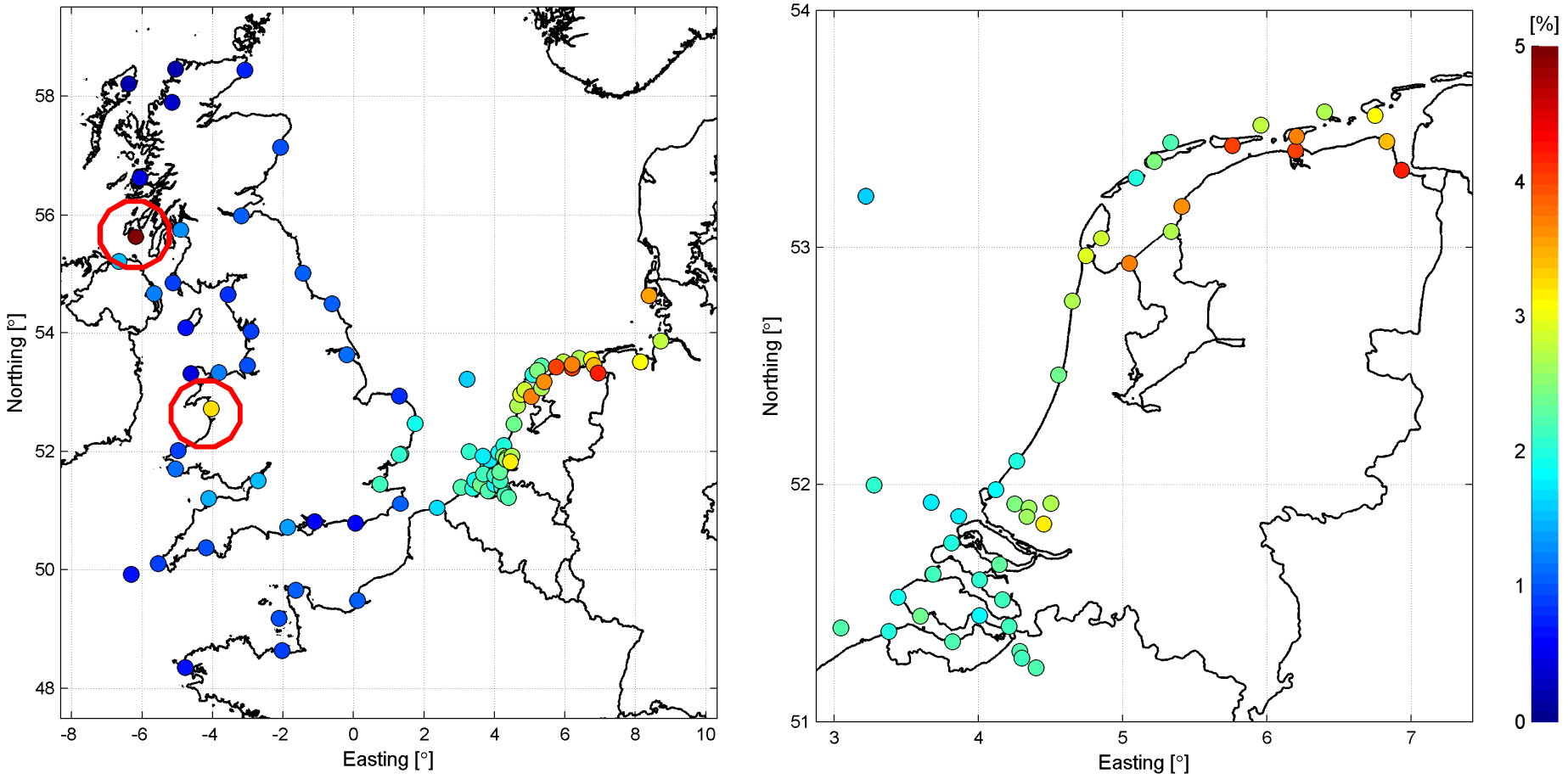
Map of modulation magnitude rel. to M2

Magnitude of H1/H2 divided by M2 magnitude



In many regions (e.g. Westrn Scheldt), the modulation amplifies together with M2 amplitude

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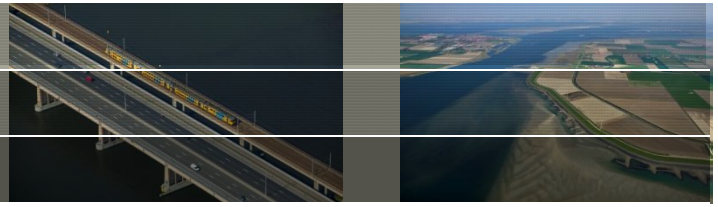
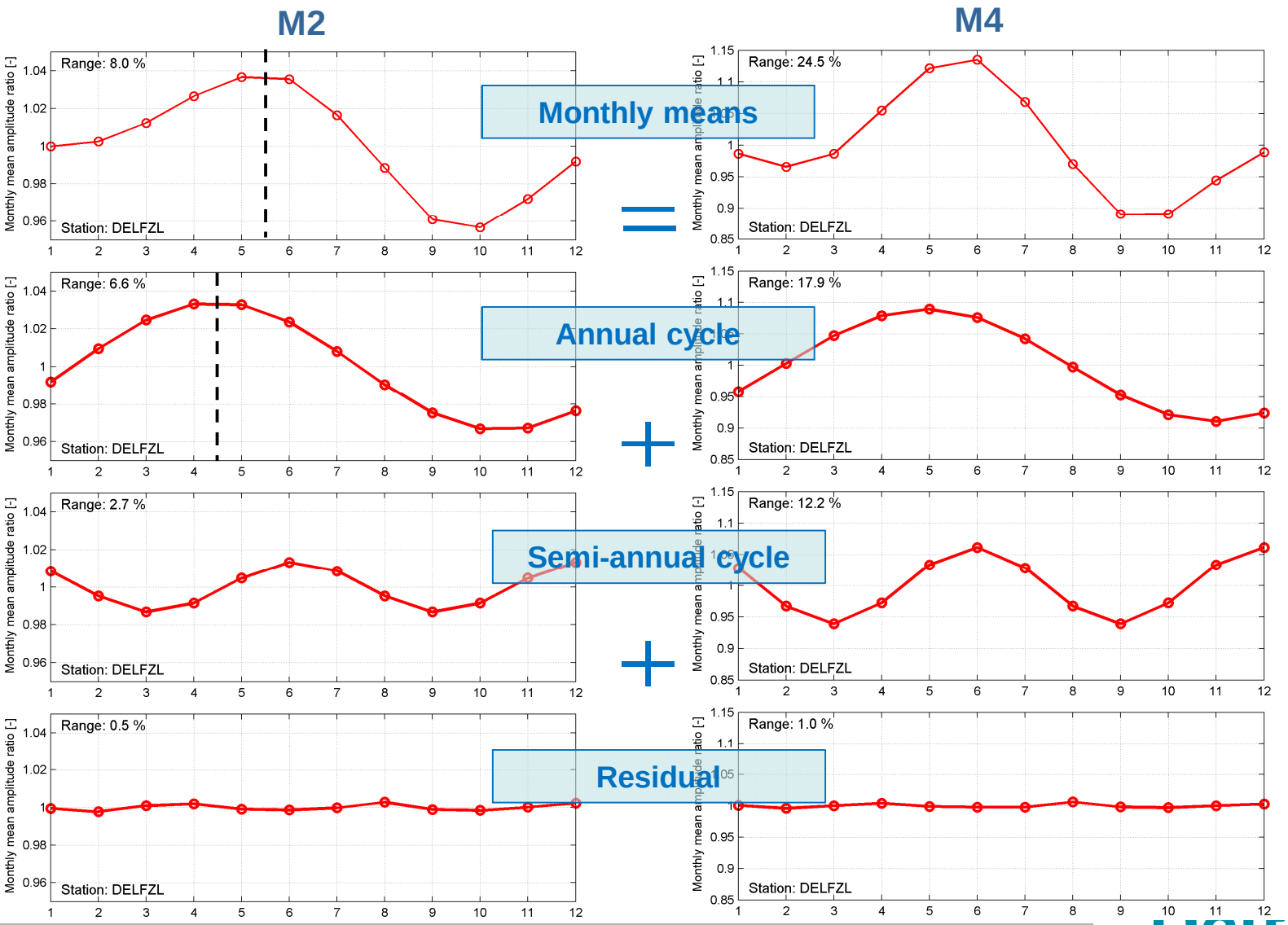
Analysis of measurements





19-year mean values for each month; window length of 3 months

Barotropic experiments

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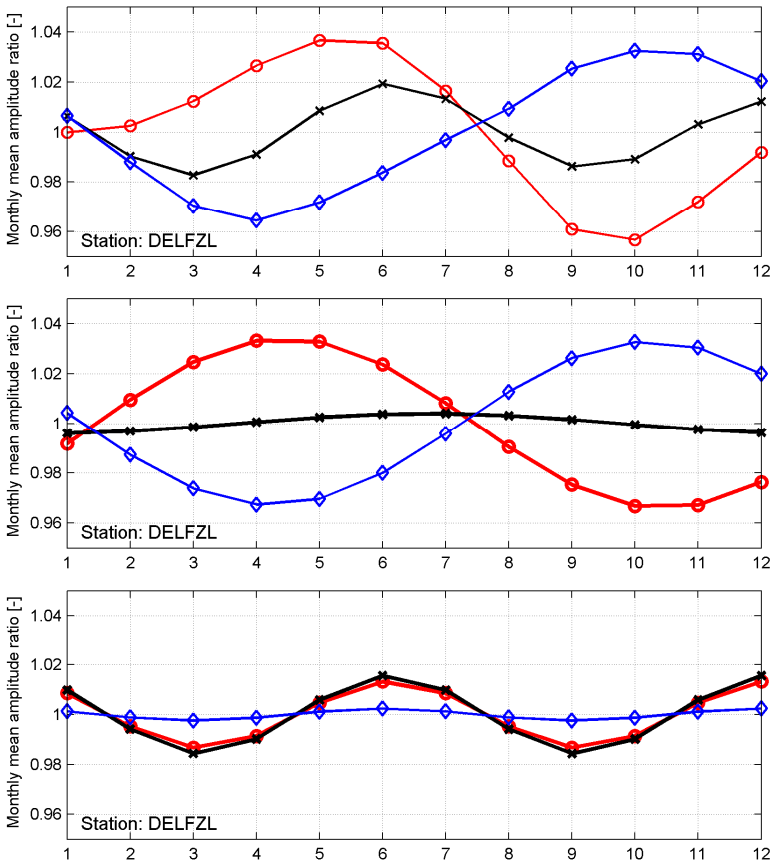
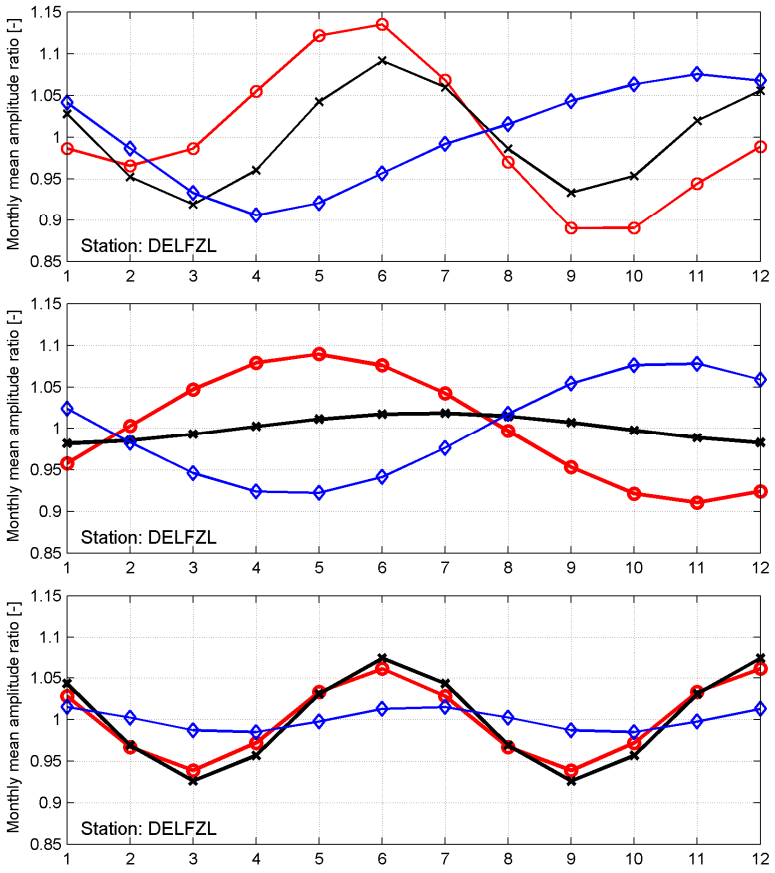
3-monthly analysis of 19-year period: M2 and M4

Tide only; no Sa

M2 **M4**





Red: Measurement Black: Computation Blue: Residual

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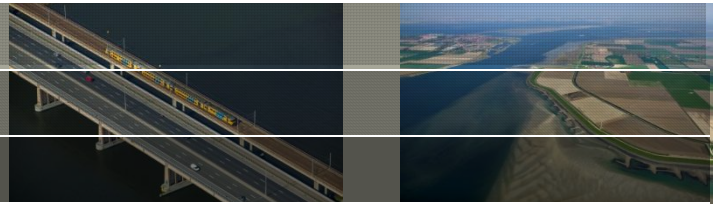
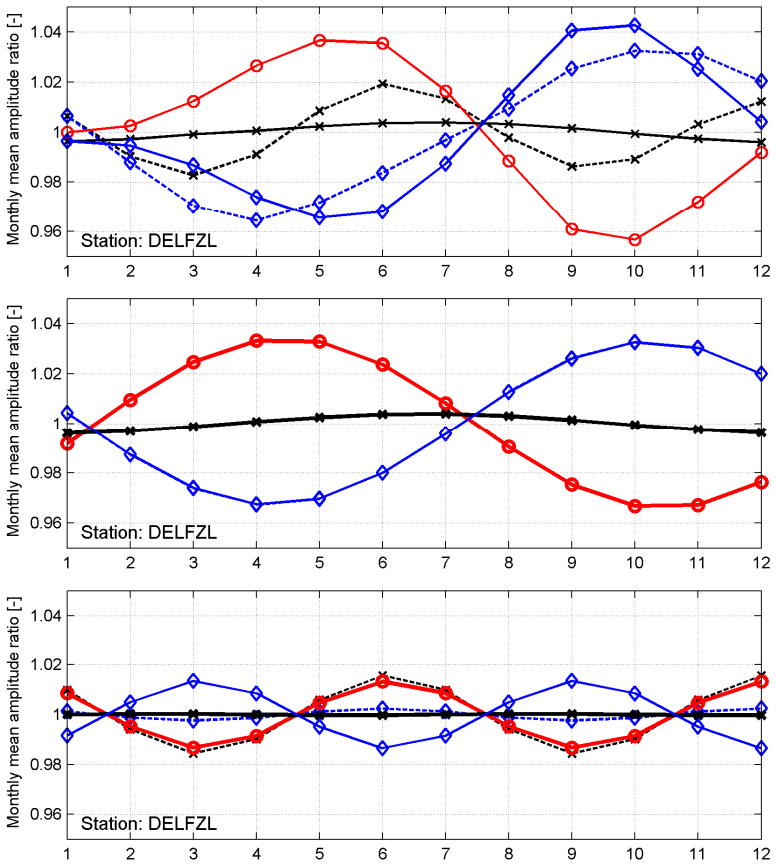
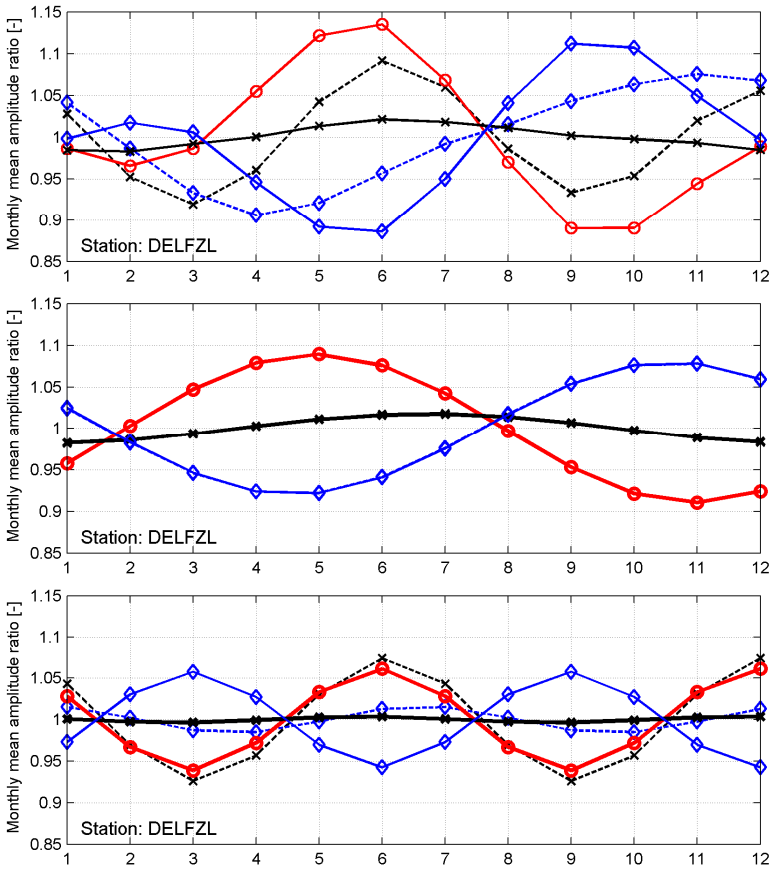
Impact of MKS2 (M2+K2-S2)



Tide only; no Sa; no K2

M2 **M4**





Red: Measurement Black: Computation Blue: Residual

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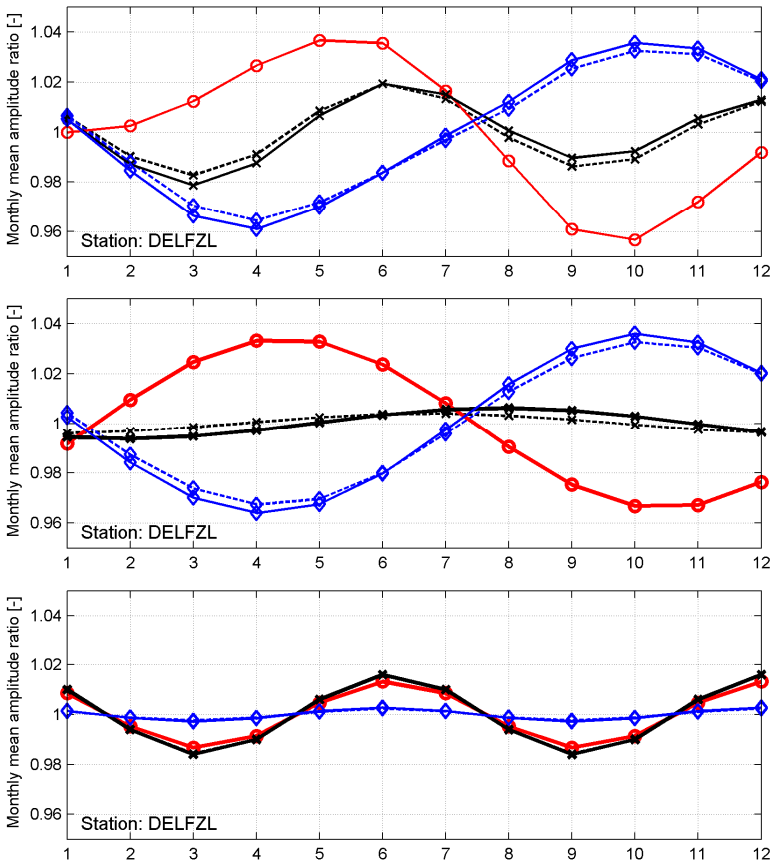
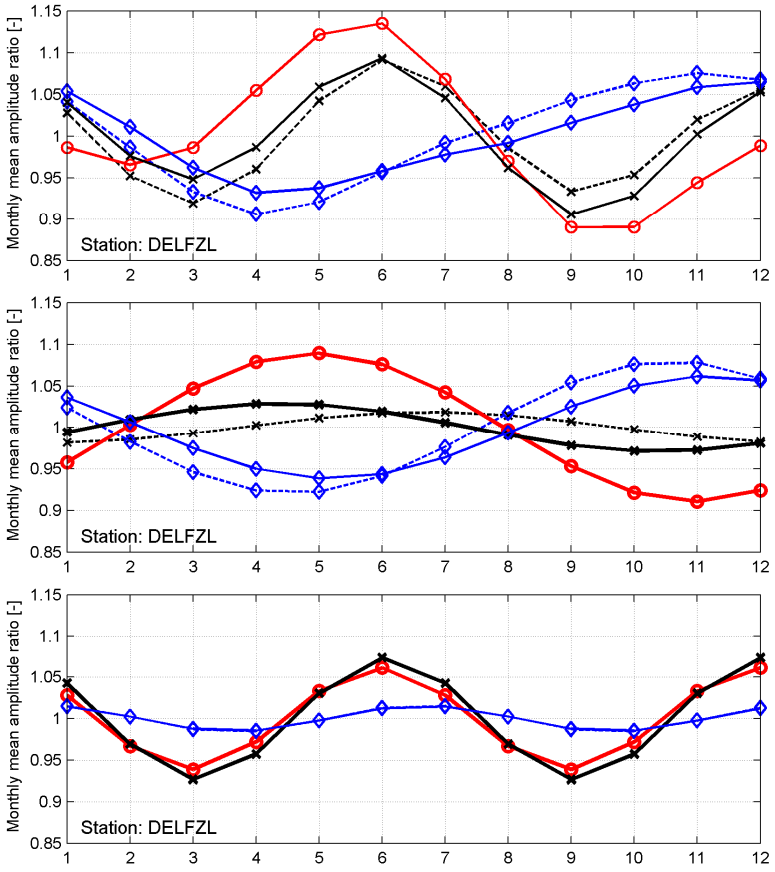
Impact of Sa

Tide only; ~~no Sa~~

M2 **M4**





Red: Measurement Black: Computation Blue: Residual

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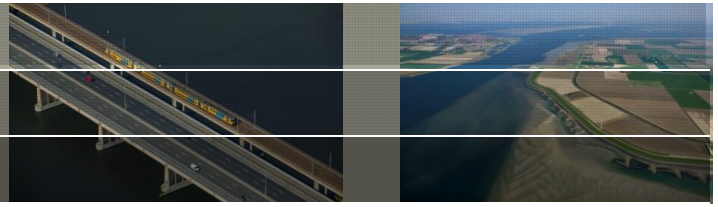
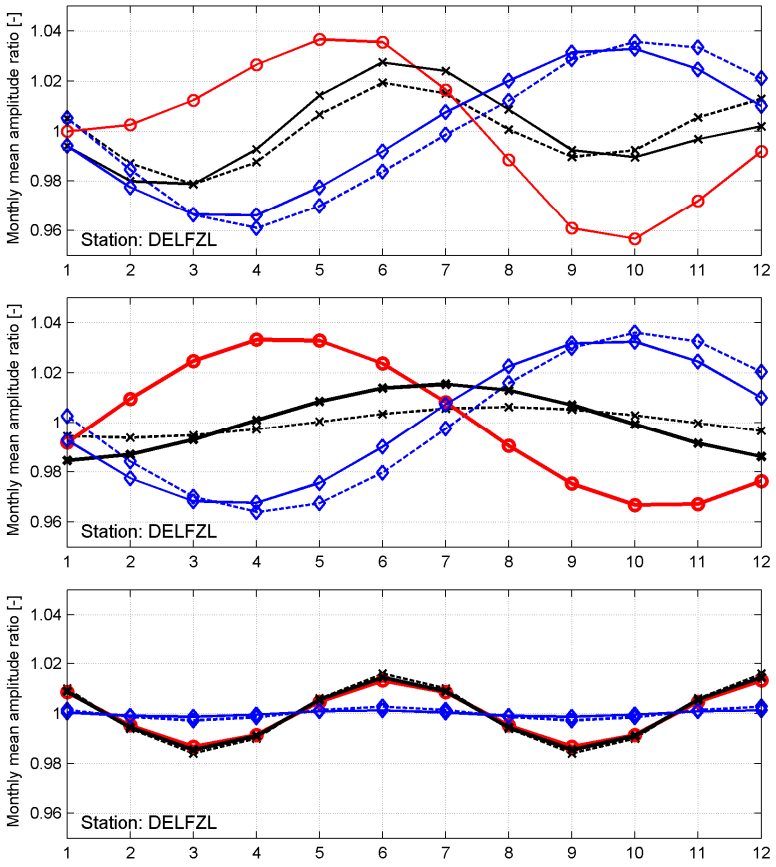
Impact of wind forcing

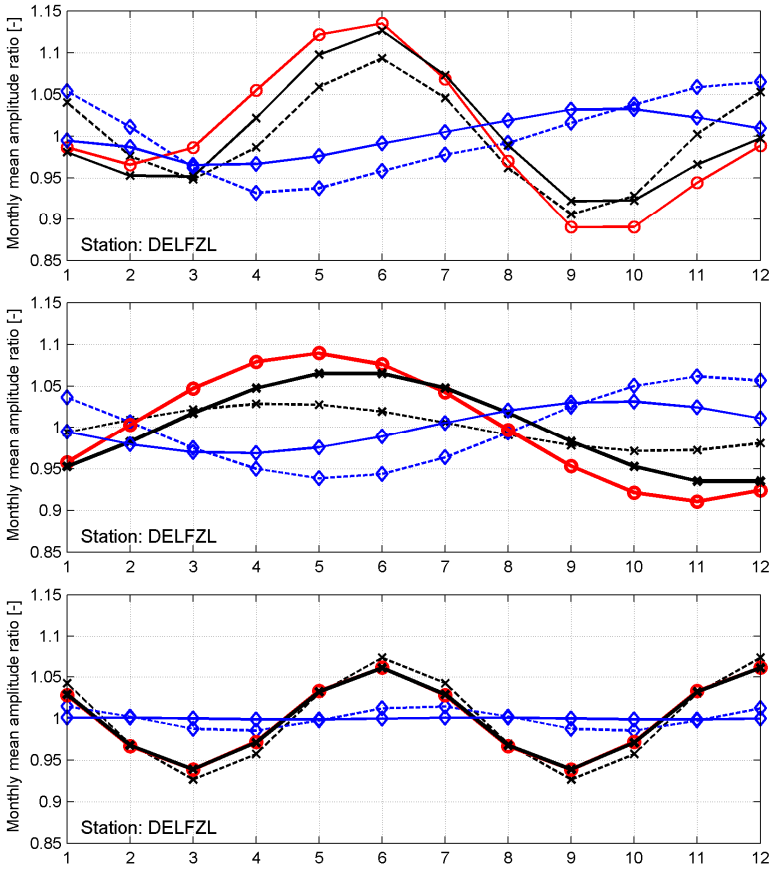


Tide + Meteo

M2



M4



Red: Measurement

Black: Computation

Blue: Residual

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3D baroclinic experiments

(And development of a Delft3D Flexible Mesh model)

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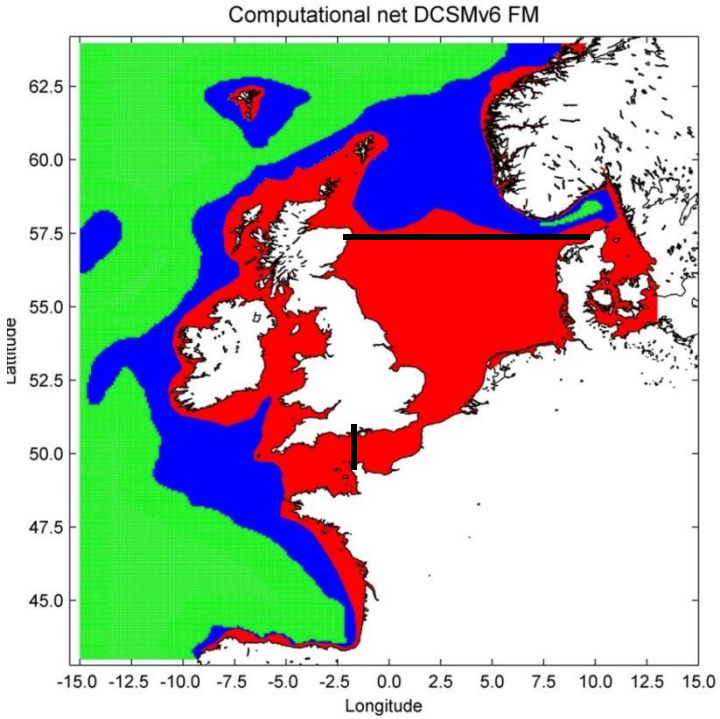
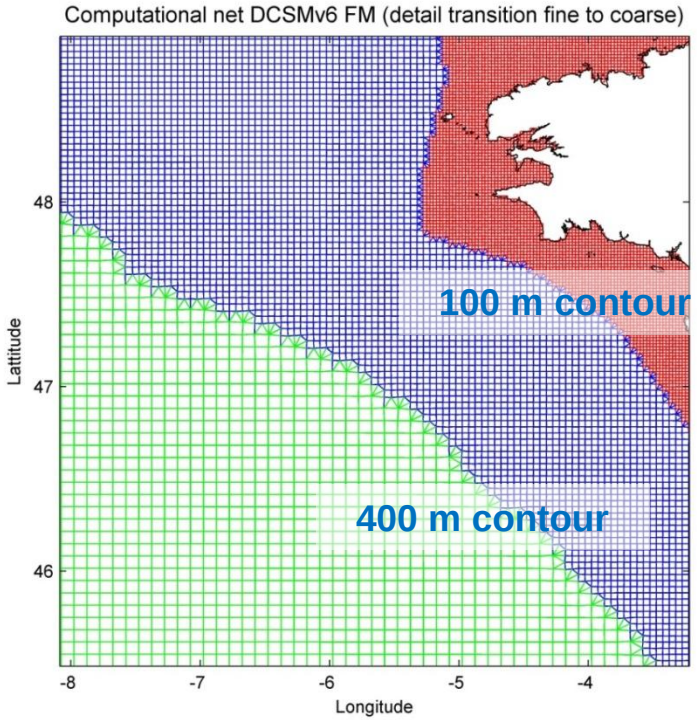
Local grid coarsening with Delft3D Flexible Mesh





Red: original grid size

Blue: 2x coarsened

Green: 4x coarsened

net nodes from 860,000 to 358,000 (factor 2.5)

net links from 1,700,000 to 752,000 (factor 2.25)

- With the upgraded flexible resolution grid and increased time step, the model is ~3-4 times faster (on one core)
- Large additional grid coverage against limited computational costs

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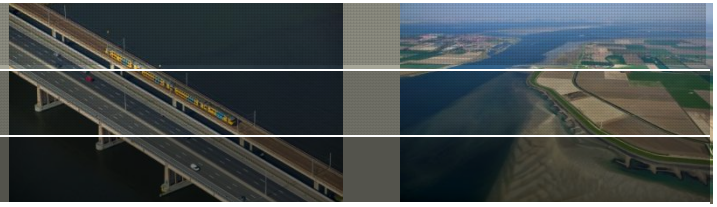
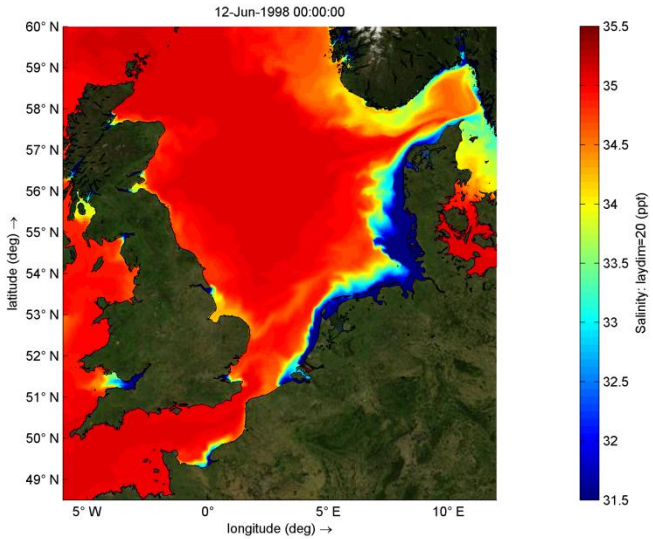
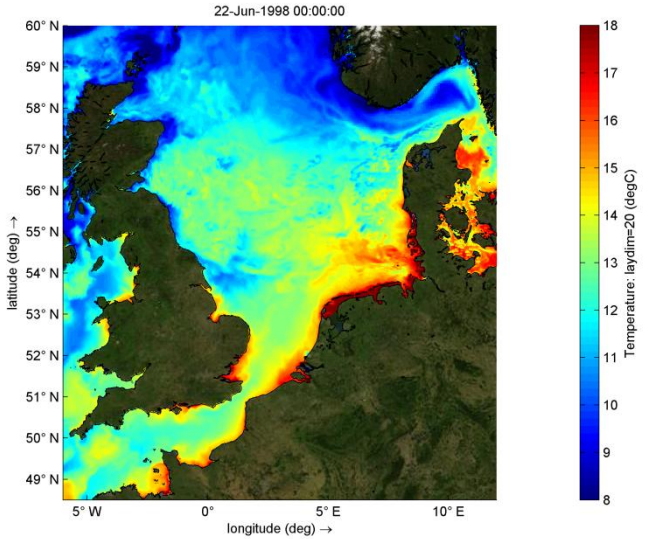
Model forcing







Lateral:

- Tide + IBC
- Temperature and salinity climatology (WOA13)

Surface forcing:

- Tidal potential
- Wind speed, Charnock coefficient and pressure
- Heat fluxes (dew point temperature, relative humidity, cloud cover)

Fresh water discharges:

- Climatology derived from EHYPE

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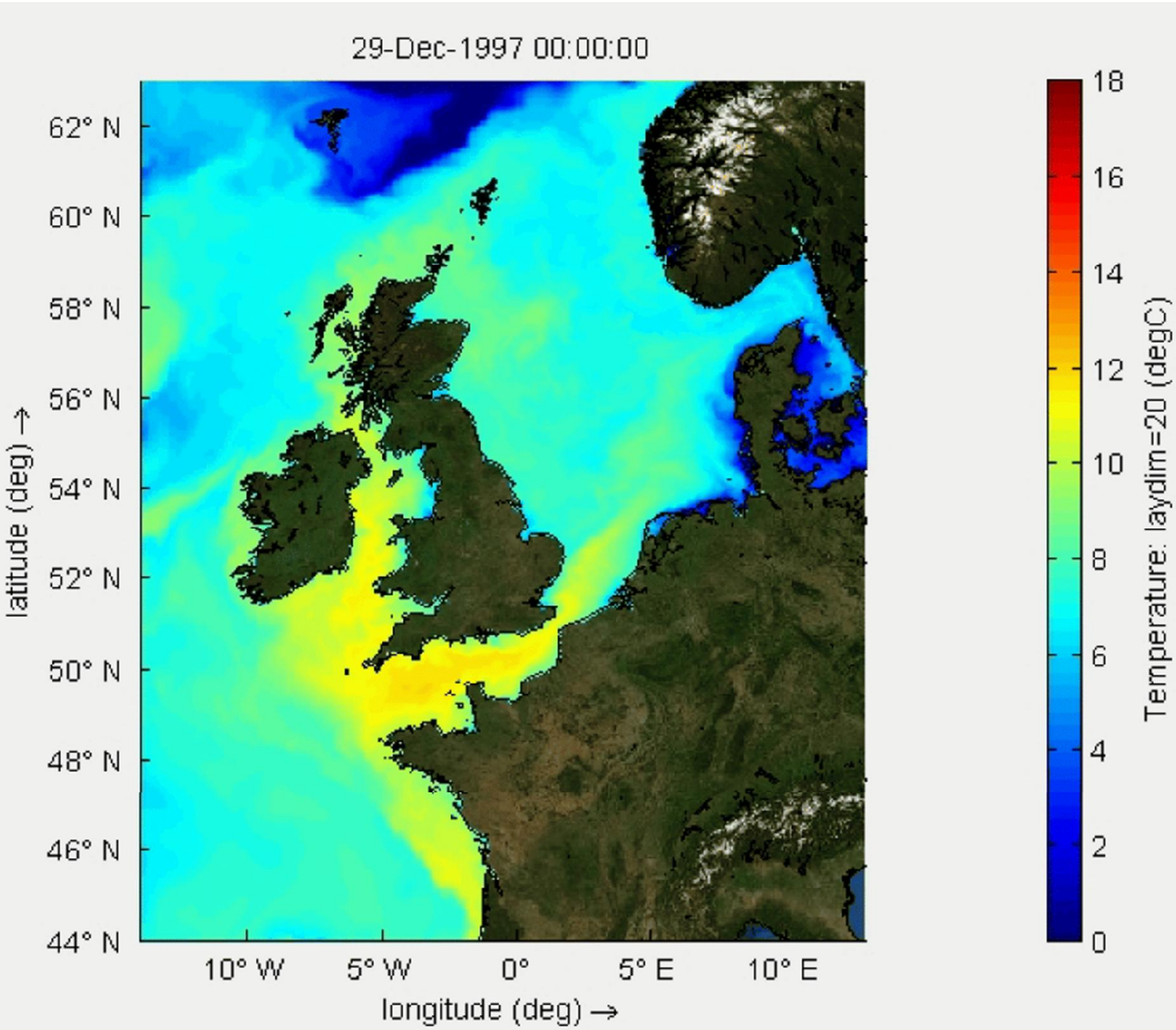
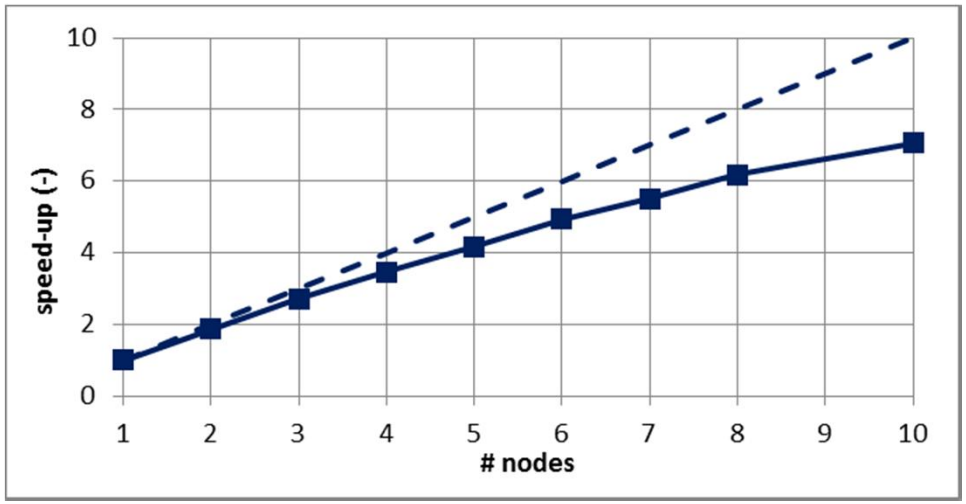
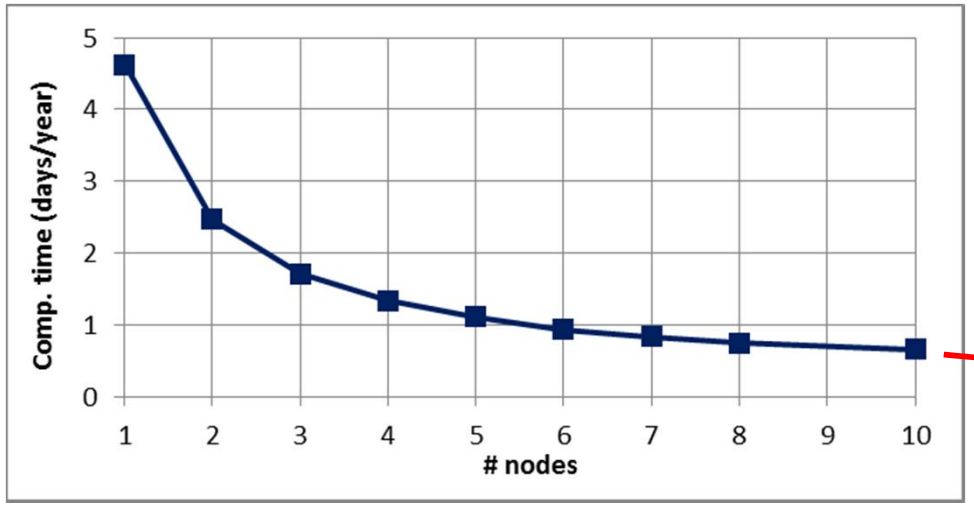

29-Dec-1997 00:00:00
62° N
60° N
58° N
56° N
54° N
52° N
50° N
48° N
46° N
44° N
latitude (deg) →
10° W
5° W
0°
5° E
10° E
longitude (deg) →
18
16
14
12
10
8
6
4
2
0
Temperature: laydim=20 (degC)

Scalability & Computational burden

with 20 equidistant σ-layers





~16 hr/yr

~2-3min/day

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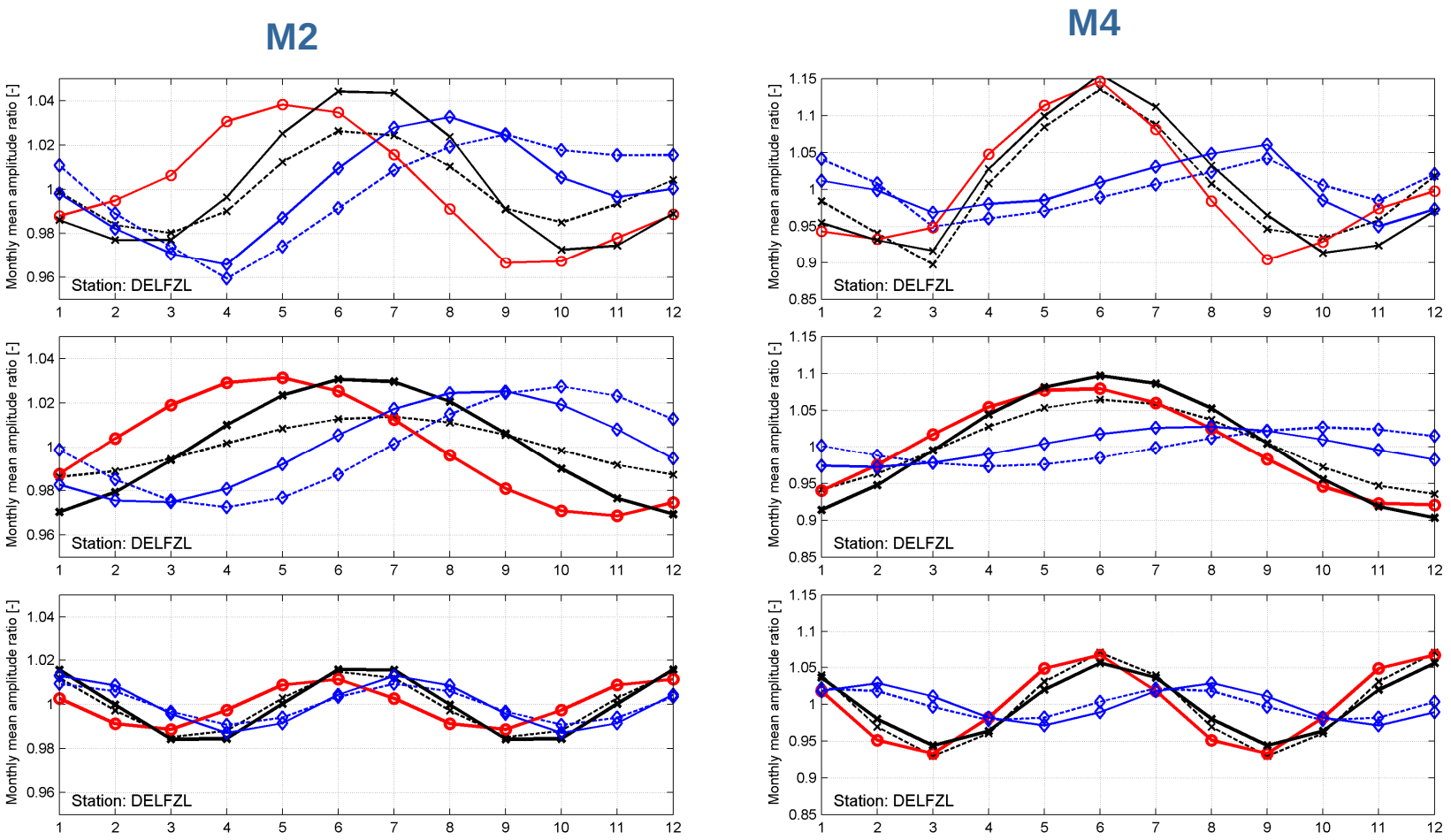
Impact of adding salinity and temperature



Red: Measurement

Black: Computation

Blue: Residual

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Summary and conclusions

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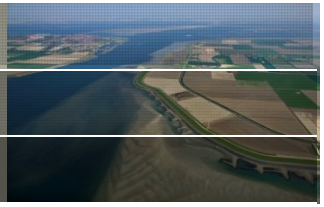
Summary and conclusions



Summary and conclusions

- Misrepresentation of annual modulation of M2 contributes to up to ~50% to the tidal error
- The seasonal modulation consists of an annual and a semi-annual part
- Semi-annual modulation is accurately represented by our barotropic model and is primarily caused by presence of MKS2 (and by wind forcing to some degree)
- Annual modulation is partially caused by wind forcing (and Sa to some degree); but this explains only half of the signal (timing is off by 2-3 months)
- To further investigate we have developed a 3D baroclinic model
- Including salinity and temperature in this model doubles the amplitude of the annual modulation (timing still of by 1-2 months)

Next steps

- Validation of (vertical) temperature and salinity distribution
- Look into representation of breaking internal waves
- Further experiments with 3D model
- Towards a 3D baroclinic model for operational water level forecasting?

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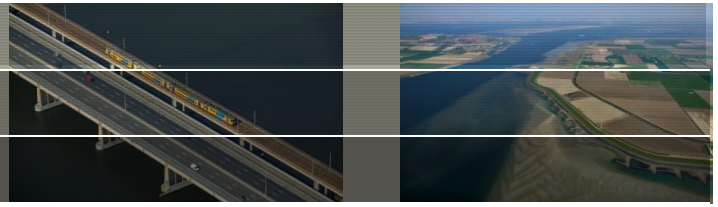

Thank you!

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