Deltares

Assessment of M2 tidal amplitude changes in the North Sea

1980-2023

Assessment of M2 tidal amplitude changes in the North Sea
1980-2023

Auteur(s)
Firmijn Zijl
Jelmer Veenstra

Assessment of M2 tidal amplitude changes in the North Sea
1980-2023

Client	Rijkswaterstaat Water, Verkeer en Leefomgeving
Contact	Martijn Klein Obbink
Reference	
Keywords	Tides, Tidal amplitudes, M2, North Sea, aalsNW European Continental Shelf, DCSM-FM

Document control	
Version	1.1
Date	2-10-2024
Project nr.	11210366-003
Document ID	11210366-003-ZKS-0002
Pages	27
Classification	
Status	definitief

Author(s)		
	Firmijn Zijl	
	Jelmer Veenstra	

Summary

Tidal amplitudes and phases are generally considered to be stationary. However, there is growing evidence from observations around the world for trends in tidal amplitudes that cannot be explained by the changes in tidal potential (i.e., the gravitational forces associated with the moon and sun). In earlier unreported work, a rapid decline in M2 tidal amplitude was reported along the Dutch coast. That work considered tide gauge measurements from 1980 up to 2017. The present study aims to investigate whether the decline in M2 tidal amplitude has continued in recent years and more generally how the amplitude has evolved since 2017. To this aim, we present an analysis of tidal records and their trends along the North Sea coasts for the period 1980-2023. We focus on M2 since this is the predominant constituent in most parts of the North Sea.

We observe a gradual but strong decline in M2 amplitudes from 2007 to 2016. The strongest trends are in the order of a decline of 0.4-0.5 % per year, equal to a decrease of 3-4 mm/year. The decline in M2 amplitude is strongest along the Dutch coast, the German Bight, Skagerrak, and Kattegat and gradually decreases away from these areas. This decline adds up to 4-5% or 3-4 cm since onset along parts of the Dutch coast. From 2016 onwards we observe a reversal in the direction of the trend, leading to a stagnation or gradual increase in M2 amplitudes. The magnitude of the trend is smaller than in the preceding period and the spatial correlation is less outspoken.

Since the cause for the decline in M2 tidal amplitude and subsequent reversal from 2016 onwards is unknown it is difficult to project the trend into the future. We emphasize that it is highly important to further investigate the mechanism behind these changes in tidal amplitude, for which several suggestions are given.

Samenvatting

Getijamplitudes en -fasen worden over het algemeen verondersteld stationair te zijn. Desalniettemin zijn er steeds meer aanwijzingen gebaseerd op wereldwijde waarnemingen dat er trends optreden in getijamplitudes, die niet verklaard kunnen worden door veranderingen in de getijpotentiaal (d.w.z., de getijopwekkende krachten veroorzaakt door de maan en de zon). In eerder niet-gerapporteerd onderzoek werd een snelle afname in M2 amplitude langs de Nederlandse kust gevonden. Dat werk was gebaseerd op metingen in de periode 1980 tot en met 2017. De huidige studie heeft als doel te onderzoeken of deze daling zich in de afgelopen jaren heeft voortgezet en, meer in het algemeen, hoe de amplitude zich sinds 2017 heeft ontwikkeld. Hiertoe presenteren we een analyse van getijmetingen en trends daarin langs de Noordzeekust voor de periode 1980-2023. Wij concentreren ons op M2, aangezien dit de grootste getijcomponent is in de meeste delen van de Noordzee.

We zien tussen 2007 en 2016 een geleidelijke maar sterke afname van de M2 amplitude. De sterkste trends liggen in de orde van grootte van een daling van 0,4-0,5% per jaar, wat neerkomt op een daling van 3-4 mm/jaar. De afname van de M2 amplitude is het sterkst langs de Nederlandse kust, de Duitse Bocht, het Skagerrak en het Kattegat en neemt geleidelijk af buiten deze gebieden. Deze daling telt sinds het begin op tot 4-5% of 3-4 cm langs delen van de Nederlandse kust. Vanaf 2016 zien we een omkering in de richting van de trend, wat leidt tot een stagnatie of geleidelijke toename van de M2-amplitudes. De magnitude van de trend is kleiner dan in de voorgaande periode en de ruimtelijke correlatie is minder uitgesproken.

Omdat de oorzaak voor de afname van de M2 getijamplitude en de daaropvolgende omkering vanaf 2016 onbekend is, is het moeilijk om te voorspellen hoe de trend zich in de toekomst door gaat zetten. We benadrukken dat het van groot belang is om het mechanisme achter deze veranderingen in de getijdenamplitude verder te onderzoeken, waarvoor verschillende suggesties worden gegeven.

Contents

	Summary	**4**
	Samenvatting	**5**
	Contents	**6**
1	**Introduction**	**7**
1.1	Changing tides	7
1.2	Possible implications	7
1.3	Possible causes	7
1.4	Present study	8
2	**Data and methods**	**9**
2.1	Approach	9
2.2	Measurements	9
2.2.1	Sources	9
2.2.2	Processing	11
2.2.3	Quality assurance	11
2.2.4	Selection	12
2.3	Hydrodynamic model	12
2.4	Model validation	13
2.4.1	M2 tidal amplitude and phase	13
2.4.2	M2 nodal amplitude cycle	14
3	**Results**	**17**
3.1	Time series	17
3.2	Spatial patterns	20
3.3	Discussion	22
4	**Conclusions and recommendations**	**24**
4.1	Conclusions	24
4.2	Recommendations for further study	24
A	**References**	**26**

1 Introduction

1.1 Changing tides

The astronomical forces that drive tides are periodic and mostly semi-diurnal and diurnal. There are also slower frequencies, with periods of 8.85 years, 18.61 years (the nodal cycle) and 20,942 years. Apart from these low-frequency modulations, tidal amplitudes and phases are generally considered to be stationary. However, tides can be altered due to large-scale change in mean sea level and ocean stratification, or local-scale changes in bathymetry, outflow of rivers and coastal morphology. There is growing evidence from observations around the world for trends in tidal amplitudes that cannot be explained by the changes in tidal potential (i.e., the gravitational forces associated with the moon and sun). In earlier unreported work, a rapid decline in M2 tidal amplitude was reported along the Dutch coast. That work considered tide gauge measurements from 1980 up to 2017.

1.2 Possible implications

Tides are the main contributor to water level changes along the Dutch coast. The understanding and accurate prediction of tides is important for many applications. Dissemination of accurate real-time operational predictions made by the Netherlands Water Management Centre (WMCN) are vital for safe harbor entrance and measures to prevent flooding. Movable barriers such as the Maeslant Barrier rely on accurate and timely warnings to close in time. Tidal dynamics are also important for the design and maintenance of coastal defenses and structures. The discharge of excessive inland water by the force of gravity to the North Sea is also controlled by tides. Moreover, tides have an important control over ocean stratification, mixing and transport of sediment, pollutants, algae and nutrients, with implication for water quality and biological processes. Therefore, changing tides can have wide-ranging implications and should be known and preferably understood.

1.3 Possible causes

The mechanisms behind the observed decline are not well understood, and while the evidence is far from conclusive, it has been suggested that the change could be related to climate change and sea-level rise. However, during the last decades the North Sea has also witnessed extensive human interference, with large-scale developments that could potentially affect tides. These include harbor extensions, such as Maasvlakte II in Rotterdam (Netherlands) and Zeebrugge (Belgium), closure of large estuaries such as the Dutch Delta area by the Delta Works, changes to the coastline due to sand nourishment (e.g. the Sand Motor), dredging of shipping channels, construction of wind farms, sand mining. It is, however, difficult to assign the observed tidal trend to any of these causes without further study.

1.4 Present study

The present study aims to investigate whether the decline in M2 tidal amplitude has continued in recent years and more generally how the amplitude has evolved since 2017. To this aim, we present an analysis of tidal records and their trends along the North Sea coasts for the period 1980-2023. We focus on M2 since this is the predominant constituent in most parts of the North Sea. M2 has the largest signal-to-noise ratio and is thus the most sensitive constituent for trend detection. While the main interest is in Dutch coastal waters, station on the wider North Sea and Northwest European Shelf are also considered since spatial patterns in trends might lead to hypothesis on the origin of amplitude variations.

2 Data and methods

2.1 Approach

In this study we present an analysis of tidal records and their trends along the North Sea coasts. To study trends in tidal amplitudes, it is important to correct for the nodal modulation of the tides. The lunar nodal cycle modulates the M2 tide (i.e. the predominant tidal constituent) with a period of 18.61 years and is caused by the precession of the lunar ascending node. This correction is often done with help of the equilibrium tide, but in the shallow waters of the North Sea this is a poor approximation. Empirical corrections can be used to compensate for this, which is for example done in HATYAN to compute the Dutch tide tables. This approach is not ideal here. Another approach is to estimate the nodal modulation from the data, but this requires very long, time-series and makes this method less flexible than the model-based method that we use here. Here we do not correct for the nodal cycle during the tidal analysis but use model-based estimates of the M2 amplitude, that do not have a trend, as a reference.

Compared to statistical removal of the nodal cycle from observations, the main methodological advantage of this approach is that it does not require long homogenous records which are generally not available, and that the removal of the nodal cycle is spatially and hydrodynamically consistent across all tidal gauge stations. Moreover, this approach also corrects for other known modulations of the tide, such as the 8.85-year period rotation of the lunar perigee, as well as potential meteorological impacts in the tide. In addition, the model also offers the opportunity to perform numerical experiments to explore potential causes of change in the tidal signal. Note that these numerical experiments are not part of the current study.

We use a relatively dense network of tide gauge stations and include records up to 2023 (section 2.2). We analyze each year separately using harmonic analysis (HA) with T_TIDE (Pawlowicz et al., 2002) using 118 constituents (43 astronomical and 75 shallow water constituents). The HA is only performed when more than 300 days are available in the year considered. The HA is performed without equilibrium nodal correction, since due to non-linear processes on the shelf the nodal modulation of M2 amplitude is not equal to the magnitude in the equilibrium tide (and tidal potential), and consequently its magnitude shows considerable spatial variation (section 2.4.2).

2.2 Measurements

2.2.1 Sources

The tide gauge observations for this study were collected from several sources. Data for Dutch stations were collected from the Rijkswaterstaat DataDistributieLaag (DDL). Since this source currently does not expose all data that is available, this was combined with a reference dataset that was previously collected for DCSM-FM model development and validation (Zijl et al., 2022). Data for German stations were requested at the Bundesanstalt für Gewässerkunde (BAFG) for the period since 2018 and combined with data previously received from BAFG. Data for stations in the UK were retrieved from the website of the British Oceanographic Data Centre (BODC) for the complete period from 1980 onwards. Data for Belgian stations were collected via the API of MeetnetVlaamseBanken (MVB). Data for other European countries (Ireland, France, Spain, Denmark, Sweden and Norway) were collected from the Copernicus Marine Environment Monitoring Service (CMEMS). An overview of available stations is given in Figure 2.1.

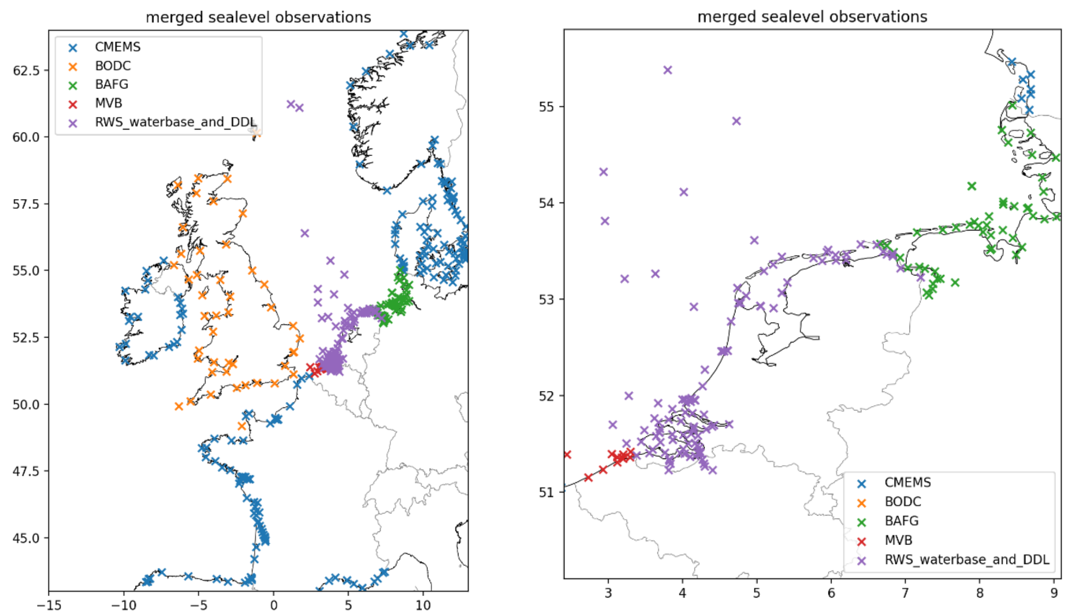


Figure 2.1 Overview of stations with sea level observations.

Table 2.1 Overview of measurements per supplier.

supplier	region	# stations	Temporal coverage indication
BAFG	Germany	49	1995/2000 - 2024
BODC	UK	46	1980/1995 - 2024
MVB	Belgium	11	2000 - 2024
CMEMS[1]	Norway Sweden Denmark Ireland France Spain	13 28 49 22 69 10	1980/1990 - 2023 1980/2012/2019 - 2023 1992/2005/2015 - 2023 2008 - 2023 varying - 2023 1993/2007/2019 - 2023
RWS DDL	Netherlands	Selected: 102 for NAP 16 for MSL	1990 - 2023 for NAP 2012 - 2023 for MSL

Only some of the stations described above cover the entire analysis period of 1980 to 2024. Therefore, the spatial coverage will vary throughout this report depending on the specific analysis period chosen. The temporal coverage of a subset of stations used is given in Figure 2.2, showing quite some variation. Furthermore, not all stations listed above can be used in the analysis. The selection criteria are documented in Chapter 2.2.4.

[1] In this study the *cmems_obs-ins_glo_phy-ssh_my_na_PT1H* dataset was used, containing hourly validated timeseries that are extended every six months. Last updated on 17 may 2024, including all data up to June 2023.

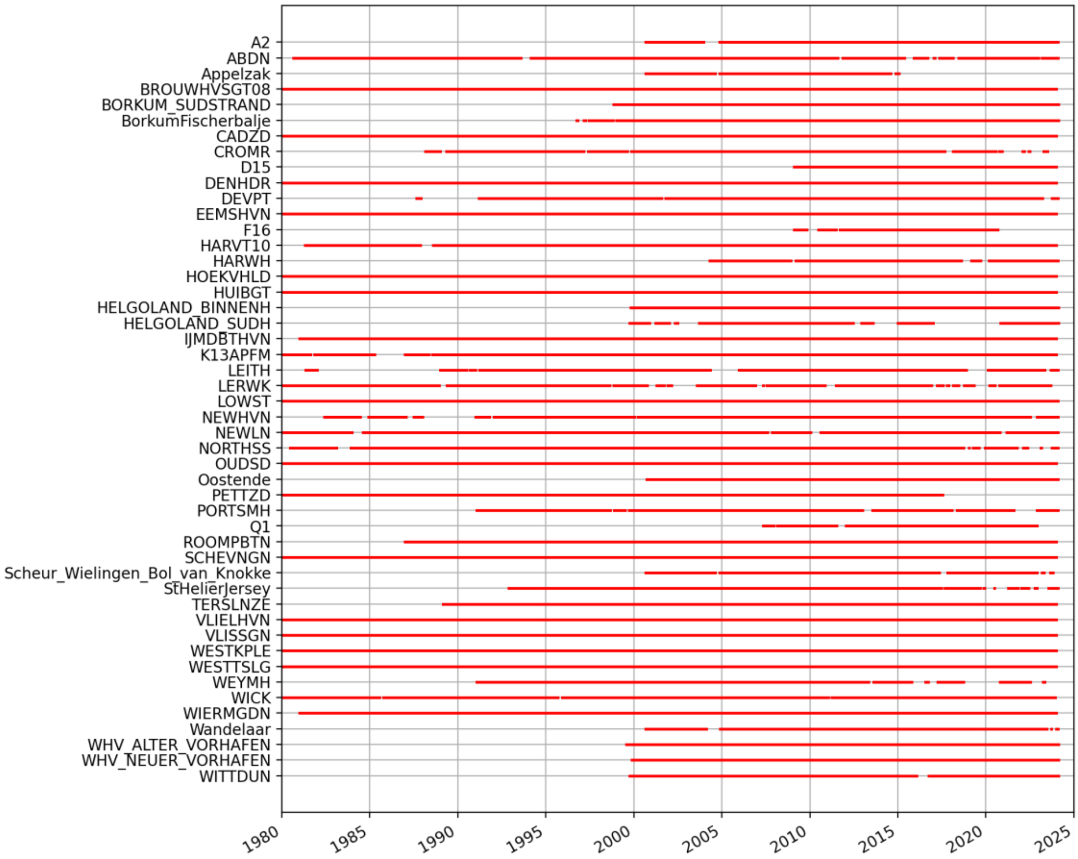


Figure 2.2 Temporal coverage of a subset of stations used in the analysis.

2.2.2 Processing

The format of the data and the available metadata is different for all sources. Where available, data that was flagged as missing, filled or potentially invalid was replaced with nan-values. Additionally, outliers were visualized and reported, this is described in more detail in Chapter 2.2.3. All observation data was converted to a generic netCDF-format supported by the post-processing toolbox used for the analysis in this study.

2.2.3 Quality assurance

Within this study, there is only limited Quality Assurance (QA) executed on the retrieved observation data. The obvious issues that were found (like large outliers) were reported back to the original providers, but there were no corrections done on the data by Deltares. This means that the data is used including all outliers that are present in the raw data. The data retrieved from CMEMS is already validated and therefore contains no outliers. BODC immediately corrected the outliers in their data after they were reported so the data for these stations are also free of outliers. The data from BAFG and RWS includes outliers which were reported but not yet corrected and therefore taken as-is in this study.

Since all results that are derived in this study went through a tidal analysis filter, the outliers have limited impact on the results.

2.2.4 Selection

Chapter 2.2.1 lists an overview of all available stations with data in the period of interest. Some of these stations were discarded in the final analysis, resulting from several selection criteria:

- Some observations are located outside of the DCSM-FM 0.5nm model domain. This holds for instance for stations in the Mediterranean Sea, the Baltic Sea, and the Rhine-Meuse Delta.
- Part of the post-processing is a tidal analysis on the water level timeseries. Since this is only possible for stations that have at least one year of data (and only stations with 300 days of data within a year), all stations with only a few months of observations are excluded because of this step. Since this study is about trend analysis, these stations would not have added value to the results if they would be included.
- Within the spatial trend analysis, stations are included if they have data for 50% of the years in the respective periods. Therefore, the spatial coverage is different for several periods.
- The resolution of the DCSM-FM 0.5nm model is not sufficient to properly represent the geometry of shallow seas and estuaries. Therefore, stations in inter-tidal areas such as the Dutch, German and Danish Wadden Sea as well as upstream parts of estuaries are omitted to prevent results being affected by poor tide representation or erroneous drying and flooding in the hydrodynamic model.

2.3 Hydrodynamic model

We apply the 2022 release of the Dutch Continental Shelf Model - Flexible Mesh (DCSM-FM 0.5nm) in our approach (Zijl et al., 2022), also referred to as *dflowfm2d-noordzee_0_5nm-j22_6-v1a*. DCSM-FM covers the northwest European continental shelf between 15°W to 13°E and 43°N to 64°N (Figure 2.3) and has a spatially varying grid size of up to 2/3’ in east-west direction and 1/2’ in north-south direction, which corresponds to about 0.5 nm x 0.5 nm or 840 m x 930 m in the vicinity of Dutch waters. DCSM-FM is run for the years 1980-2023 (using the last days of 1979 as spin-up) by forcing the model with neutral wind and mean level pressure obtained from the ERA5 reanalysis. Wind speed is converted to wind stress using the Charnock drag formulation, applying the time- and space-varying Charnock coefficient provided by ERA5. The air density used for deriving the wind stress is also obtained from ERA5. At the lateral boundaries total water levels are prescribed, consisting of tide and surge. The tidal levels are derived by harmonic expansion using the amplitude and phase of 39 harmonic constituents, based on a blend of three different global sources, namely FES2014 (Lyard et al., 2021), GTSMv4.1 (Muis et al., 2016) and EOT20 (Hart-Davis et al., 2021). In the D-HYDRO software the specified amplitudes and phases are converted into timeseries covering the required period by means of harmonic prediction. Implicitly it is assumed that the nodal cycle at the location of the open boundaries can be obtained from the equilibrium tide.

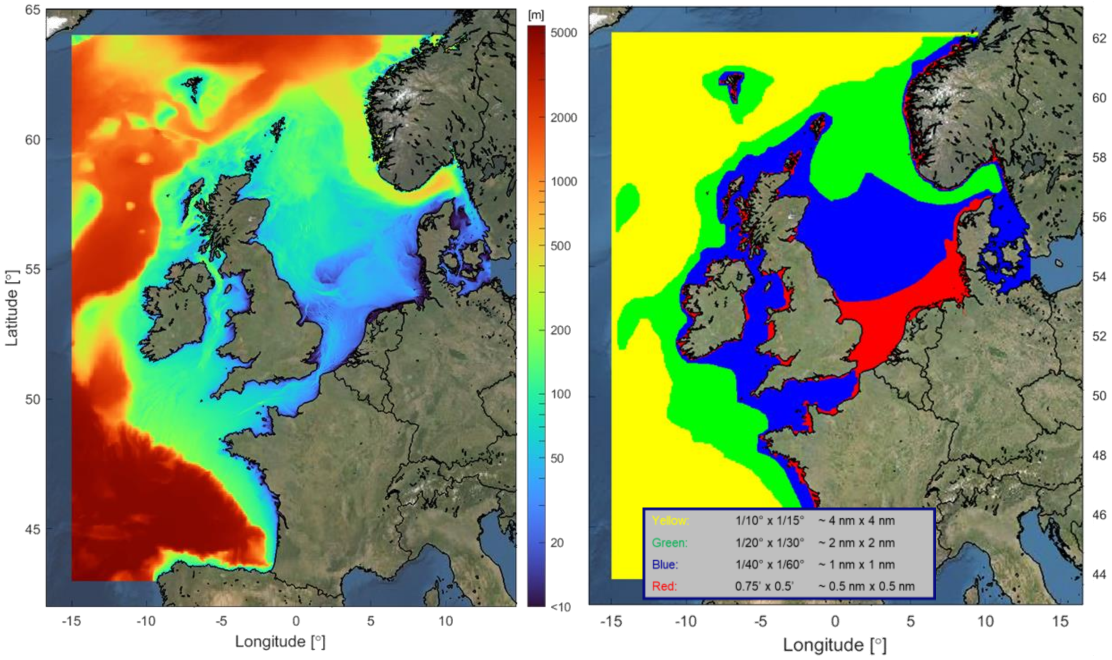


Figure 2.3 DCSM-FM 0.5nm model domain and bathymetry (left) and horizontal network resolution (right).

2.4 Model validation

2.4.1 M2 tidal amplitude and phase

DCSM-FM 0.5nm has been validated extensively, also with respect to tides (Zijl et al., 2022). To illustrate the excellent skill, the time-averaged observed and modelled M2 amplitudes and phases are presented in Figure 2.4. Note that the stations with outliers in the phase are in the Skagerrak and Kattegat, where the quality of the tide is affected by the exclusion of the Baltic Sea from the model domain.

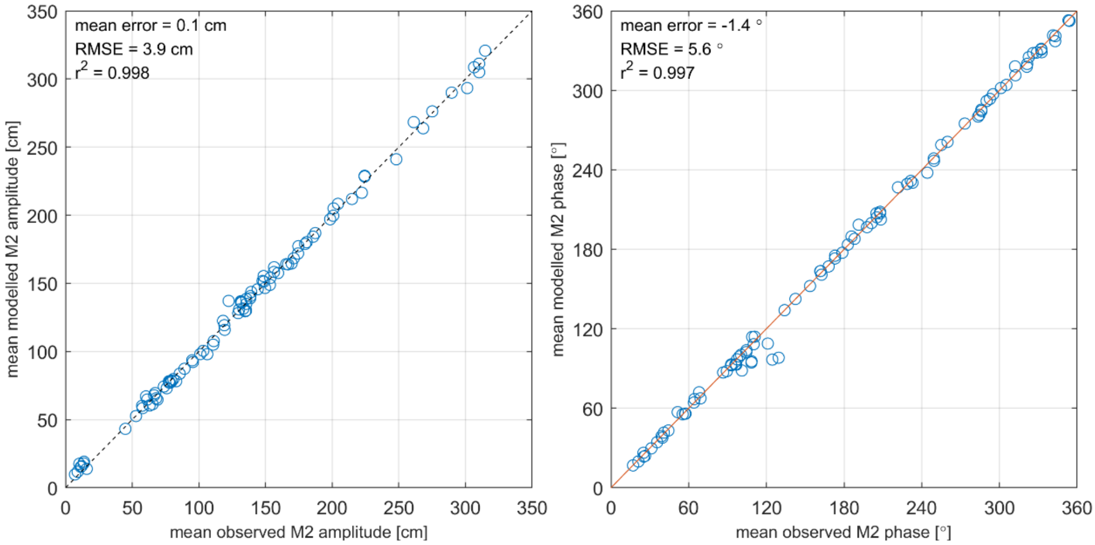
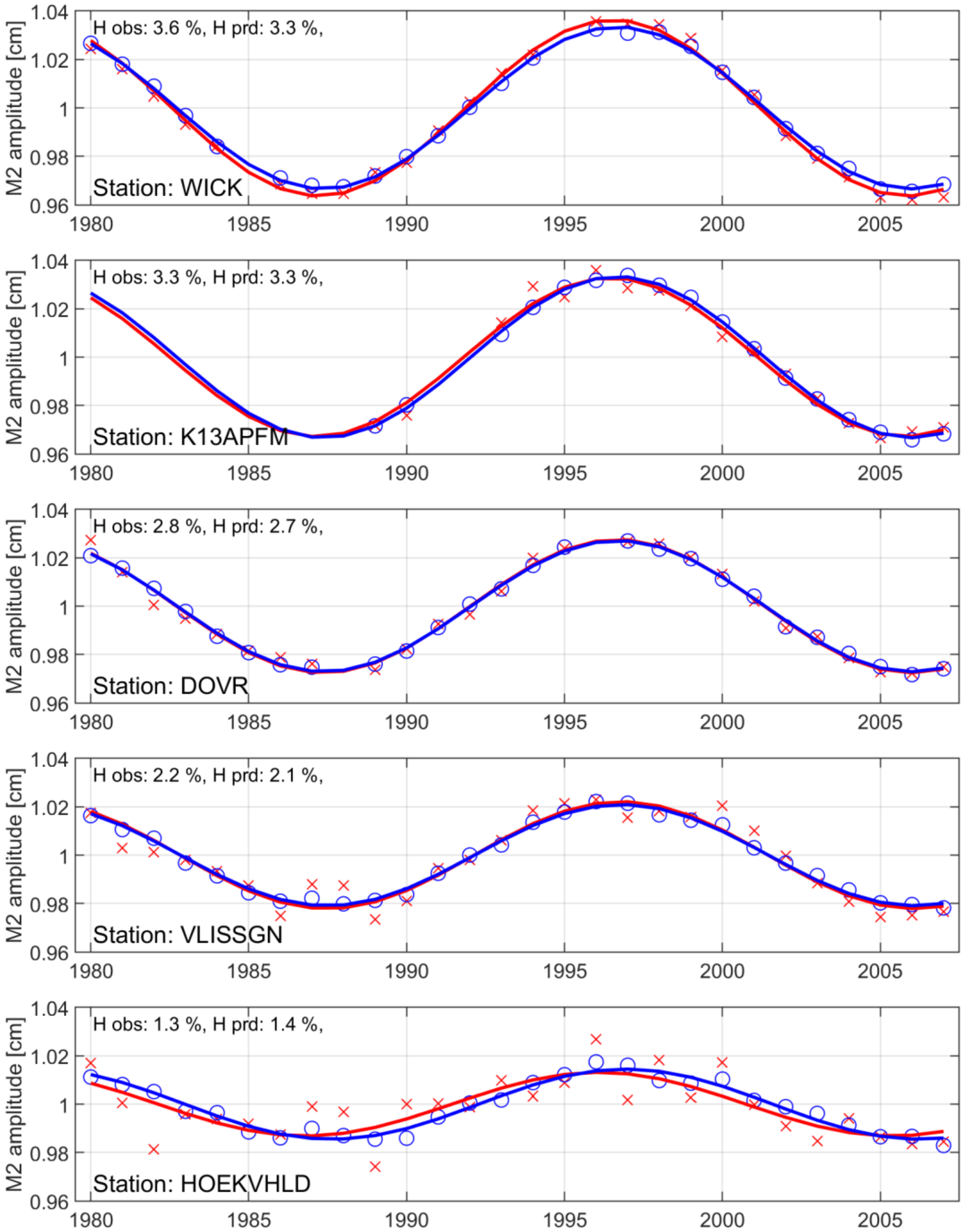


Figure 2.4 Comparison of modelled and measured time-averaged M2 amplitudes (left) and phase lags (right).

2.4.2 M2 nodal amplitude cycle

For this specific application, we also verified the representation of the M2 nodal cycle by DCSM-FM. For this analysis, only the years 1980 to 2007 were considered to not interfere with the changes described further in this memo. Stations with less than 15 years within this period were disregarded. The harmonic parameters of the nodal cycle as well as the long-term linear trends were estimated by a least squares estimation model. In Figure 2.5 time series of the modelled and observed amplitudes of M2, normalized with the time-averaged M2 amplitude, are presented for six selected stations, showing the nodal cycle. These results show significant variation in normalized amplitudes, which are well represented in the model. Some stations show a large signal-to-noise ratio and the relatively large deviations in some of these stations (such as Hoek van Holland) may reflect that a record length of up to 38 years is too short for an accurate statistical fit of the 18.6-year nodal cycle.



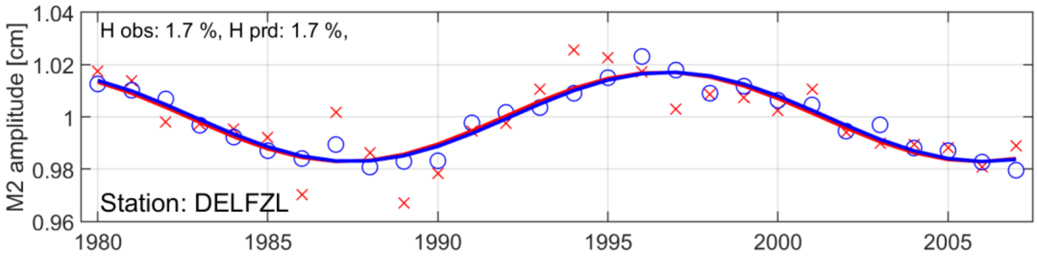


Figure 2.5 Modelled (blue circles) and observed (red crosses) amplitudes of M2 showing the nodal cycle for six selected stations. The solid lines represent the fitted nodal cycle.

The measured and modelled nodal amplitude of all stations are presented in Figure 2.6 as a scatterplot, both as absolute values and normalized with the time-averaged M2 amplitude and expressed as a percentage. These results show that significant reductions in normalized amplitudes compared to the equilibrium tide M2 amplitude ratio (3.7%) occur, with the reduction well captured by DCSM-FM.

In Figure 2.7 and Figure 2.8, the spatial pattern of the amplitude ratios of the M2 amplitude nodal cycle, normalized with the equilibrium tide M2 amplitude ratio (3.7%), are presented for both the observations and model results. These figures shows that the reduction in amplitude compared to the equilibrium tide occurs mostly in the southern North Sea and German Bight as well as the Skagerrak and Kattegat. This spatial pattern is well represented by DCSM-FM.

Note that the colour scale in Figure 2.8 is centred around an M2 amplitude nodal cycle reduction factor of 0.53, used for most stations in the HATYAN harmonic analysis package of RWS (the so-called 'Xfactor'). These results show that also in Dutch waters significant deviations from this value of 0.53 occur.

Overall, the validation results in this section show that DCSM-FM accurately represents the nodal cycle at various locations, and thus we conclude that the model can be used to remove natural tide variability from the observations. The lack of nodal periodicity in the results (section 3.1) confirms the validity of this approach.

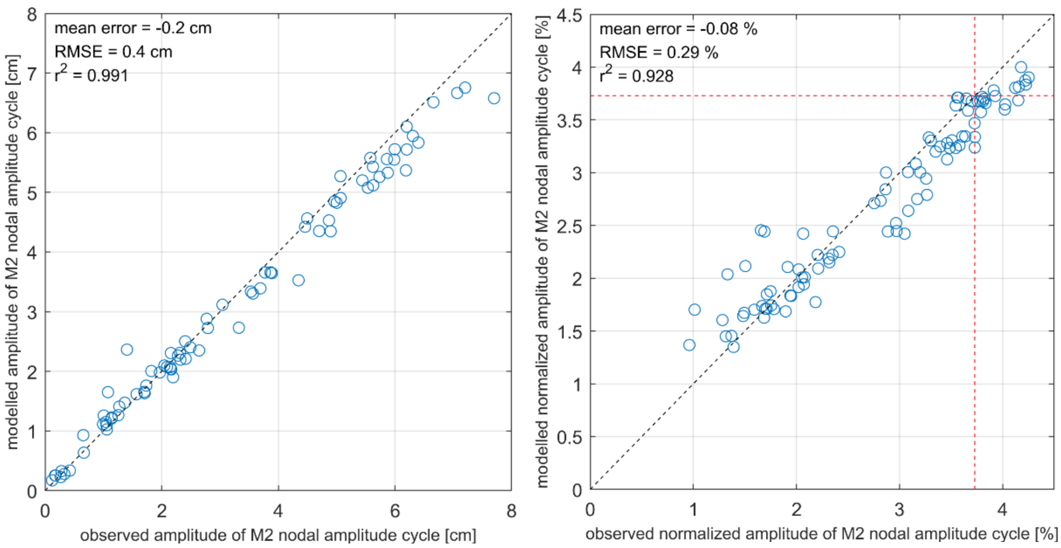


Figure 2.6 Comparison of measured and modelled amplitudes of the M2 amplitude nodal cycle as absolute values (left) and normalised with the time-averaged observed M2 amplitude (right). The red dashed lines represent the equilibrium tide M2 amplitude ratio (3.7%).

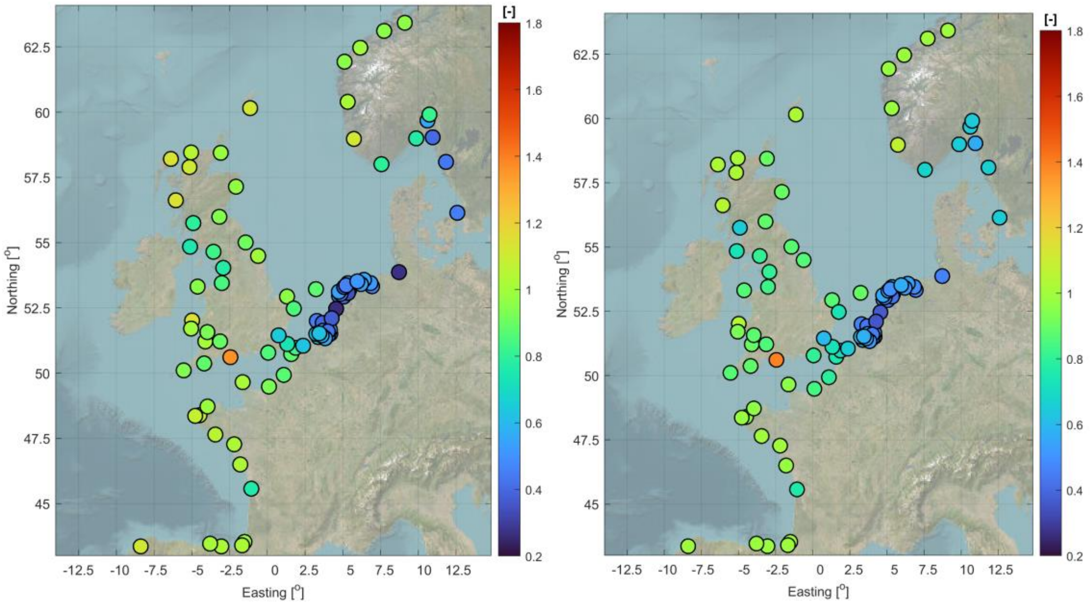


Figure 2.7 Measured (left) and modelled (right) amplitude ratios of the M2 amplitude nodal cycle, normalised with the equilibrium tide M2 amplitude ratio (3.7%).

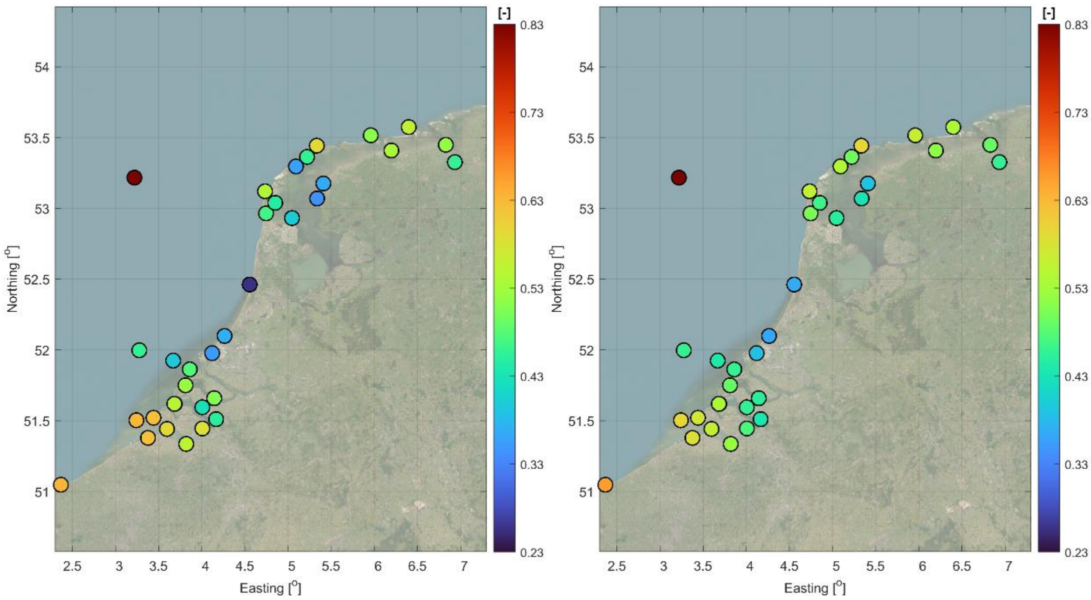


Figure 2.8 Measured (left) and modelled (right) amplitude ratios of the M2 amplitude nodal cycle, normalised with the equilibrium tide M2 amplitude ratio (3.7%).

3 Results

3.1 Time series

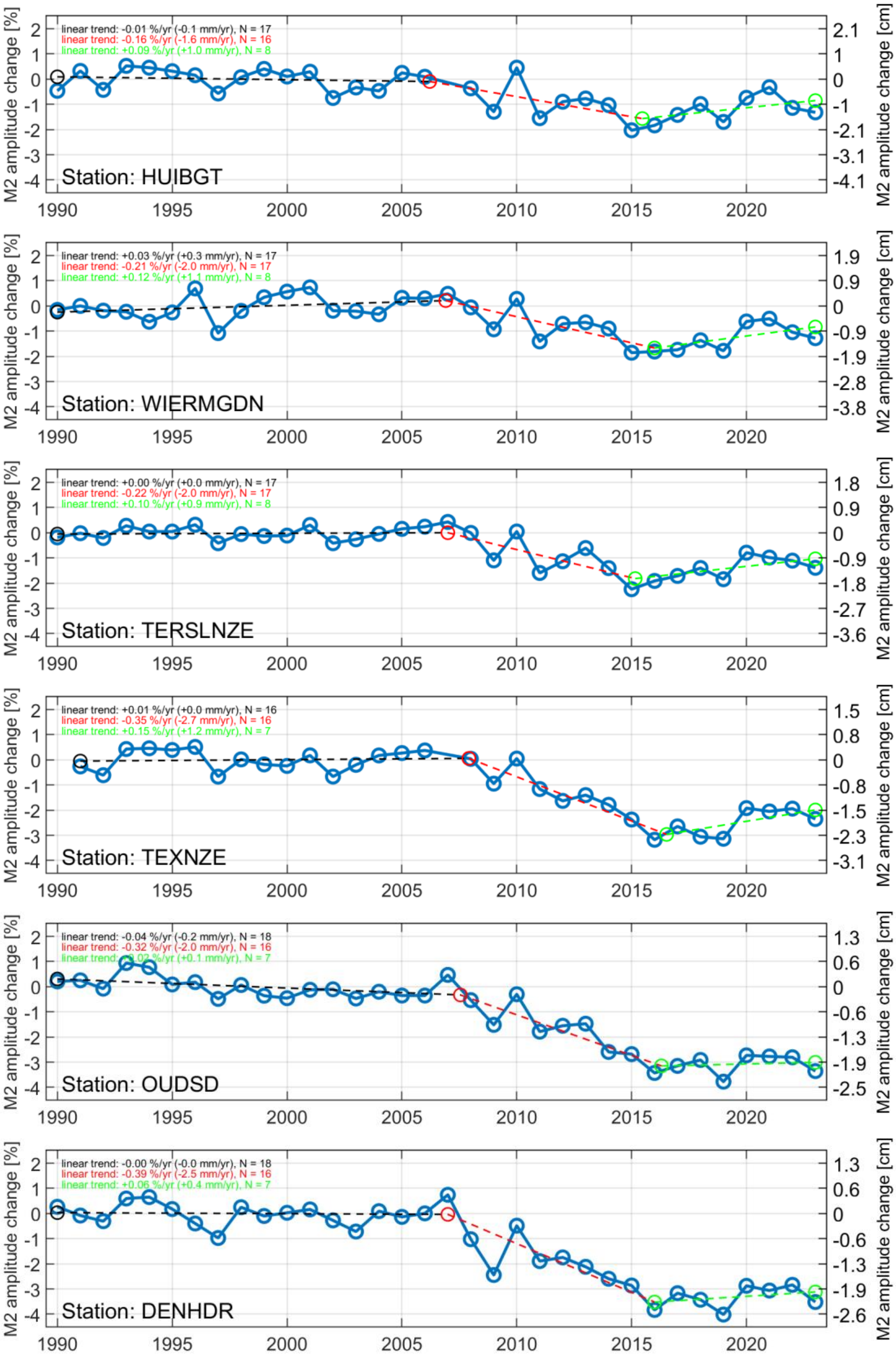
Natural tidal variability is removed from the observed M2 tidal amplitudes by subtracting the modelled values, after which the mean over the years up to 2007 is removed. After this we detect any changes over time by fitting a linear segmented regression ('broken-sticks') model to the resulting time-series of M2 tidal amplitudes at each station. Each fit is based on the least-squares method, assuming a pre-described number of breakpoints with arbitrary timing. For the final analysis we selected two breakpoints and consequently three sections. Based on the fitted regressions we compute the trend in each section as mm/year and %/year (by dividing by the mean observed amplitude).

Figure 3.1 plots the linear trend in M2 amplitude from 1990 to 2023 for twelve selected stations along the Dutch coast (locations in Figure 3.2). Note that the observed M2 values are the values after the modelled (nodal) variability has been subtracted and the mean difference with the model in the years up to 2007 has been removed.

The M2 amplitude shows considerable interannual variability, which appears to be spatially correlated. For example, this is clearly visible in the years 2009 (below the trend line in most stations), 2010 (above the trend line) and 2011 (below the trend line again). However, no trend is visible prior to 2006-2007.

After 2007, most stations along the Dutch coast show a gradual but strong and significant decline in M2 amplitude. With a trend of -0.47% per year (i.e. -3.2 mm/year), the strongest decline occurred at station IJmuiden. The magnitude of the cumulative decline in tidal amplitude over the period 2007-2016 is substantial with up to 5% for stations such as IJmuiden. Towards the southern Dutch waters, the rate of decrease of the M2 amplitude, averaged over the period 2007-2016, decreases. This is partly because the downward trend at other stations starts later in time, as is illustrated for the station Brouwershavense Gat 08. At this station, the tidal amplitude remains relatively constant until 2012, after which we observe a strong decline until 2017.

In the years from 2016 onwards the gradual decline suddenly stops and is even slightly reversed in some stations.


M2 amplitude change [%]
M2 amplitude change [cm]
linear trend: -0.01 %/yr (-0.1 mm/yr), N = 17
linear trend: -0.16 %/yr (-1.6 mm/yr), N = 16
linear trend: +0.09 %/yr (+1.0 mm/yr), N = 8
Station: HUIBGT
linear trend: +0.03 %/yr (+0.3 mm/yr), N = 17
linear trend: -0.21 %/yr (-2.0 mm/yr), N = 17
linear trend: +0.12 %/yr (+1.1 mm/yr), N = 8
Station: WIERMGDN
linear trend: +0.00 %/yr (+0.0 mm/yr), N = 17
linear trend: -0.22 %/yr (-2.0 mm/yr), N = 17
linear trend: +0.10 %/yr (+0.9 mm/yr), N = 8
Station: TERSLNZE
linear trend: +0.01 %/yr (+0.0 mm/yr), N = 16
linear trend: -0.35 %/yr (-2.7 mm/yr), N = 16
linear trend: +0.15 %/yr (+1.2 mm/yr), N = 7
Station: TEXNZE
linear trend: -0.04 %/yr (-0.2 mm/yr), N = 18
linear trend: -0.32 %/yr (-2.0 mm/yr), N = 16
linear trend: +0.02 %/yr (+0.1 mm/yr), N = 7
Station: OUDSD
linear trend: -0.00 %/yr (-0.0 mm/yr), N = 18
linear trend: -0.39 %/yr (-2.5 mm/yr), N = 16
linear trend: +0.06 %/yr (+0.4 mm/yr), N = 7
Station: DENHDR
1990
1995
2000
2005
2010
2015
2020

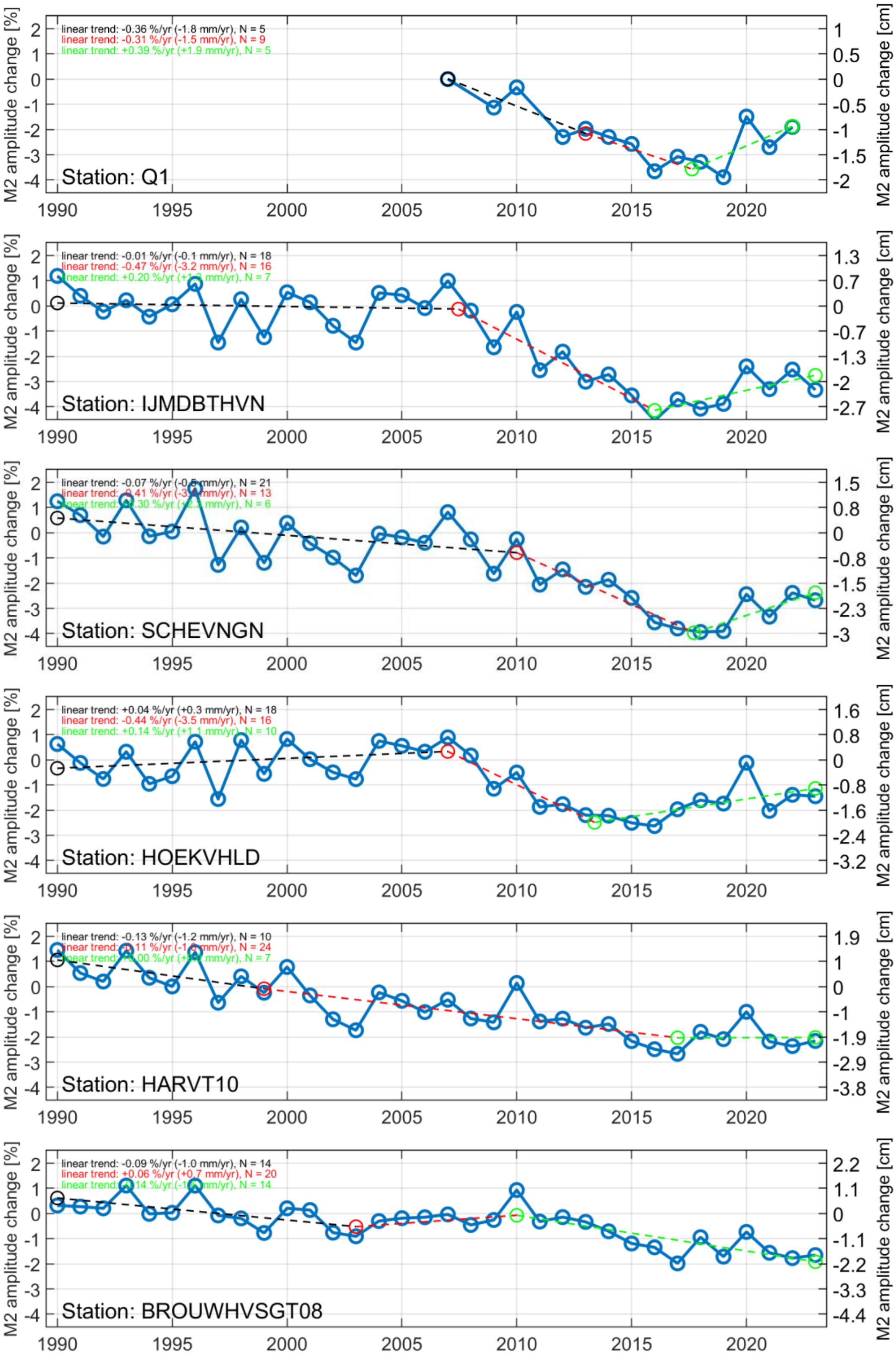


Figure 3.1 Deviation from the 1990-2007 average M2 amplitudes, expressed as %/year (left axis) and cm/yr (right axis), for selected stations, from 1990 to 2023 (solid blue line with open circles) and the best fit of the broken-stick regression model with two arbitrary breakpoints and three sections (black, red and green dashed lines).

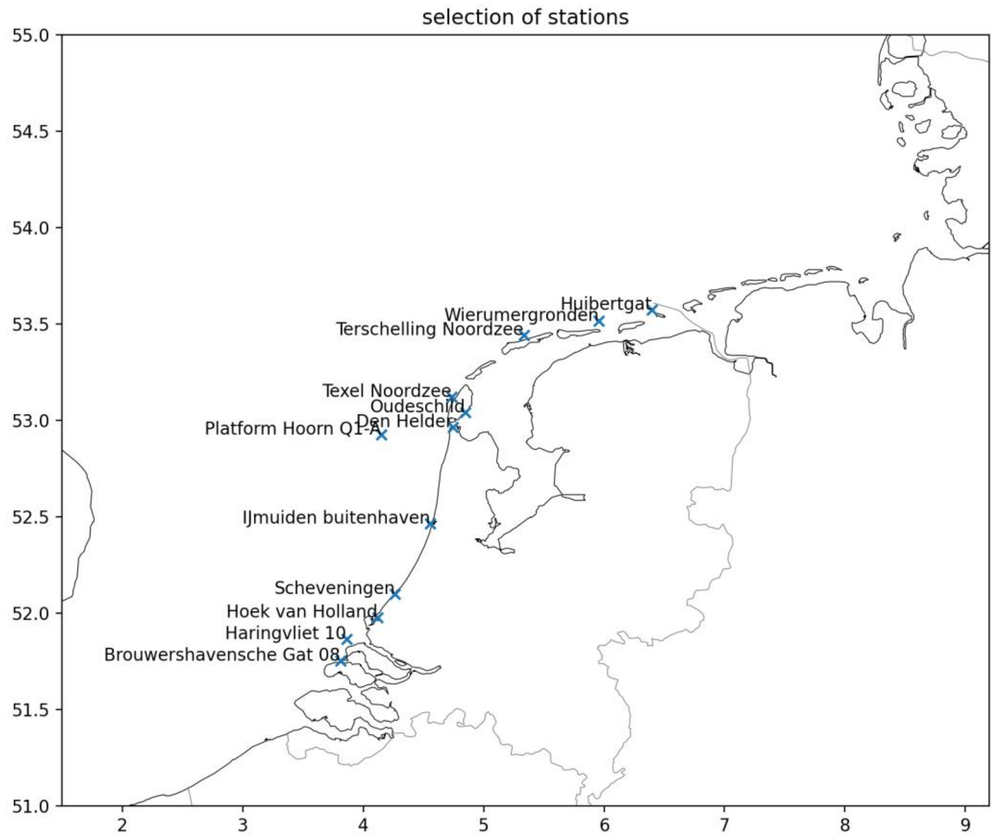


Figure 3.2 Overview of locations of selected stations in Figure 3.1.

3.2 Spatial patterns

Based the time series in the southern North Sea we have identified three periods, with no significant trend up to 2007, a gradual but strong decline in the years 2007-2016 and a stagnation or gradual increase for 2016 onwards. In this section we will further investigate spatial patterns in the observed temporal trends, by computing and visualising the linear trends in all available stations in three fixed periods: 1990 to 2007 (Figure 3.3), 2007 to 2016 (Figure 3.4) and 2016 to 2023 (Figure 3.5).

In the period 1990-2017 (Figure 3.3) most stations show a negligible trend (less than 0.1%/yr). The exceptions are the German Wadden Sea with increases of around 0.1 %/yr and the Skagerrak and Kattegat with increases of 0.3-0.6 %/year, albeit from a low mean amplitude in case of the latter areas. The period 1980-2017 shows similar trends, but is not presented since less stations are available for this longer period.

The years 2007-2016 (Figure 3.4) show a strong decline of 0.5 %/yr in M2 tidal amplitudes stretching from the south of the Holland coast along the German Bight towards the Skagerrak and Kattegat. No spatially coherent trend is found in tidal records from the English Channel, or in UK tidal gauges on the North Sea coast. There is a slight increase in M2 amplitude at Lowestoft and Westhinder, which might indicate a slight shift in the location of the amphidromic point in the southern North Sea.

The period from 2016 to 2023 (Figure 3.5) shows a reversal in the direction of the trend, the magnitude is smaller, and the spatial correlation is less outspoken, with some stations showing a continuing decline.

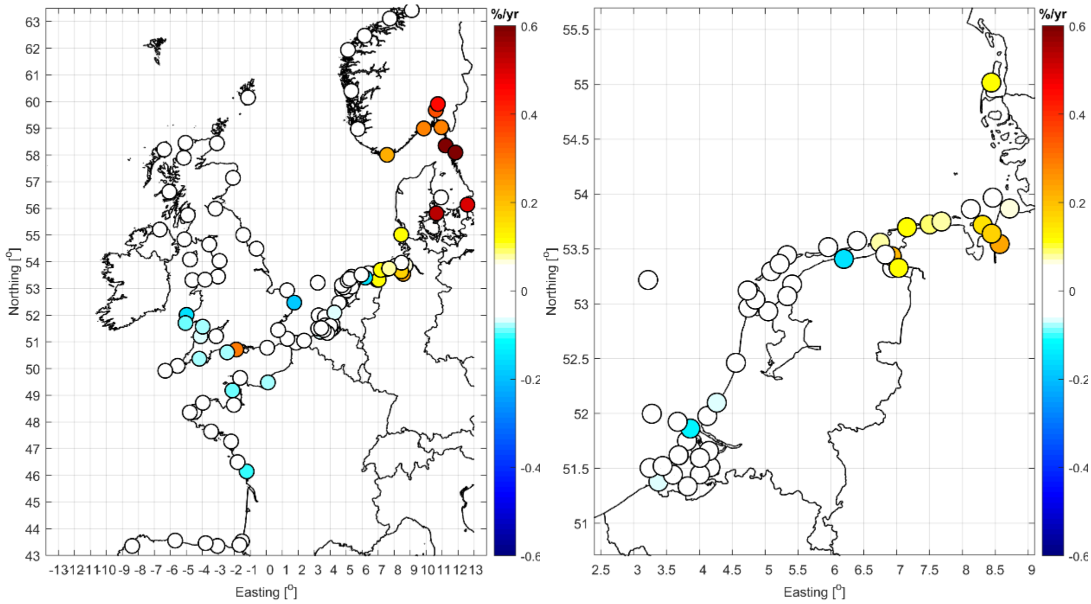


Figure 3.3 Linear trend in M2 amplitude in % per year from 1990-2007 for stations on the Northwest European Shelf (left) and stations along the Dutch coast and German Bight (right).

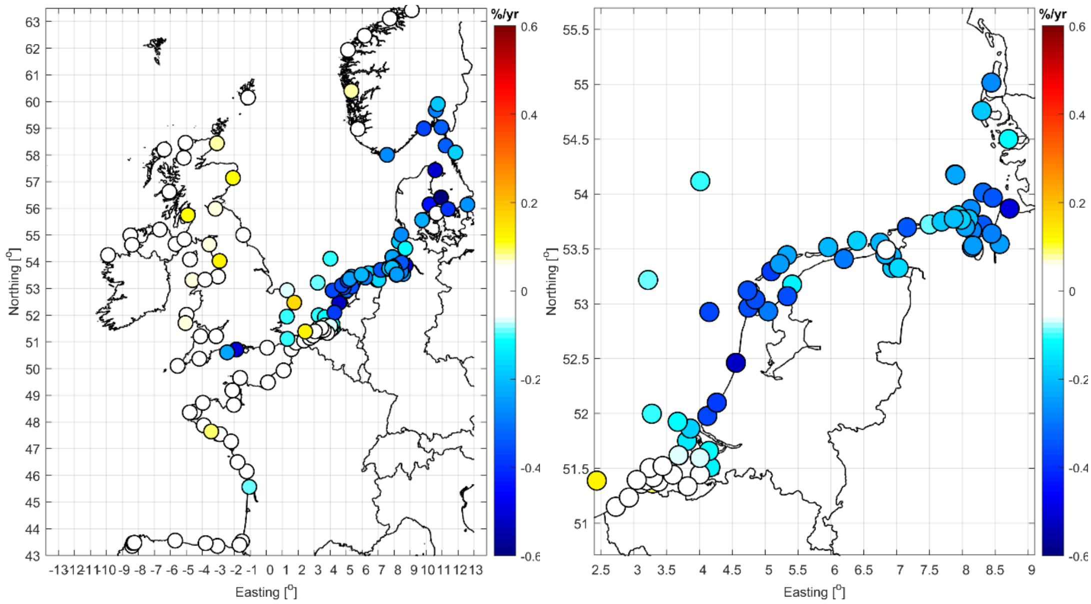


Figure 3.4 Linear trend in M2 amplitude in % per year from 2007-2016 for stations on the Northwest European Shelf (left) and stations along the Dutch coast and German Bight (right).

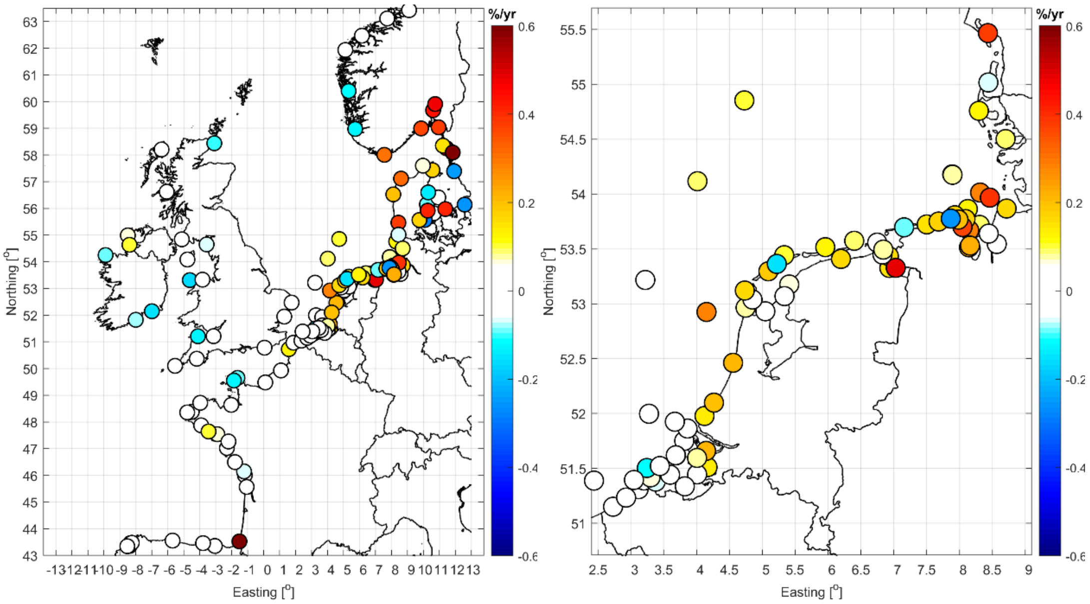


Figure 3.5 Linear trend in M2 amplitude in % per year from 2016-2023 for stations on the Northwest European Shelf (left) and stations along the Dutch coast and German Bight (right).

3.3 Discussion

The clear spatial pattern in the tidal trend in Figure 3.5 as well as the stagnation or reversal of this trend at around the same time in many stations suggests a common cause. Furthermore, the relatively strong (cumulative) decline in M2 amplitude suggests a process of significant scale. The gradual decline over time suggests that the cause is a gradual process that is increasing over time, rather than a single instantaneous intervention.

Potentially, the trend in M2 amplitude could originate from changes in the Atlantic Ocean, such as changes in circulation patterns. However, if the change in M2 tidal amplitude is imported from the Atlantic Ocean larger changes in M2 tidal amplitude along the UK and French coasts would be expected. In the observations, the higher trends are found along the Dutch and German North Sea coast as well as the Skagerrak and Kattegat, while no significant trend is found at the English Channel or the UK North Sea coast.

Changes due to sea-level rise or glacial isostatic adjustment would equally affect the other coastal stations along the North Sea, and not be spatially concentrated along the Dutch and German coast and Skagerrak/Kattegat. In addition, changes due to (relative) sea-level rise are expected to be positive and smaller in magnitude than the observed changes. Also, the sudden break in the trend in 2007 cannot be explained by changes in mean sea level, although the trend reversal in 2016 more or less coincides with an increase in annual mean water levels (corrected for tidal and meteorological effects) along the Dutch coast (cf. Figure 3.6), following from a similar method as used for the analysis of M2 amplitudes.

Potentially, climate change could have an impact on (seasonal) temperature stratification in the North Sea and surrounding waters. It is known that stratification has an impact on tidal amplitudes, for example due to generation of internal waves. Since stratification of temperature and salinity is not considered in the two-dimensional hydrodynamic model, the effects of changes therein are not removed from the measured M2 amplitude signal and could potentially contribute to the observed changes.

Human interventions, such as the construction of wind farms, occur offshore. The large-scale construction of offshore wind farms may affect the tide through enhanced drag on piles and weakening of the wind field. In addition, seasonal thermal stratification in the relatively deep parts of the North Sea contribute to the annual modulation of the M2 tidal amplitude, reduction of stratification due to offshore wind farms may also have a longer-term impact. However, numerical experiments that include these effects show much smaller impact on M2 tidal amplitudes, even under future hypothetical upscaling scenarios (Zijl et al., 2021).

Another possible mechanism that could cause the decline in tidal amplitude is changes in the bottom roughness in the shallow coastal zone of the Netherlands. Beam trawling (i.e. dragging heavy chains and a large net attached to a beam across the seabed) is reported to lead to flattening of the bottom. It redistributes sand at the surface and destroys any biogenic mounds and other small-scale surface features. This causes a reduction in bottom roughness. Therefore, changes in fishing practice, could lead to a decreased bottom impact and consequently an increase in bottom friction.

In summary, there are many potential causes for the observed changes in M2 tidal amplitude, some more likely than others. However, the real cause or causes have not yet been identified.

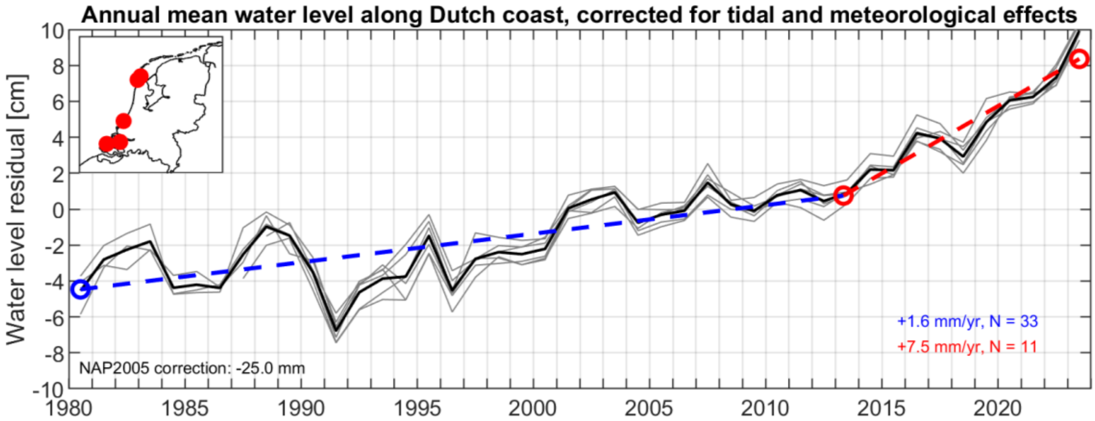


Figure 3.6 Annual mean water level corrected for meteorological and tidal effects, at six stations along the Dutch coast (grey lines, black line: station-averaged) and best fit of the broken-stick regression model with one arbitrary breakpoint and two sections (blue and red dashed lines). Observed water levels before 2005 are lowered by 2.5 cm to account for the 2005 NAP revision. Stations: Roompot buiten, Roompot binnen, Krammersluizen west, Scheveningen, Den Helder, Oudeschild.

4 Conclusions and recommendations

4.1 Conclusions

We observe a gradual but strong decline in M2 amplitudes from 2007 to 2016. The strongest trends are in the order of a decline of 0.4-0.5 % per year, equal to a decrease of 3-4 mm/year. The decline in M2 amplitude is strongest along the Dutch coast, the German Bight, Skagerrak, and Kattegat and gradually decreases away from these areas. This decline adds up to 4-5% or 3-4 cm since onset along parts of the Dutch coast. This magnitude of the total change in M2 amplitude in the period 2007-2016 is approximately equal to the natural tidal variability due to the nodal cycle. From 2016 onwards we observe a reversal in the direction of the trend, leading to a stagnation or gradual increase in M2 amplitudes. The magnitude of the trend is smaller than in the preceding period and the spatial correlation is less outspoken. Since the cause for the decline in tidal amplitude and subsequent reversal from 2016 onwards is unknown it is difficult to project the trend into the future.

4.2 Recommendations for further study

The mechanisms behind the decline in tidal amplitude and subsequent reversal from 2016 onwards are not well understood. We emphasize that it is highly important to further investigate the mechanism behind these changes in tidal amplitude. These changes as of a similar magnitude to SLR, thus very relevant for changes to coastal flood risks. Improved understanding of the origins could contribute to predicting any changes in tides in the long term (decadal scale) as well as any potential impacts of climate change and sea-level rise. Also, for the forecasting of low and high water in an operational context it is important to understand which processes are responsible for the observed changes in tidal amplitude. The accuracy of tides in models (and tide tables) deteriorates if the tides change and they're not updated. A change in tidal amplitude also has implications for the possibility of discharging excess fresh water under gravity, e.g. in IJmuiden and the sluices near Kornwerdenzand and Den Oever. Moreover, a change in tidal amplitude has wide-ranging and important implications for Dutch coastal management. A reduction may for example lead to a decrease in vertical mixing and consequently an increase in stratification and currents. This can have major impacts on residual sediment transport and coastal morphology. The same holds for changes in relative M2/M4 amplitude and phase differences, which result in asymmetry of the bottom shear stress. Also, water quality and ecosystem dynamics can be affected by changes in location of tidal mixing fronts.

In the absence of any understanding of the cause of these changes, monitoring changes is crucial, and it is recommended to update the estimated trends regularly. To get more insight in the mechanisms behind the observed changes in M2 tidal amplitudes, we propose the following data analyses and numerical model experiments:

- Climate change could have an impact on (seasonal) temperature stratification in the North Sea. It is known that stratification has an impact on tidal amplitudes, for example due to generation of internal waves. While stratification of temperature and salinity is not considered in the two-dimensional hydrodynamic model used for the present study, a three-dimensional version of this model is available (Zijl et al., 2023), which includes transport and stratification of temperature and salinity. With this three-dimensional model, historical changes in stratification and its impact on tidal amplitudes could be investigated.

- Shallow, intertidal areas such as the Wadden Sea play an important role in the dissipation of tides, resulting in decreased amplitudes. The presently used model is too coarse to accurately represent the smaller channels in these areas and consequently has difficulties in representing the energy transfer from M2 to higher harmonics such as M4, M6 and M8 and overtides such as MS4, MN4 and 2MS6. With a higher resolution model such as DCSM-FM 100m (Zijl et al., 2022b), the impact of improved representation of these areas on the analysis could be investigated.
  Also, the present model used for this study uses a constant bathymetry, even though morphological changes on the time scales considered here can be significant, especially in intertidal areas. The impact of these morphological changes on tides can be investigated by rerunning this model with a bathymetry representing a different year.
  The analysis of the role of intertidal areas could also involve exploring spatial patterns of tidal energy fluxes, including dissipation through bottom friction.
- In 2D hydrodynamic models, bottom friction is the main mechanism to include dissipation and tidal propagation and damping. In the presently used model, the space-varying Manning bottom friction coefficient was calibrated based on shelf-wide tide-gauge observation for the year 2017, using the open-source data assimilation toolbox OpenDA. Repeating this automated calibration using observations for a different year might result in a different magnitude and spatial pattern of the bottom roughness. Especially the spatial pattern could give insight in the origins of the observed changes in tidal amplitude. Note that resulting changes in bottom friction could also indicate changes in other dissipating mechanisms, such as through buoyancy destruction due to dissipation.
- The role of sea-level rise on temporal changes in tidal amplitudes could be further investigated by forcing the open boundaries with annually changing mean sea levels from e.g. global ocean models, satellite products or in-situ observations.
- The observed M2 amplitude shows considerable interannual variability, which appears to be spatially correlated. To gain insight into the mechanisms that modulate tidal amplitudes, it would be useful to also investigate the correlation with other, annually averaged parameters, such as wind speed and direction, waves, surface temperature and temperature stratification, salinity and mean sea-level. Since relationships between parameters can be complex and don’t have to be local, the use of machine learning techniques should be considered. Note that success of this approach is not guaranteed, since the amount of data is limited and correlated.

A References

Hart-Davis, M. G., Piccioni, G., Dettmering, D., Schwatke, C., Passaro, M., & Seitz, F. (2021). EOT20: a global ocean tide model from multi-mission satellite altimetry. Earth System Science Data, 13(8), 3869-3884.

Lyard, F., D. Allain, M. Cancet, L. Carrere, N. Picot (2021). FES2014 global ocean tides atlas: design and performances. Ocean Science 17, 3, 615–649.

Muis, S., M. Verlaan, H.C. Winsemius, J.C.J.H. Aerts, P.J. Ward (2016). A global reanalysis of storm surges and extreme sea levels. Nature Communications 7, 11969.

Pawlowicz, R., Beardsley, B., Lentz, S. (2002). Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. Computers and Geosciences 28 (2002), 929-937.

Zijl, F., S.C. Laan, A. Emmanouil, T. Van Kessel, M. van Zelst, L.M. Vilmin, L.A. Van Duren (2021). Potential ecosystem effects of large upscaling of offshore wind in the North Sea. Bottom-up approach. Deltares, report 11203731-004-ZKS-0015, Delft.

Zijl, F., T. Zijlker, S.C. Laan, J. Groenenboom. (2022). DCSM-FM 0.5nm: a sixth-generation model for the NW European Shelf (2022 release). Deltares, report 11208054-000-ZKS-0010, Delft.

Zijl, F., Groenenboom, J., Laan, S., Zijlker, T. (2022b). DCSM-FM 100m: a sixth-generation model for the NW European Shelf (2022 release). Deltares, report 11208054-000-ZKS-0010, Delft.

Zijl, F., T. Zijlker, S.C. Laan, J. Groenenboom. (2023). 3D DCSM-FM: a sixth-generation model for the NW European Shelf (2022 release). Deltares, report 11208054-004-ZKS-0003, Delft.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl