Rapid decline in tidal amplitude along the Dutch coast

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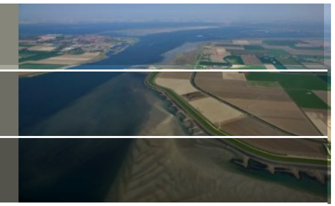
Background



- Operational models with good quality tide representation
  - Advantage is that other phenomena are more easily visible
- Evaluation of operational models found the following:
  - There appears to be a gradual decrease in the model skill to represent the tide.
  - The M2 representation has deteriorated by almost 50% from 2007 to 2014/2015. Indeed, the M2 tide is the largest contributor to the deterioration of the diurnal and higher frequency tides along the Dutch coast.
  - Changes in the M2 tide representation quality are mostly due to changes in amplitude and to a much smaller extent changes in phase.

M2 error at 13 Dutch coastal tide-gauge stations

	RMS ΔA (cm)				RMS ΔG (°)				RMS VD (cm)			
	2007	2008	2013/ 2014	2014/ 2015	2007	2008	2013/ 2014	2014/ 2015	2007	2008	2013/ 2014	2014/ 2015
DCSMv6	**1.1**	**1.5**	**1.8**	**2.4**	**1.1**	**1.2**	**1.4**	**1.4**	**2.1**	**2.5**	**2.7**	**3.1**

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Background

Would could be the cause?

- As the astronomical forces that drive tides are constant, tides are generally considered to be stationary
- First hypothesis: 18.6-year lunar nodal cycle not well represented in model
  - Nodal cycle represents variation of lunar declination
  - Modulates the M2 tidal potential
  - Imposed on boundary, but damping inside model domain not checked

- Decadal scale computations to check this showed:
  - ➢ M2 nodal cycle is well represented
  - ➢ M2 tidal amplitude along the Dutch coast is declining steadily from 2007 onwards

Outline of this presentation

1. Approach
   - ✓ Method
   - ✓ Model description
2. Time series analysis
3. Spatial patterns
4. Discussion and conclusions

Method

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Method

- Standard approach for long-period analysis of tidal records:
  - Harmonic analysis, without nodal correction, separate for each year
  - Fit a sinusoidal cycle with an 18.61-year period (Multiple Linear Regression analysis)
- We propose an alternative, mixed approach:
  - Process model used to remove natural variability incl. nodal cycle
    - ✓ The analysis of nodal variability requires long homogenous records which are generally not available.
    - ✓ It allows testing potential mechanisms behind changes in tide.

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Model (DCSM-FM)

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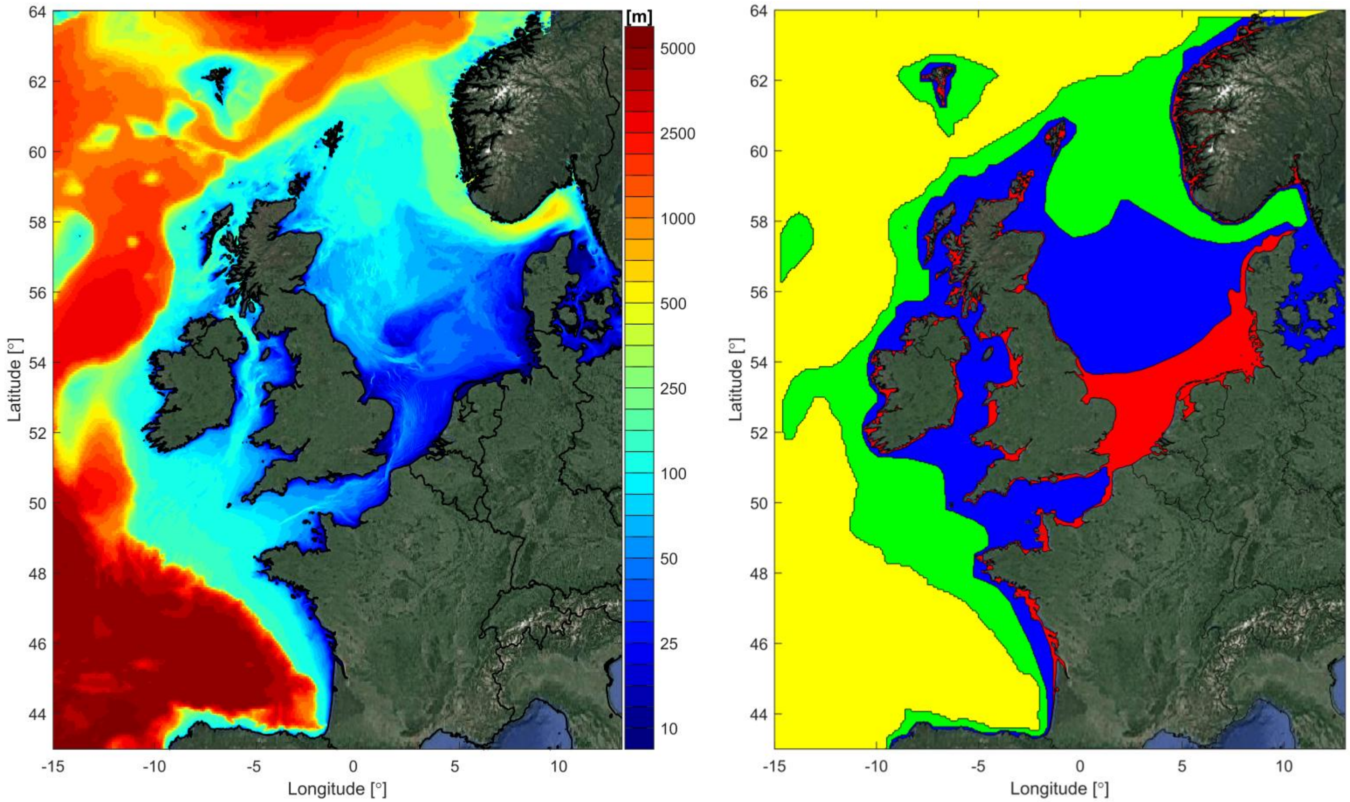
DCSM-FM Network

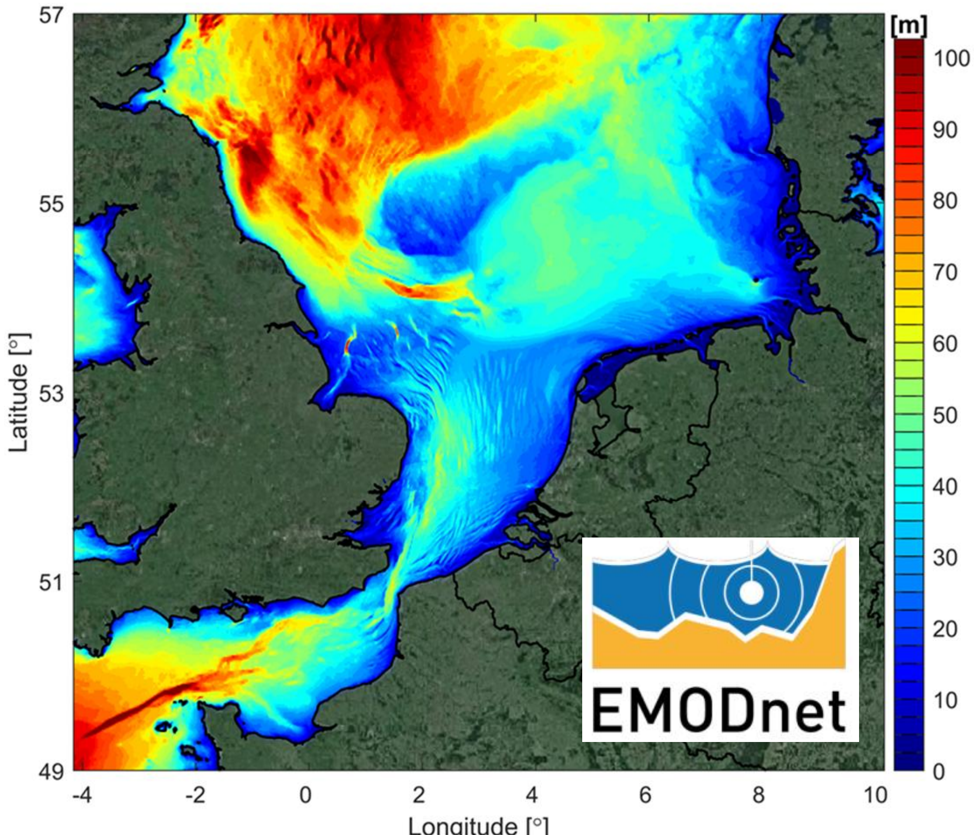
Delft3D-Flexible Mesh, 630,000 nodes with variable resolution

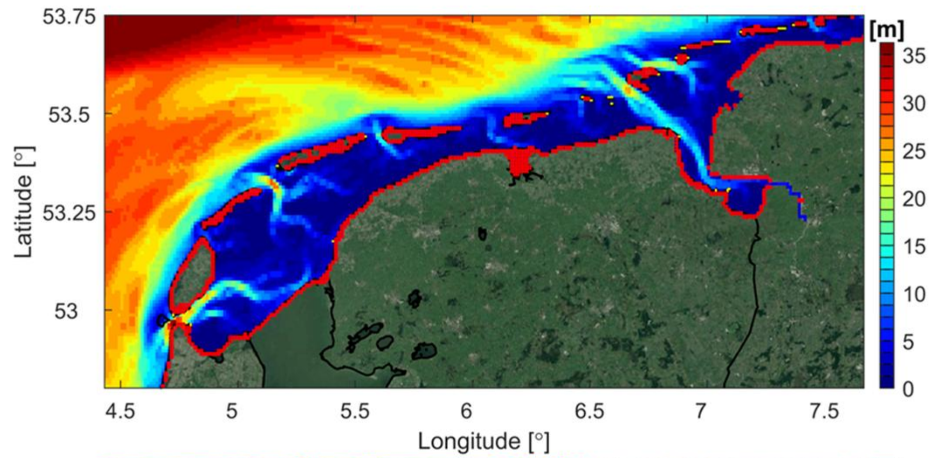


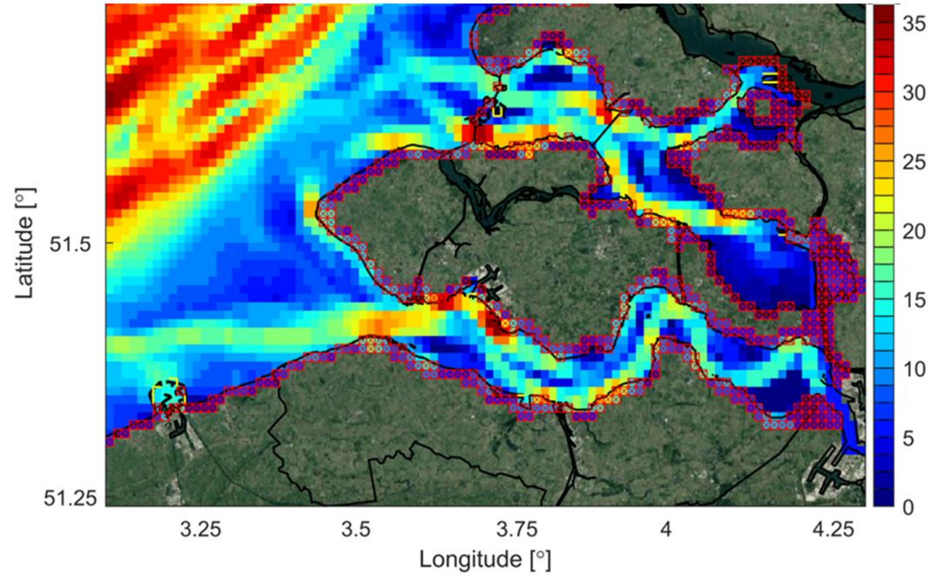
Yellow:	1/10° x 1/15°	~ 4 nm x 4 nm	→ **800 m isobath**
Green:	1/20° x 1/30°	~ 2 nm x 2 nm	→ **200 m isobath**
Blue:	1/40° x 1/60°	~ 1 nm x 1 nm	→ **50 m isobath**
Red:	0.75’ x 0.5’	~ 0.5 nm x 0.5 nm	

Model bathymetry

Details of model bathymetry
(at 0.5 nm model resolution, to be used for EPS probability forecasting)







LAT-MSL realization derived from a 19-year simulation with DCSMv6

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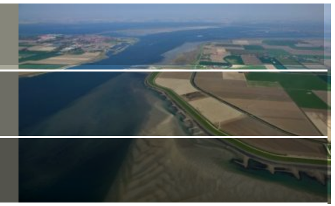
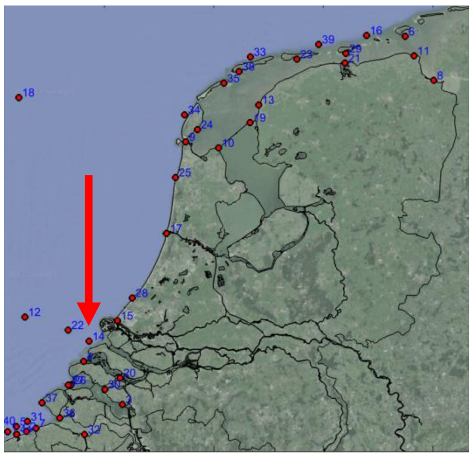


Impact EMODnet bathymetry

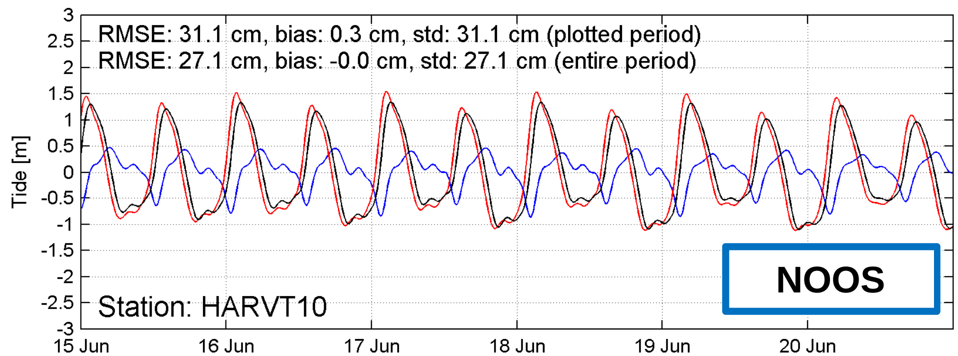
- Computations with uncalibrated model with uniform manning roughness coefficient
- Based on harmonic analysis of year-long time series using 118 constituents

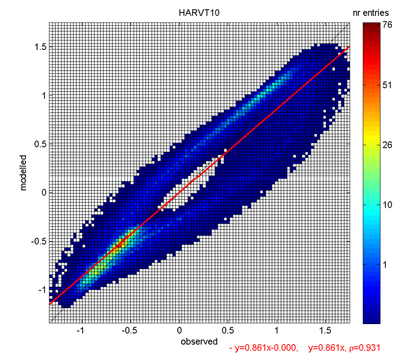


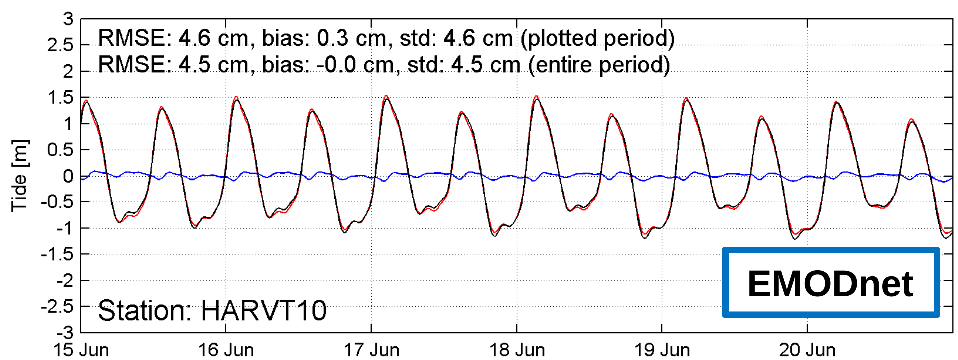
Red: Measurement

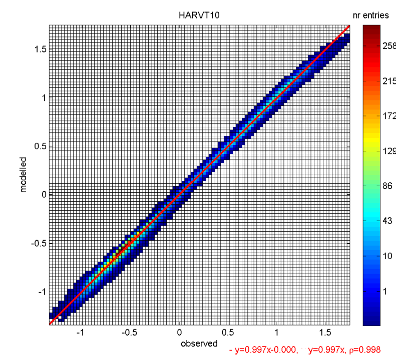
Black: Computation

Blue: Residual









Goodness-of-Fit for 2007 (13 Dutch coastal stations)

	RMSE tide (cm)	RMSE surge (cm)	RMSE total (cm)
NOOS	27.9	8.8	29.3
EMODnet	**6.7**	**6.0**	**9.0**

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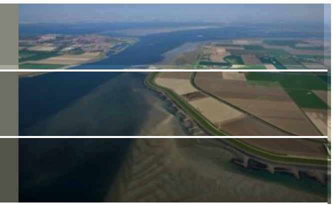
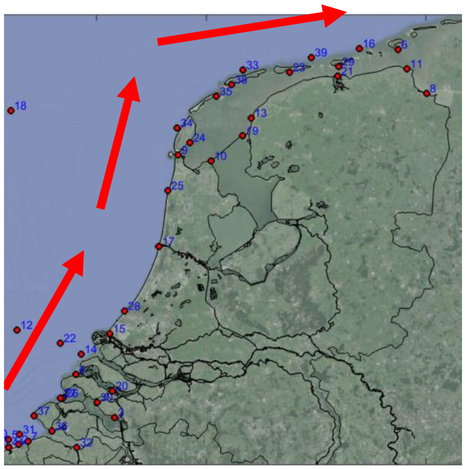
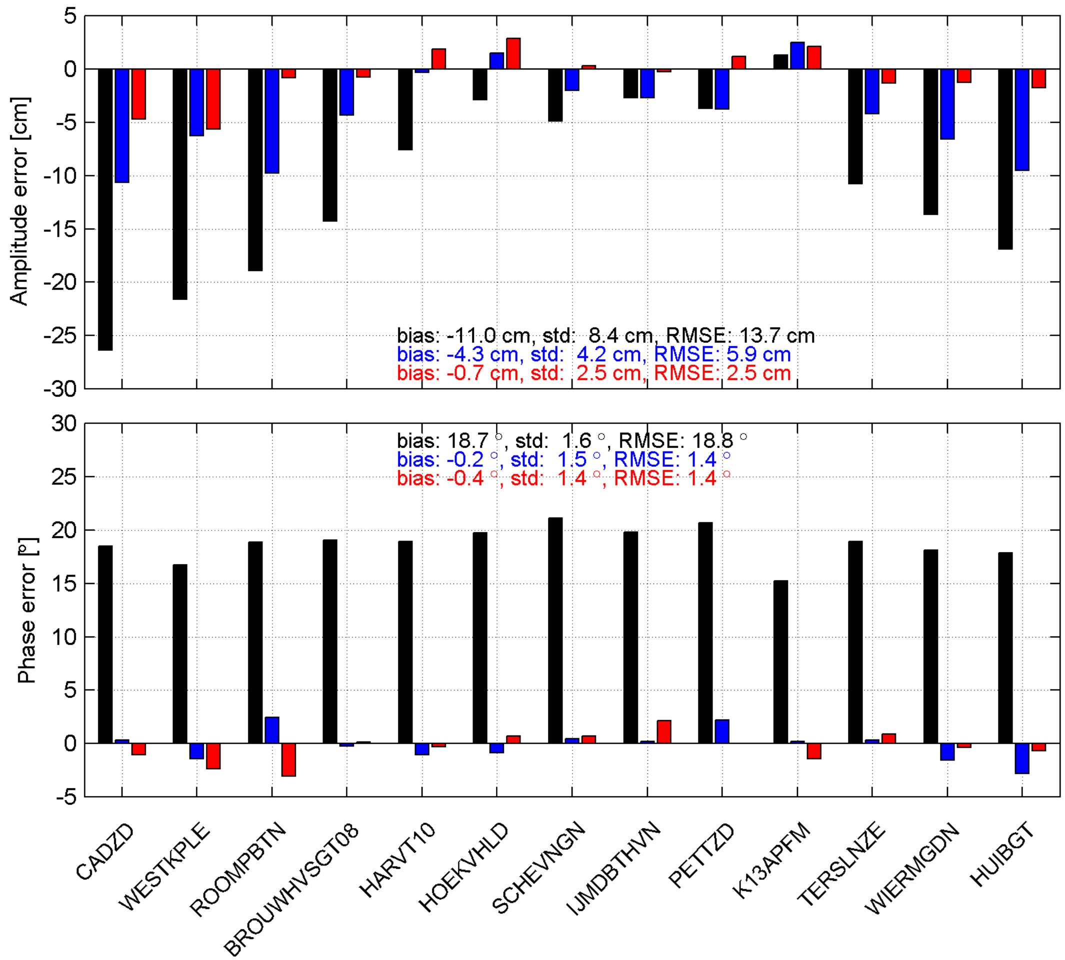
M2 tide representation



Based on harmonic analysis of year-long time series using 118 constituents

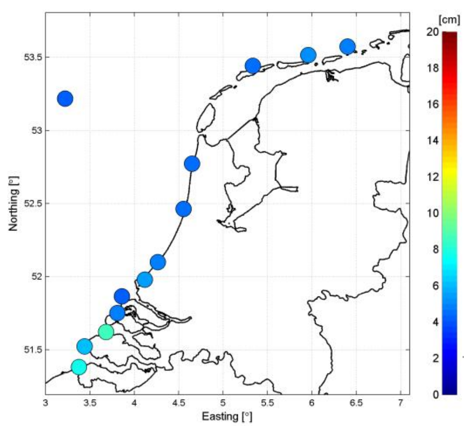




NOOS

EMODnet

EMODnet, after limited roughness calibration

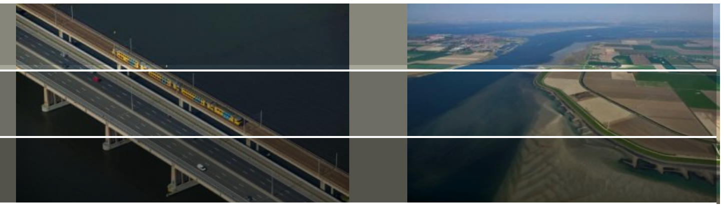


RMSE tide (cm)	RMS (ΔH_{M2})	RMS (ΔG_{M2})	RMSE (VD_{M2})
5.5	**2.5**	**1.4**	**3.8**

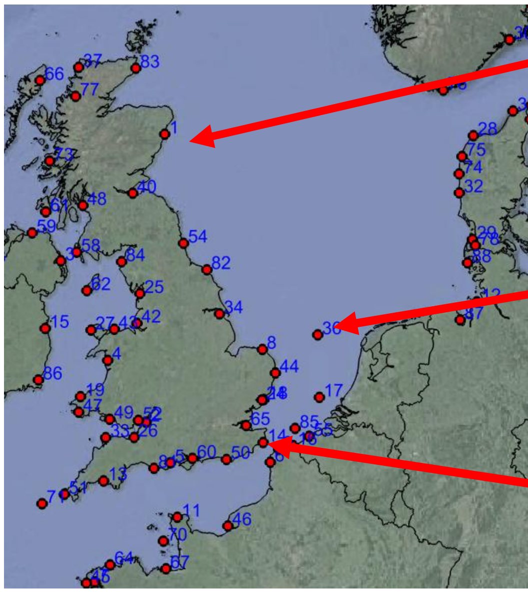
Validation nodal cycle

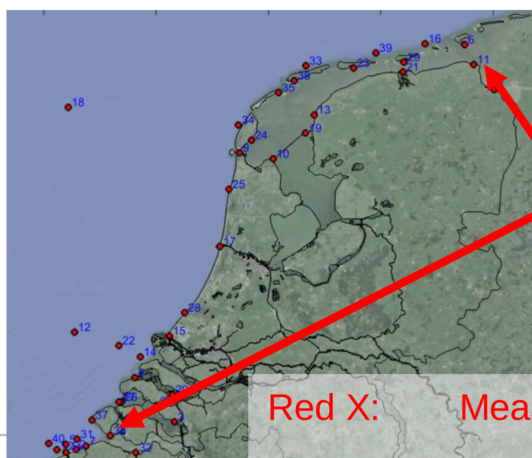
- Computation with DCSM-FM for the period 1980-2017
- ERA-Interim meteorological forcing
- Harmonic analysis of measurements and model results for each year separately, using t_tide (118 constituents), without nodal correction
- linear trends trend removed
- nodal cycle with 18.6-year period fitted (1980-2007)
- normalized on average M2 amplitude in same period

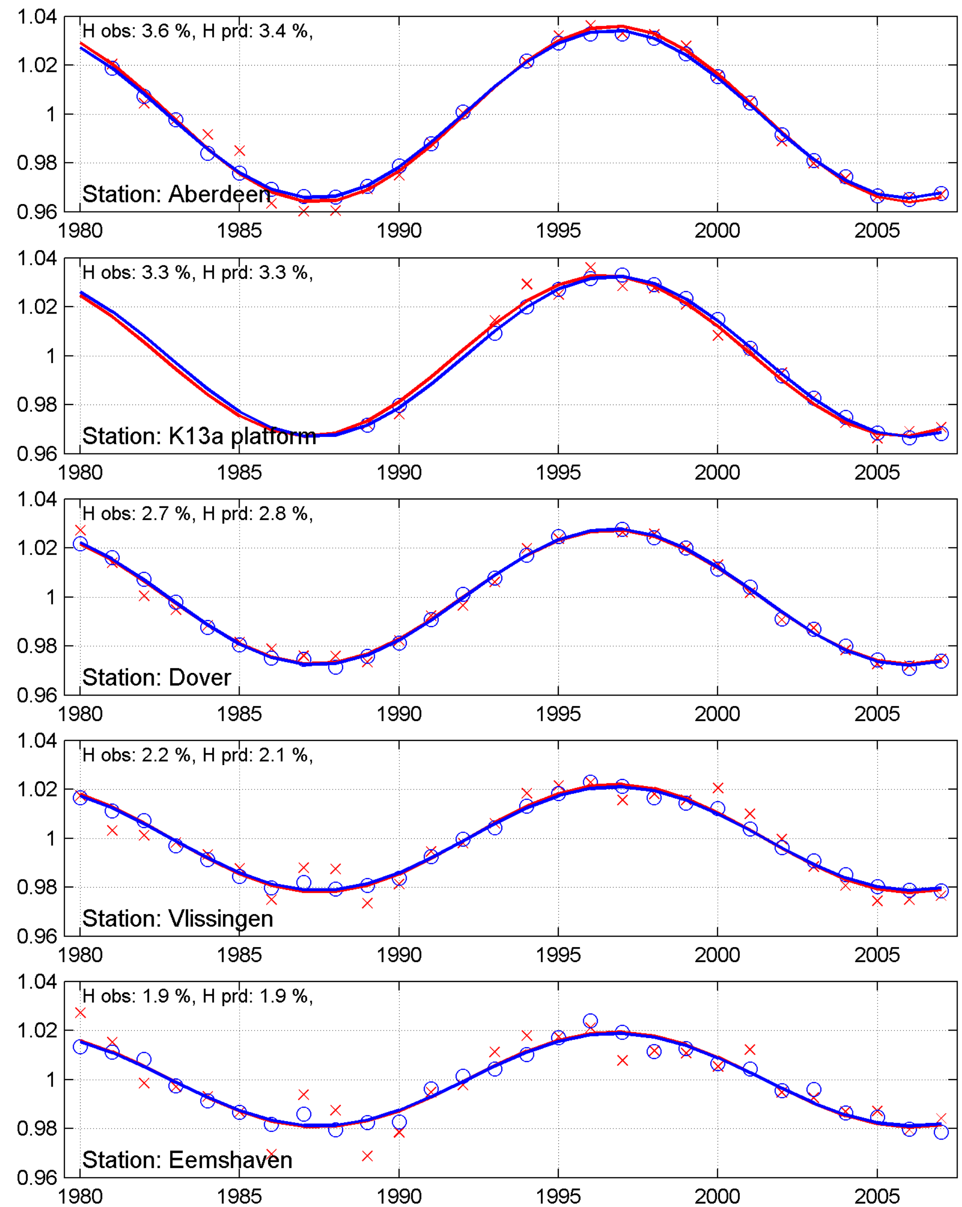
Validation nodal cycle



Nodal amplitude equilibrium tide = 3.7%







Red X: Measured

Blue O: Computed

Results

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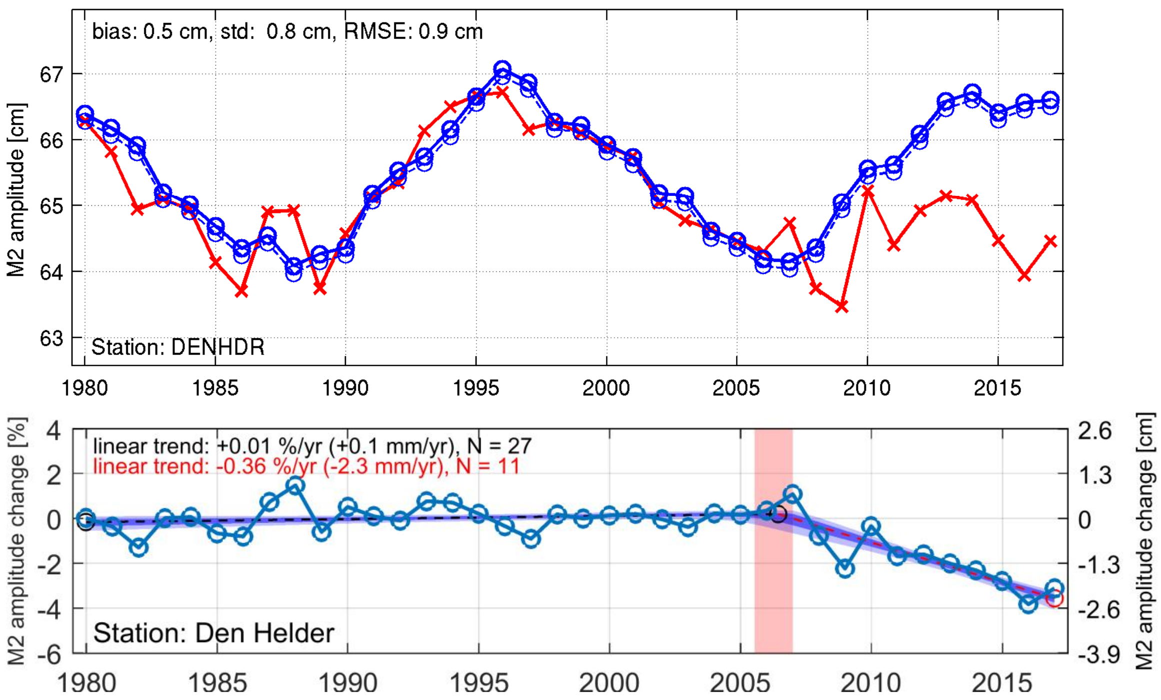
Results

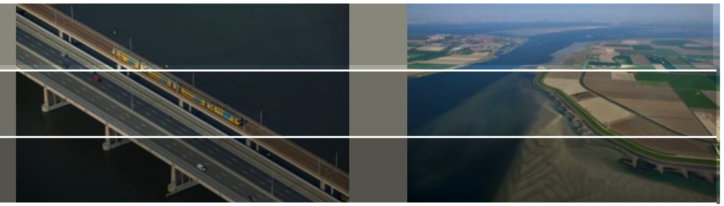


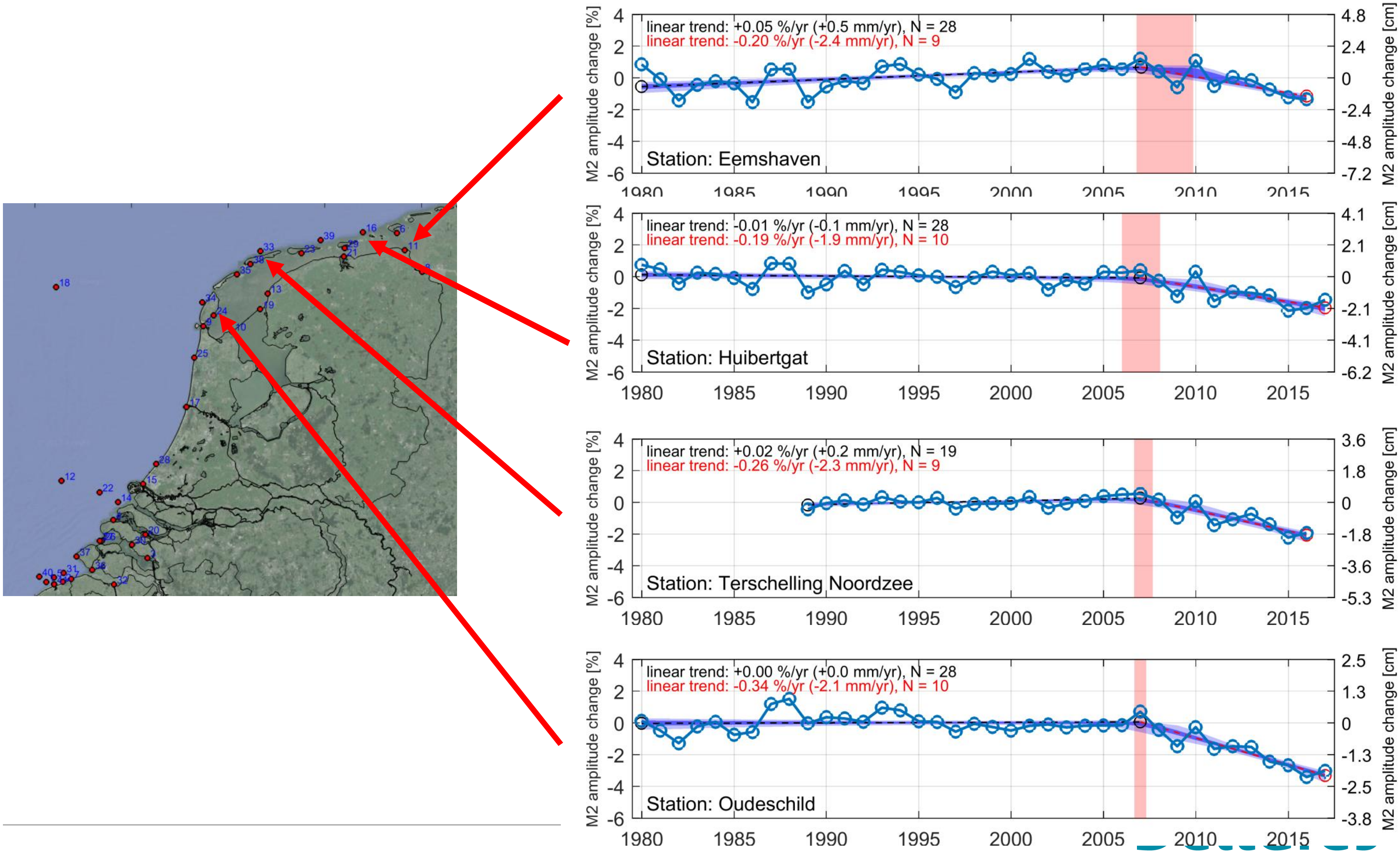
Red X: Measured

Blue O: Computed

- Linear segmented regression model ('broken sticks') to find
  - break points
  - rate of change
- Sensitivity determined with bootstrap method (95% confidence interval plotted)
- Focus on M2 (largest signal-to-noise ratio), but trend also present in e.g. S2 and M4

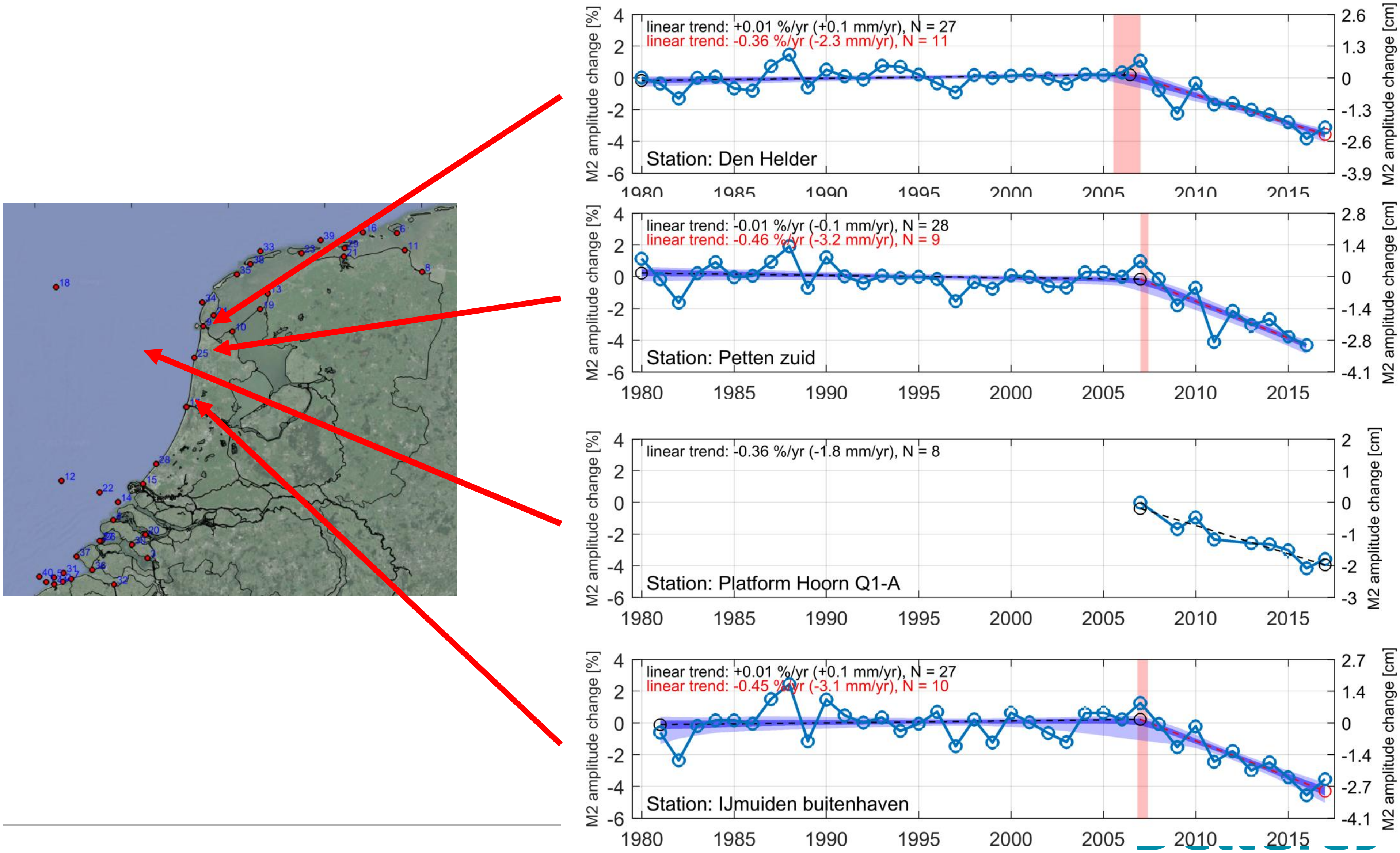
Results



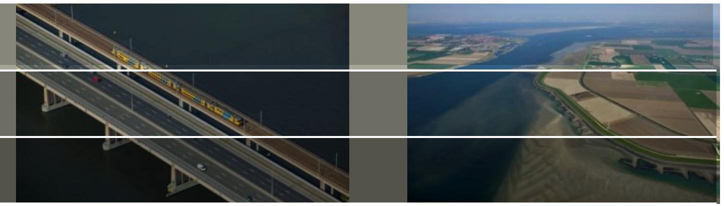


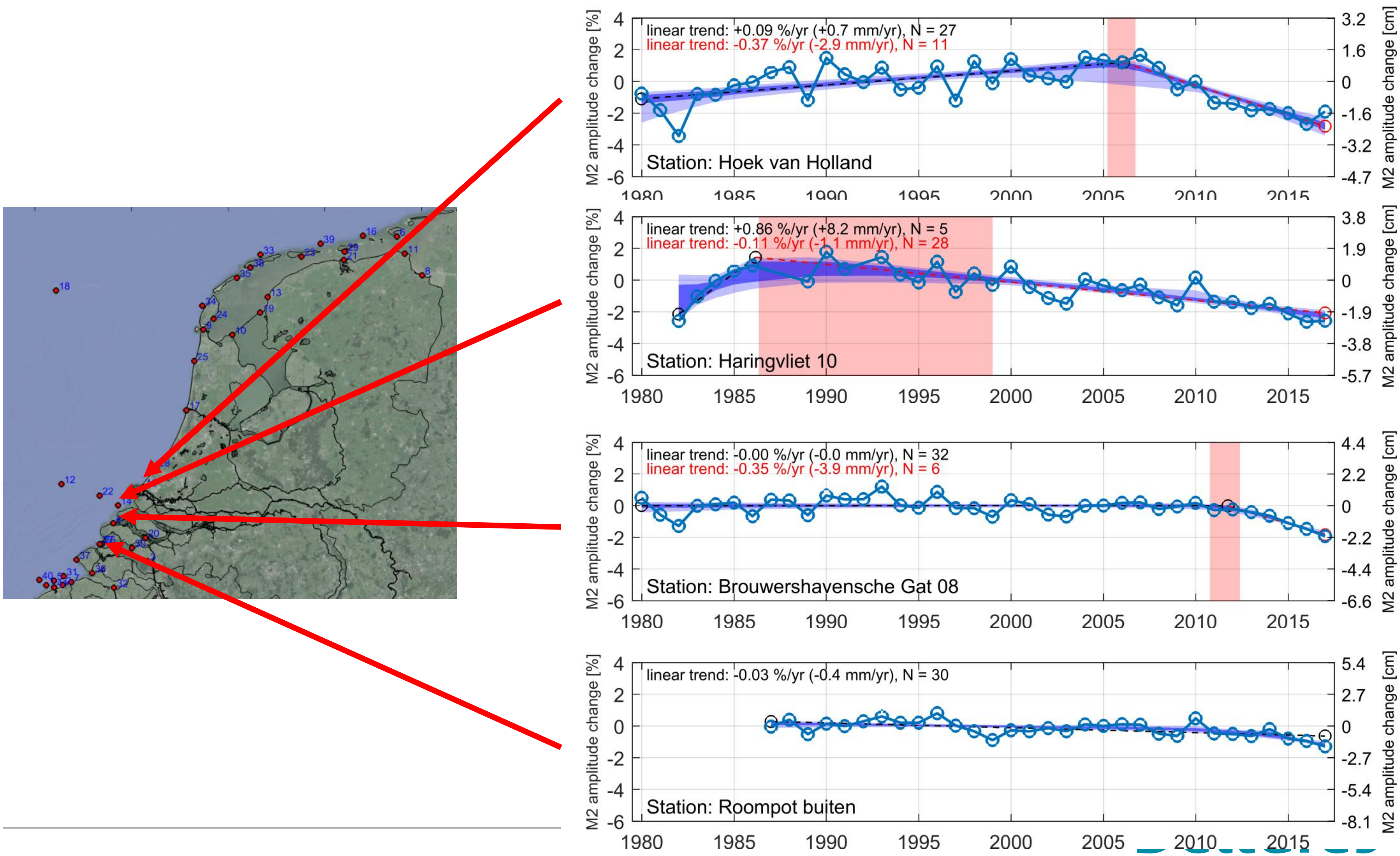
linear trend: +0.05 %/yr (+0.5 mm/yr), N = 28
linear trend: -0.20 %/yr (-2.4 mm/yr), N = 9
Station: Eemshaven
linear trend: -0.01 %/yr (-0.1 mm/yr), N = 28
linear trend: -0.19 %/yr (-1.9 mm/yr), N = 10
Station: Huibertgat
linear trend: +0.02 %/yr (+0.2 mm/yr), N = 19
linear trend: -0.26 %/yr (-2.3 mm/yr), N = 9
Station: Terschelling Noordzee
linear trend: +0.00 %/yr (+0.0 mm/yr), N = 28
linear trend: -0.34 %/yr (-2.1 mm/yr), N = 10
Station: Oudeschild
M2 amplitude change [%]
M2 amplitude change [cm]

Results


linear trend: +0.01 %/yr (+0.1 mm/yr), N = 27
linear trend: -0.36 %/yr (-2.3 mm/yr), N = 11
Station: Den Helder
linear trend: -0.01 %/yr (-0.1 mm/yr), N = 28
linear trend: -0.46 %/yr (-3.2 mm/yr), N = 9
Station: Petten zuid
linear trend: -0.36 %/yr (-1.8 mm/yr), N = 8
Station: Platform Hoorn Q1-A
linear trend: +0.01 %/yr (+0.1 mm/yr), N = 27
linear trend: -0.45 %/yr (-3.1 mm/yr), N = 10
Station: IJmuiden buitenhaven
M2 amplitude change [%]
M2 amplitude change [cm]
1980
1985
1990
1995
2000
2005
2010
2015

Results

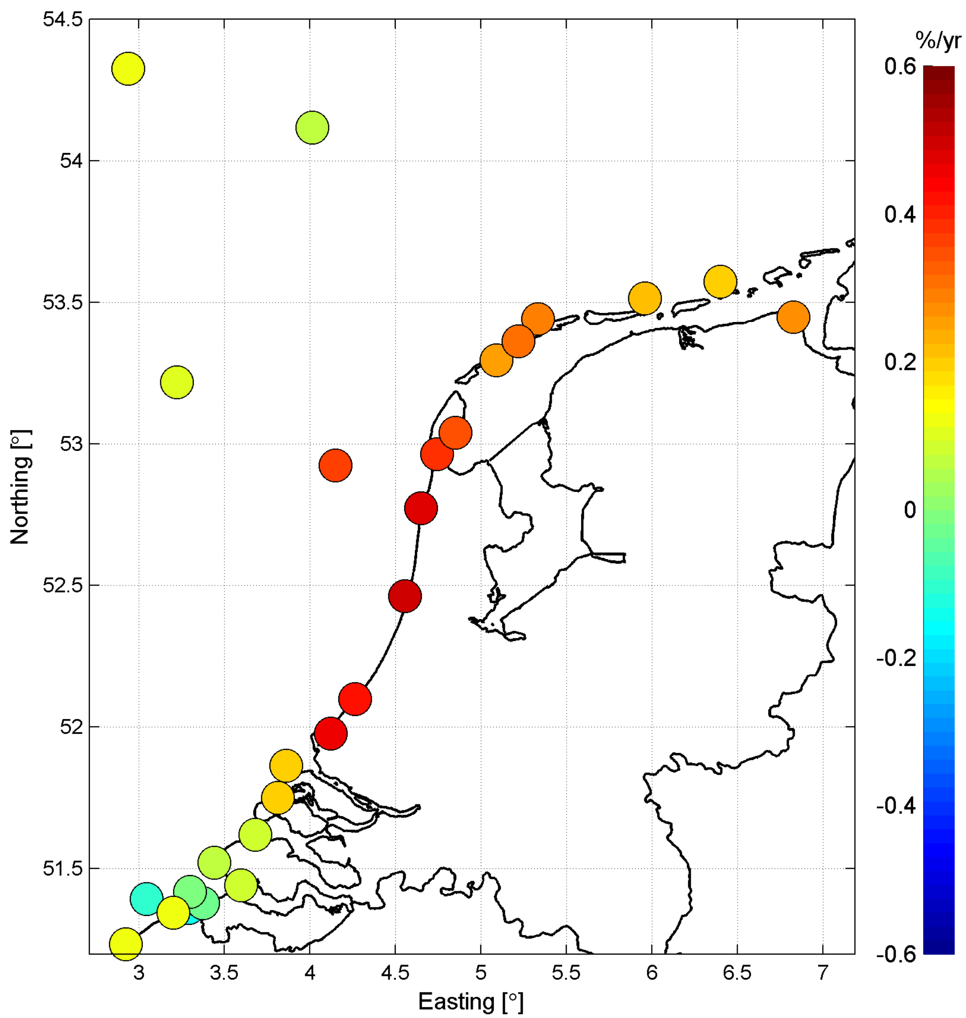




linear trend: +0.09 %/yr (+0.7 mm/yr), N = 27
linear trend: -0.37 %/yr (-2.9 mm/yr), N = 11
Station: Hoek van Holland
linear trend: +0.86 %/yr (+8.2 mm/yr), N = 5
linear trend: -0.11 %/yr (-1.1 mm/yr), N = 28
Station: Haringvliet 10
linear trend: -0.00 %/yr (-0.0 mm/yr), N = 32
linear trend: -0.35 %/yr (-3.9 mm/yr), N = 6
Station: Brouwershavensche Gat 08
linear trend: -0.03 %/yr (-0.4 mm/yr), N = 30
Station: Roompot buiten
M2 amplitude change [%]
M2 amplitude change [cm]
1980
1985
1990
1995
2000
2005
2010
2015

Spatial distribution

Linear trend 2007-2017 minus linear trend 1980-2007



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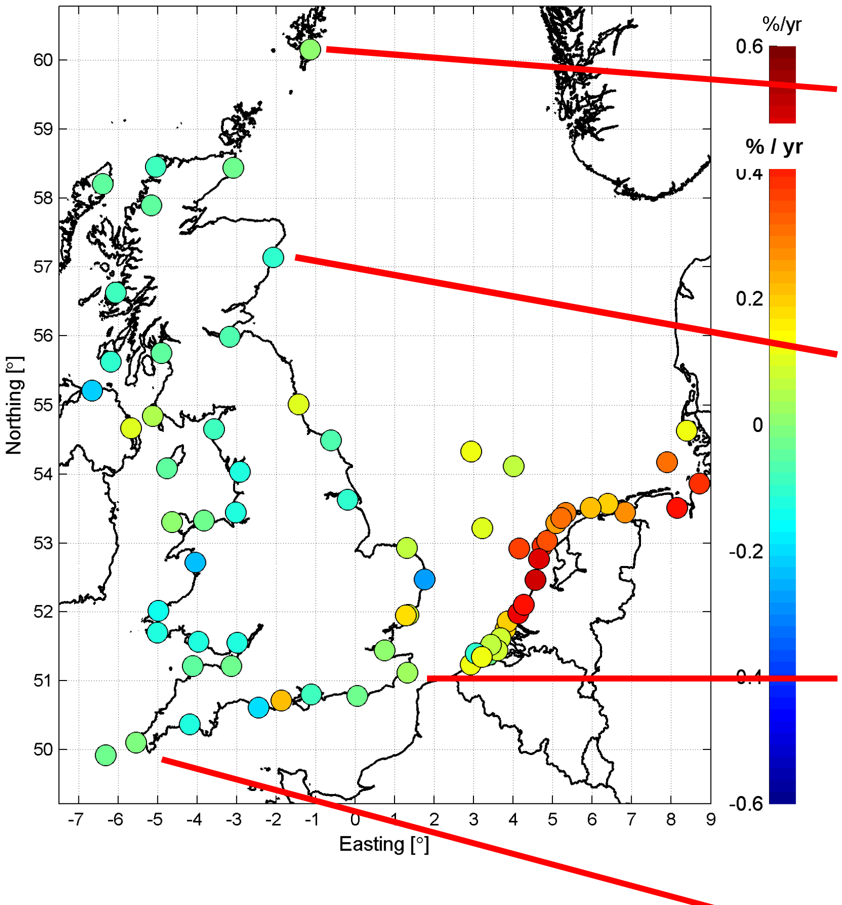
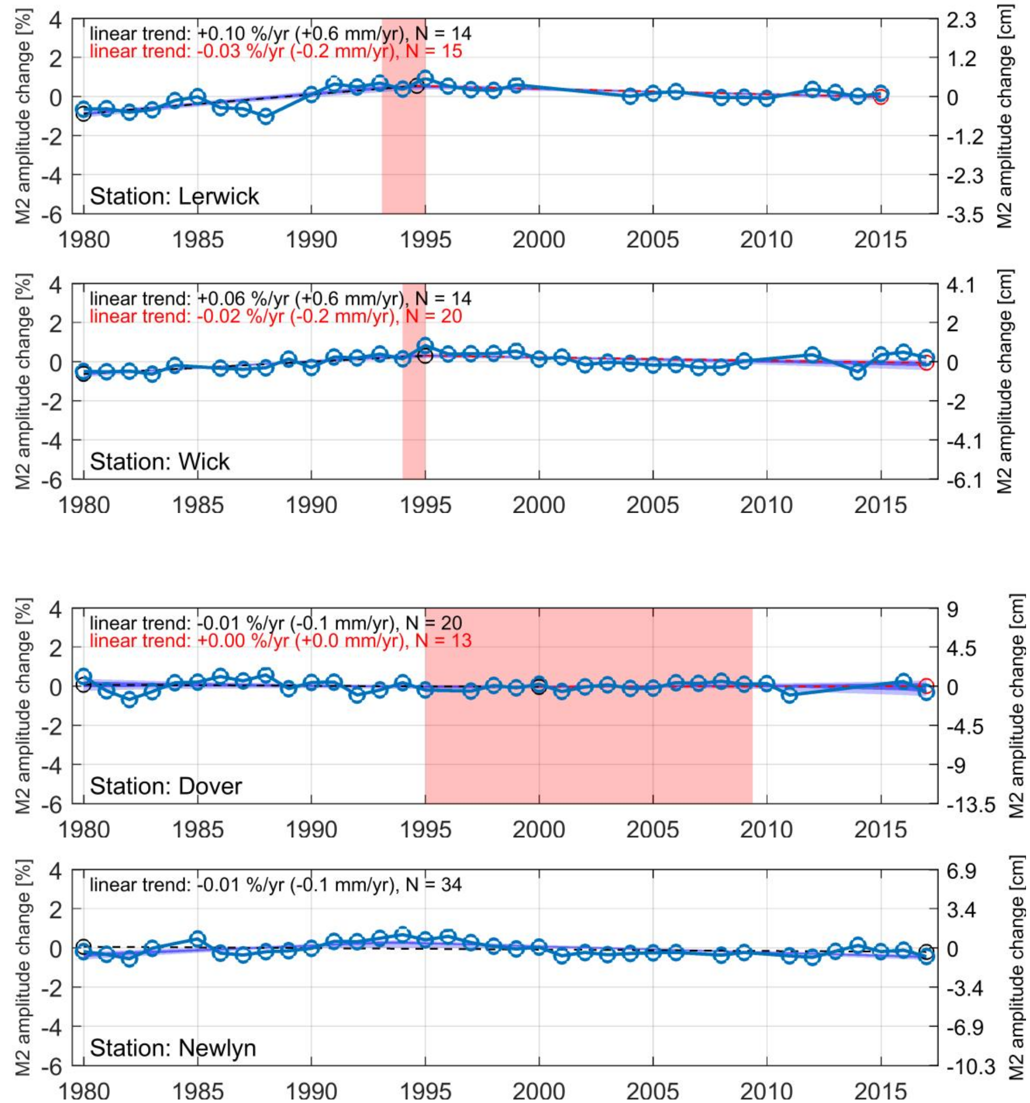
Changes in large-scale oceanic processes?

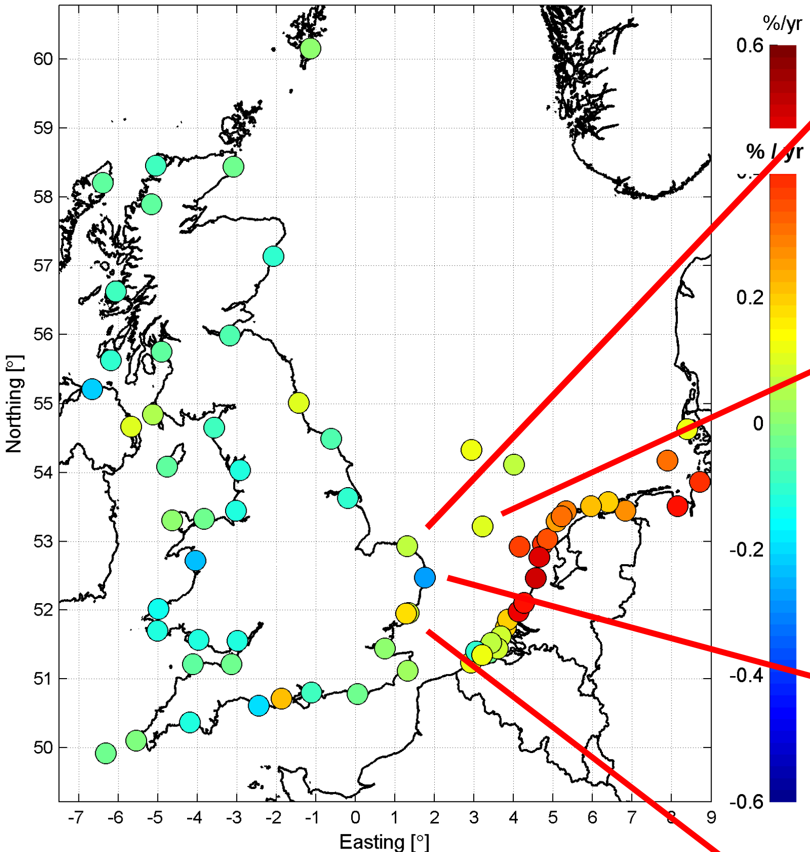
Change in Arctic sea ice extent? Weakening of Atlantic circulation?

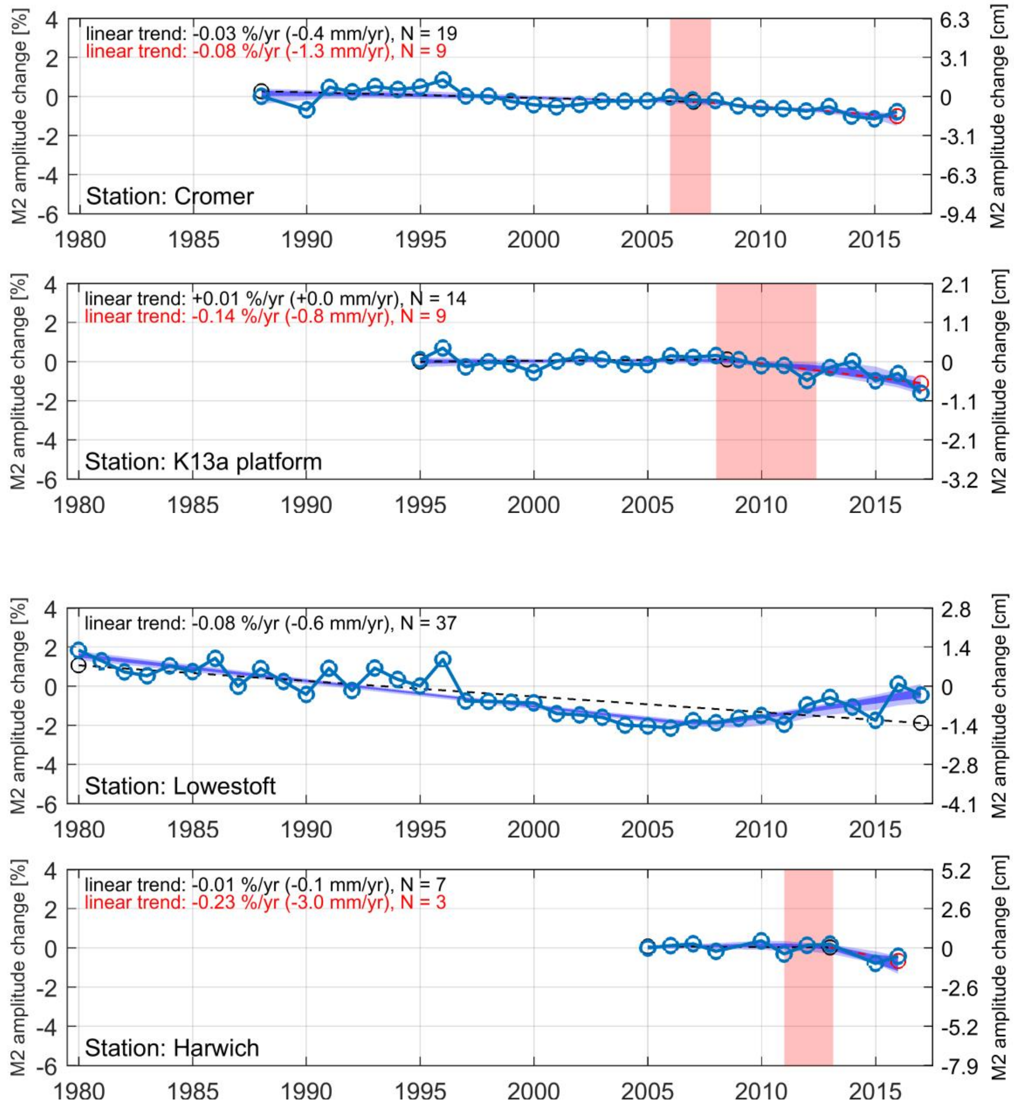


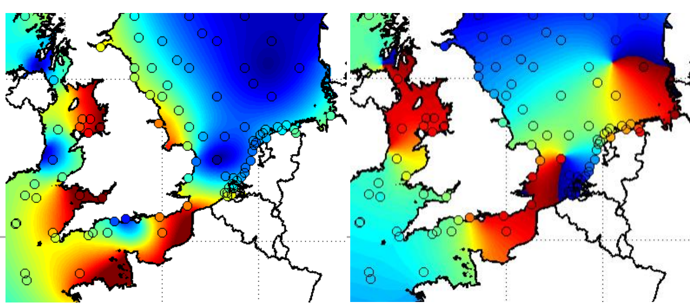


Hollebrandse (2005) – changes in North Atlantic Ocean are damped in North Sea

Change in amphidromic point?







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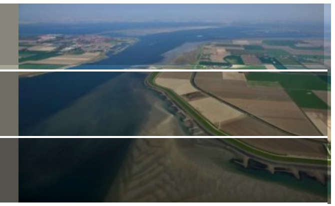
Other potential mechanisms

Where to look?

- Spatial coherence suggest a common cause
- Large magnitude suggests a cause should be of significant scale
  - Hollebrandse (2005) computed a 2% change following closure of entire estuary
- Gradual change suggests that it is caused by a gradual process

- Related to rising sea levels?
  - 1 m SLR results in increased tidal amplitude of 1-2 % (Müller et al. 2011, Pickering et al. 2012, 2017)
  - does not explain sharp trend break
- The North Sea has also witnessed extensive human interference, with large-scale developments that could have the potential to influence tides:
  - harbour extensions (Zeebrugge or Rotterdam harbours)
  - closure of large estuaries such as the Dutch Delta area,
  - changes to the coastline (e.g. the Sand Motor),
  - dredging of shipping channels,
  - construction of offshore wind farms,
  - sand mining

Conclusions

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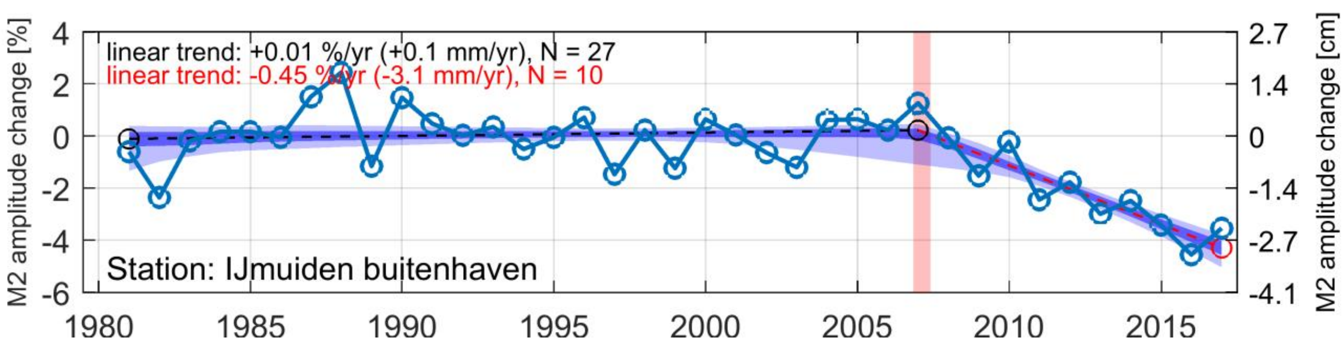
Conclusions

- We observe a gradual decline in M2 amplitudes from 2007 onwards
- The strongest trends are in the order of 0.4-0.5 % per year
- This adds up to 4-5% or 3-4 cm since onset, which is similar to natural variability due to the nodal cycle. From now on, a continuation would imply that the tidal amplitude goes below the level of natural variability.
- The current rate of amplitude change is larger than the observed rate of sea-level rise reported for the North Sea over the period 1980-2005 (~2mm/yr)
- The stations with the strongest declines in M2 amplitude are concentrated along the Dutch coasts and gradually decrease in all directions.
- It is highly important to further investigate the mechanism behind these changes in tidal amplitude.



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Thank you for your attention!