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Robust validation of trends and cycles in sea level and tidal amplitude in the Dutch North Sea

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Abstract

In this paper I present a new method for analyzing long series of observed sea levels. My method provides insight in sea level and the changes over time that are required by practicing engineers, assigned the design of new, modified or renovated structures along the coast.

After extensively reviewing earlier research of sea level and tide, I present my method. The analysis relies on the application of classic harmonic analysis, which is made operational in a script in the programming language Python. Rigorous statistical testing is introduced to test the significance of trends and cycles in sea level and tide. This application of harmonic analysis *and* the introduction of formal statistical testing are both to new in this field. I call this combination of methods *robust*.

The method is tested on six locations in the Dutch North Sea, all with continuous sea level records of at least 130 years. The results of the statistical quality tests are shown. Subsequently, I show my findings related to mean sea level, lunar and solar semidiurnal tide and wind setup.

Subsequently I analyze the long-term trends and cycles in Mean Sea Level. Long-period cycles with periods equal to the oceanic perigean and nodal tide are found to be important for a correct interpretation of sea level over time. Statistical tests show that acceleration of the rate of sea level is not significant up to 2021; the last year in the dataset.

I compare my results with contemporary projections of sea level rise. The comparison reveals that in the Dutch North Sea the projected rates of rise are a factor two or more higher than the empirical rates established in this paper.

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Keywords

Hydraulic structures, mean sea level, sea level rise, tidal amplitude, harmonic analysis, statistical testing

1 Introduction

Sea levels, tides and changes therein are important parameters for the design of coastal and hydraulic structures such as locks, regulators and storm surge barriers. The design of flood retention structures requires estimates of the anticipated ranges of high water levels, in most locales caused by a combination of tide and surge (Geyer et al., 2020; Kunz, 2023; Mooyaart et al., 2023; Voortman, 2003; Voortman & Vrijling, 2004; Vrijling et al., 1980; Vrijling & Bruinsma, 1980; Vrijling & Van Beurden, 1990; Wahl et al., 2017; Voortman et al., 2009; Webbers et al., 2003; Hawkes et al., 2002).

Much less obvious is that a lot of hydraulic structures also require estimates of low water levels or even the full shape of the tide (Lely, 1892; Thijsse, 1972). Access to ship locks relies on the sill to be sufficiently low to allow vessels to pass over it with sufficient keel clearance (Partenscky, 2013; PIANC, Permanent task group for climate change, 2022; Vrijburcht, 2000). In several places in the world, estuaries have been closed off from the sea creating an artificial coastal lake. The water level in such a lake is very often controlled by so-called *regulators*, sluices that open at low tide to discharge water and hence control the lake at a desired level (Ha et al., 2010; Lely, 1892; Thijsse, 1972; Voortman & Van der Kolk, 2013). The time-averaged discharge capacity of those facilities depends on the shape of the tide, specifically the maximum head difference between lake level and sea water level and the duration of water levels below lake level.

Figure 1: the regulator near the Dutch town Den Oever (photo: Rijkswaterstaat image library)

In certain situations it is desired that the estuary remains open and is closed only when water levels become dangerously high. In such cases, storm surge barriers are constructed (Tuin et al., 2017). Sometimes, the ecological quality of the estuary is the driver for choosing such a solution (Nienhuis, 1994). The long-term health of the ecosystem then depends upon the day-to-day water exchange and therefore upon the shape and level of the tides. For future management of such an area, the anticipated changes of sea level *and* of the tidal shape need to be taken into account.

To compound the problem, a large number of structures in the coastal zone has existed for decades and is often in need of adaptation or renewal. Assessing the need for adaptation or renewal requires insight in the tides and water levels at the time of construction and the changes that occurred since (Jonkman et al., 2018; Voortman & Van der Kolk, 2013). When designing a renovation or a fully new structure, anticipated ranges of future conditions need to be considered. Accounting for projected sea level rise by adopting one or more scenarios can be considered common practice (ENW, 2017; UK Gouvernment, Environment Agency, 2022; US Army Corps of Engineers, 2023).

Finally, maintenance of structures in the coastal zone needs to be planned according to the tides. Sea level rise and changes of tides may necessitate modification of maintenance strategies. Research in this topic appears to have just started with a first analysis done by Trace-Kleeberg et al (2023).

The subject of this paper is a data-driven method for analyzing long series of observed sea levels to provide insight in sea level and the changes over time that are required by practicing engineers, assigned the preparation of construction, renewal and maintenance of objects along the coast. I use harmonic analysis to estimate mean sea level without the effect of wind. The presence or absence of accelerations of sea level rise is tested using well-defined and well-established statistical methods using only water level data as input. The combination of harmonic analysis and statistical testing is less complex and relies less on subjective choices by the analyst than studies to date. I therefore call this method *robust*.

The paper is structured as follows. An overview of previous work on sea level, tides and sea level rise is presented in section 2. In section 3 I introduce my data and methods. Section 3.1 shows the six locations in the Dutch North Sea that were used for development and testing of the methods. The methods themselves are introduced in section 3.2 and consist of a combination of classic harmonic analysis *and* well-established methods for regression and statistical testing. This is a new combination of known methods. It is made operational for the analysis of large sets of water level observations in the programming language *Python*.

The results of the analysis are shown in section 4, showing first the (statistically judged) quality of the calculated tidal water levels and subsequently showing the findings related to Mean Sea Level, amplitudes of the lunar and solar semidiurnal tide and of the wind effect. Trends and cycles of mean sea level over time are explained in section 5. A comparison with contemporary projections of sea level rise is also made. In section 6 I reflect upon my findings related to a few recent papers on the same topic. I end in section 7 with the conclusions.

2 Earlier work on sea level and tide

2.1 Observed sea level in a global perspective

From the geological record it is clear that sea level changes are common and that a stable sea level would be a rare event. The principal driving mechanisms behind global or eustatic sea-level change are growth and melting of land-ice in response to climatic changes, thermal expansion and shrinkage of ocean water and changes in the rate of plate tectonics, causing changes in the volume occupied by mid-oceanic ridges. In addition, the relative sea-level position in individual basins is affected by changes in subsidence or uplift rates related to local tectonics (Murray-Wallace & Woodroffe, 2014). In periods considered recent from a geological perspective (multiple hundred thousands of years), sea level has varied over more than 100 meters in tandem with glacial and interglacial periods (Jelgersma, 1971; Kroonenberg, 2017; Murray-Wallace & Woodroffe, 2014).

Current observed rates of sea level rise are considerably less than in the geological past (Amin, 1985; Deltares, 2023; Führböter, 1989; I. D. Haigh, Eliot, Pattiaratchi, et al., 2011; I. D. Haigh et al., 2020; Mawdsley & Haigh, 2016; Rasheed & Chua, 2014; Ross et al., 2017; Rossiter, 1967; Torres Parra, 2013; White et al., 2014; P. L. Woodworth et al., 1991). Despite the modest rate of sea level rise in modern times, society is considered to be more vulnerable to it because of dense population and human activity in coastal zones (Abuodha & Woodroffe, 2010; Allenbach et al., 2015; Chhetri et al., 2015; Diez et al., 2007; Frihy, 2003; Gornitz et al., 1994; Yin et al., 2012).

Sea level studies are done on a global as well as a regional scale and are based on observations, models or a combination thereof. A highly valuable collection of historic sea level observations with global coverage is maintained by the Permanent Service for Sea level Rise (Holgate et al., 2013). Since 1993, global sea level is also observed with satellite altimetry (Leuliette et al., 2004; Nerem, 1995). The rates of sea level rise found by satellite altimetry are higher than the rates derived from gauges. The reasons for this are not fully known. Proposals for calibration and potentially reconciling the difference are published to this day (Christensen et al., 1994; Fu & Haines, 2013; Rovere et al., 2016; Ruf et al., 1994; Visser et al., 2015; Wang et al., 2021).

Several studies have attempted to reconstruct the global trends in sea level change, taking different methods and different datasets (Church & White, 2011; Dangendorf et al., 2019; Holgate & Woodworth, 2004; Mawdsley et al., 2015;

Mawdsley & Haigh, 2016; Pan & Lv, 2021; Rovere et al., 2016; Wahl et al., 2017; Woodworth, 1985). In a recent paper, Frederikse et al (2020) claimed to have *"closed the sea level budget"*, suggesting in the title that the *"causes of sea level rise"* had been identified. Albeit Frederikse's paper is an impressive scientific achievement, I feel that this conclusion is too rash. Estimating that the number of unknowns in this problem is larger than the number of equations available, I tentatively suggest that the reconstruction by Frederikse et al. is one of many plausible reconstructions that close the sea level budget.

Setting aside the methodological doubts related to global reconstructions, their value appears to be limited to identifying a global climate signal revealed in a global acceleration of the rate of rise. Several suggestions have been made as to the value and starting point of that acceleration. Several authors identify an acceleration that commenced in the 19th century (Church & White, 2006; Douglas, 1992; Jevrejeva et al., 2014; P. Woodworth et al., 2009). Others have pointed to recent anomalous increases of the acceleration (Dangendorf et al., 2019; Merrifield et al., 2009; Nerem et al., 2018).

2.2 Sea level projections

Coastal planning requires estimates (projections) of *future* sea level, tide and wind setup. Observations can inform projections, but can obviously not *be* projections. The literature on sea level projections is vast. In a review paper, Slangen et al. (2022) attempt to bring some structure in the available projections by identifying families of projections. It appears that all projections of sea level rise rely heavily on modelling. In "blended models", empirical data of glaciers and ice sheets play a role. Surprisingly, observations of sea level and the observed rate of rise appears to play no role in the development or validation of the sea level projections.

The set of projections shown by Slangen et al. is too vast for practical application. In real-life coastal planning, the designer is required to justify the robustness of the design by judging the design against a set of sea level scenarios. Subsequently, the designer must be able to explain the proposal to a decision maker, often coming from a non-technical/non-scientific background. A limited set of scenarios covering a wide range of possible futures is workable in such a context and enables responsible decision-making, accounting for uncertainties (Voortman & Van der Kolk, 2013).

The selection of scenarios proposed by Fox-Kemper et al. (2021) is large but just workable. This set for the first time provides projections of *relative* sea level per location and per decade until 2150, published on an interactive website (Fox-Kemper et al., 2021; Kopp, R.E. et al., 2023; NASA, 2023). This is a considerable improvement with respect to earlier projections, which were estimates of *absolute* sea level rise on a global scale only (Oppenheimer et al., 2022) which forced investigators to translate global projections to their own location themselves, as was for instance done by Wahl et al (2013).

2.3 Sea level and tide in the North Sea

From my personal experience, coastal planning requires *local* estimates of *relative* sea level, rather than *global* estimates of *absolute* sea level and tide. Parker & Ollier (2016) make a similar claim. In this paper I will focus on the Dutch Coast and hence on relative sea level, tide and wind setup in the North Sea; a shelf sea of the North Atlantic in North-West Europe.

Sea levels and tides in the North Sea have been under investigation for a very long time. Examples of early papers are the investigation of the trend of sea level in Amsterdam since 1700 by Van Veen (1945) and the statistics of storm surges in Hoek van Holland by Wemelsfelder (1939). The scientific consensus at the time was that the sea level is constant in time. Any trends in observations were associated with land motion and settlement.

More recently, trends in regional mean sea level in the North Sea are widely investigated (Rossiter, 1967; Wahl et al., 2013; P. L. Woodworth et al., 1991; Wöppelmann et al., 2006). Some investigators explicitly try to identify acceleration or the lack thereof in the regional trends (Baart et al., 2012; Dangendorf et al., 2014; Keizer et al., 2022; Steffelbauer et al., 2022; Watson, 2017). For coastal zone management in the Netherlands, a trend analysis is published on an interval of four years (Deltares, 2023).

Albeit the astronomic drivers of the tides can be considered unchanged on a human timescale, the regional response of the sea level to these drivers may change over the years, changing the shape of the tides. Doodson & Lamb (1924) investigated long-term changes in amplitudes and phase of the lunar semidiurnal tide, in the North Sea the dominant component of the tide. More recently the shape of the tide, sometimes combined with mean sea level, was investigated in several studies (Amin, 1985; Arns et al., 2015; Führböter, 1989; Führböter & Jensen, 1985; Hagen et al., 2021).

Haigh et al. (2020) identify six possible causes of long-term changes in tides, recognizing that the most dramatic changes of the tides are observed in estuaries. They indicate that changes of tides due to artificial deepening of channels is a major influence in some locations, especially in densely populated and heavily used estuaries. Winterwerp et al (2013) and Winterwerp & Wang (2013) show that this is the case for four rivers in North-West Europe and introduce a framework for quantifying the effects, aimed at undesired turbidity of the estuaries.

A quite dramatic example with clear impact on the local tides is the closure of the “Zuiderzee” between 1928 and 1932 (Thijsse, 1972). The effects were foreseen and studied beforehand and affected the final plans (Lorentz, 1926). Smaller modifications of the coast, such as maintenance dredging and coastal nourishment are daily practice in the Netherlands.

The Dutch Coast is the focus of the present study and it is long known that relative mean sea level is rising there (Baart et al., 2012; Deltares, 2023; Van Veen, 1945; Vrijling & Bruinsma, 1980). A rising sea level measurably influences the tides (Dangendorf et al., 2014; Führböter, 1989; Führböter & Jensen, 1985), consistent with theory (Battjes & Labeur, 2017; Pugh, 1987; Pugh & Woodworth, 2014).

Acceleration of sea level rise has received a lot of attention for it is expected to be the hallmark effect of climate change on sea level (Fox-Kemper et al., 2021; Pörtner et al., 2019). But acceleration of sea level rise is not easily identified (Gehrels & Woodworth, 2013; I. D. Haigh et al., 2014; Visser et al., 2015). In the North Sea, Baart et al. (2012) found no acceleration in the Dutch North Sea while Steffelbauer et al (2022) and Deltares (2023) reported an acceleration that commenced in 1993, using almost the same set of tide gauges as Baart et al. The difference is due to a different selection of the regression model. Both Steffelbauer et al and Deltares use a piecewise linear model while Baart et al use a second degree polynomial.

A recent paper by Keizer et al (2022) also reports an acceleration of relative sea level in the North Sea. That paper starts from the assumption that the global pattern of sea level rise suggested by Frederikse et al (2020) *should* show up in the North Sea. The lack of acceleration in the observations is explained by suggesting that a trend in the wind effect masks the “real” trend of sea level and thus masks the acceleration. But other assumptions could have been made. Chambers et al (2012) already showed that sea level patterns show regional difference with the North Atlantic deviating from the global pattern. The assumption that the North Sea follows local North Atlantic pattern would have been better.

A detailed but important point is that Steffelbauer et al, Keizer et al and Deltares appear to use the same method for quantifying the effect of wind on the water level. Wind effect is described as a linear combination of two directions of wind shear stress on the water surface. The parameters of the linear combination are derived from data and a decrease of the standard error of the fit is taken as an indication that the sea level estimate has improved. This method appears to be used in this way for the first time by Frederikse & Gerkema (2018). This method for quantifying the wind effect is probably incorrect in a shelf sea with an irregular shape such as the North Sea. Vrijling & Bruinsma (1980) and, based on them, Voortman (2003) and Webbers et al. (2003) showed that this is indeed the case. I will elaborate on this topic in the discussion.

Visser et al (2015) evaluated a number of studies into accelerated sea level rise and argued that differences of opinion in this matter are the norm, rather than the exception. The current paper is no exception. I will reflect further on the papers of Steffelbauer et al, Keizer et al and Deltares in section 6, in view of my own findings.

3 Data and methods

3.1 Data

In this paper I use a data driven approach to gain more insight in the changes of sea levels and tides in the Dutch North Sea. The Netherlands has an extremely fine network of water-level monitoring stations (Figure 2).

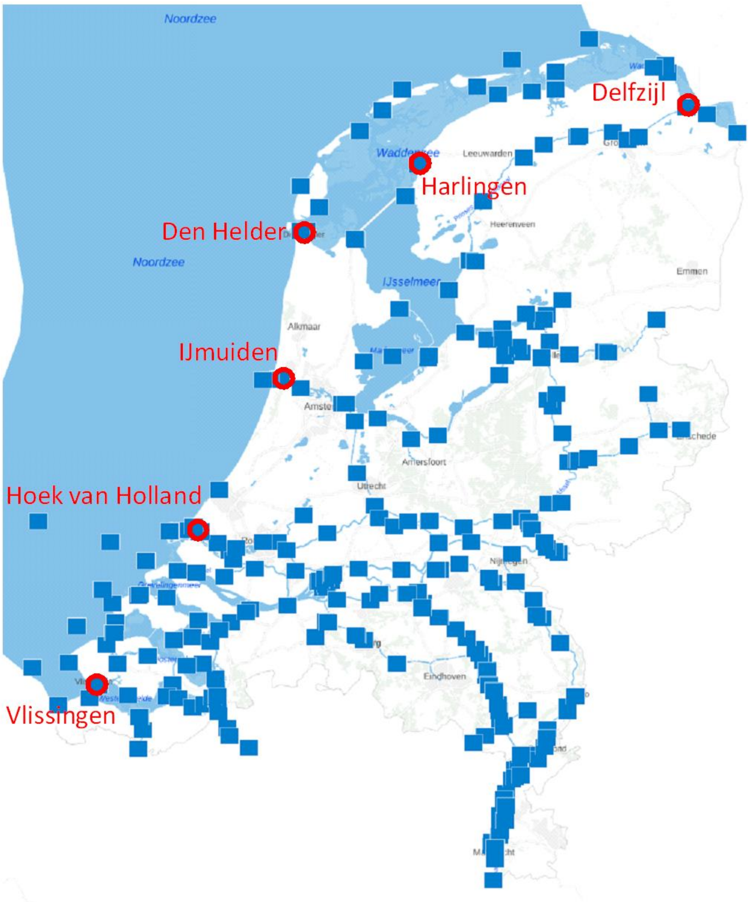

Figure 2: water level stations in the Dutch Delta. Stations used in this study are indicated in red

Six locations are selected for the analysis. The same stations were used in the *Zeespiegelmonitor* (Deltares, 2023) and by Steffelbauer et al (2022). Deltares relies on an average over multiple stations for the analysis and, because of doubts regarding subsidence in Delfzijl, that station was ultimately omitted. Steffelbauer et al. included Cuxhaven and Maassluis next to the six stations in this study.

The dataset used herein consists of data available online from 1900 onwards (Rijkswaterstaat, 2022) supplemented by older data (going back to year 1850) kindly provided by Rijkswaterstaat (J. Doekes, personal communication). Table 1 gives an overview.

Table 1: Overview of dataset

Station	Range	Total number of years
Delfzijl	1878 – 2021	144
Den Helder	1851 – 2021	171
Harlingen	1876 – 2021	146
Hoek van Holland	1887 – 2021	135
IJmuiden	1883 – 2021	139
Vlissingen	1877 - 2021	159
Total		**894**

Observation methods and sampling frequencies have changed over the years. In the oldest records, only high and low water were registered. Later, water levels were recorded on regular three hour intervals. The change to three hourly data was made between 1879 and 1939. Starting in 1971, data was recorded at hourly intervals on all locations. Even shorter intervals were introduced in the 1980s. For my purposes, observations on one hour intervals are deemed sufficient. Data with a sampling interval shorter than one hour has been down-sampled and only the observations on the hour have been kept. Hourly data, three-hourly data and registrations of high and low water levels were used "as is".

Observation methods also have changed considerably over the years. The oldest records were obtained by visually reading scales. Recent records are obtained with automatically registering equipment. In between, mechanical "level writers" were used and records were taken by hand.

I noted previously that most research into sea levels relies on the monthly or yearly averaged data from the Permanent Service for Mean Sea Level or PSMSL (Holgate et al., 2013). Because of the time-averaging, such data cannot be used for an analysis of tides which is what I envisage here. Where possible, I will compare results to the data of PSMSL.

3.2 Methods

3.2.1 Harmonic analysis

The Dutch coast lies in the shallow part of the North Sea and hence, water levels are determined by the tide and by the velocity and direction of the wind. My interest lies in the mean sea level (MSL) and tidal amplitude that would occur *without* wind effect. I apply harmonic analysis (Doodson, 1921; Pugh, 1987; Pugh & Woodworth, 2014) to find the amplitudes of tidal species *and* an estimate of mean sea level. *Unified Tidal Analysis* (UTide) as described by Codiga (2011) and implemented in the programming language Python (Bowman, 2022; van Rossum & Drake, 2002) is applied.

The UTide functions have a few characteristics that are of great advantage in the present study. My dataset consists of observations taken at non-constant intervals and UTide is capable of running the analysis for such data. Further, UTide provides an estimate of the reference level, together with the amplitudes and phases of the tidal constituents. I will consider the reference level z_0 in the result as an estimate of Mean Sea level (MSL). This is in contrast with earlier studies such as Mawdsley et al. (2015) where the arithmetic average of the observations is taken to be the estimate of MSL and tidal analysis is applied only after subtraction of MSL from the observations.

In this paper I take a long term view of the changes of tides. For every location separately I take all available data and run a tidal analysis in the described manner for every calendar year in the dataset. This results in a time series of mean sea level and tidal constituents for every location and year in the record.

The set of constituents is selected prior to the analysis and used for all years in the dataset to enable analysis of trends in constituent amplitudes. The semidiurnal lunar tide *M2* and the semidiurnal solar tide *S2* are known to be important drivers of the tide in the North Sea (Pugh & Woodworth, 2014; Quante & Colijn, 2016). Additional constituents are selected by running the tidal analysis for the year 2020 for all locations and requiring that at least 90% of the tidal power is resolved. Table 2 shows the result. The same set of seven constituents is used for all locations to ensure consistency over the locations.

Table 2: constituents resolving at least 90% of the tidal power in 2020

Station	Constituents
Delfzijl	M2, S2
Den Helder	M2, S2, M4, SA, N2, O1
Harlingen	M2, S2, N2, SA
Hoek van Holland	M2, S2, M4, N2
IJmuiden	M2, M4, S2, MS4, O1, N2
Vlissingen	M2
All	**M2, S2, M4, SA, N2, O1, MS4**

3.2.2 Trend analysis and statistical testing

Once the tidal analysis is complete, I have a time series of mean sea level and the amplitudes of the tidal constituents. Subsequently, I investigate which patterns are present in the time series. Based on a set of working hypotheses, I establish a regression model of which I determine the parameters using the well-known least-squares algorithm.

Insight into the long term patterns of the sea level is enhanced by applying statistical tests. An important parameter is the *adjusted coefficient of determination* (Ott & Longnecker, 2016), defined as:

$$R^2_{adj;k} = 1 - \frac{N-1}{N-k-1}\frac{SS_{residual}}{SS_{total}}$$

Where N is the size of the sample (number of independent datapoints in the set), k the number of parameters in the regression model, $SS_{residual}$ the sum of the squared residuals and SS_{total} the sum of squared difference of every observation to the mean.

The adjusted coefficient of determination is comparable to the concept of *explained variance*. The difference is that this measure penalizes for the number of parameters in the regression model. Adding additional parameters in general increases the explained variance, but not necessarily the adjusted coefficient.

A second measure to determine the relevance of parameters in a model is the *F*-statistic for reduced models, which explicitly compares a simpler (reduced) model with the full model (Ott & Longnecker, 2016). The *F*-statistic is given by:

$$F = \left(\frac{SS_{reduced} - SS_{full}}{k-m}\right) \div \left(\frac{SS_{full}}{N-k}\right)$$

Where $SS_{reduced}$ and SS_{full} are the sum of squared residuals of the reduced and the full model respectively, k is the number of parameters in the full regression model and m is the number of parameters in the reduced regression model.

Loosely stated, the *F*-test tests the null hypothesis that the reduced model is as good as the full model in explaining the variance of the observations. The *F*-test is executed by comparing the calculated *F*-statistic to a value obtained from an *F*-distribution. Visser et al. (2015) applied the same statistical test for sea level trends, calling it "*F-testing consecutive models*". A special case of the *F*-test is the Chow-test (Chow, 1960) which specifically tests for breakpoints in datasets.

All statistical tests require the number of observations *N* as input. Statistical tests rely on the assumption that the residuals calculated from the regression are statistically independent (Ott & Longnecker, 2016; Visser et al., 2015). This condition is fulfilled if the regression model fully captures all dependencies so that the residuals are truly independent. In reality it is prudent to assume that some dependence between residuals remains. This reveals itself in correlation between residuals. In this study I correct the sample sizes with the method described by Bence (1995), which uses the correlation between residuals as input. The result is called the *effective sample size* which is never larger than the actual sample size and in case of correlated residuals smaller than the sample size.

4 Results of tidal analysis

4.1 Overview

In this section I present the results of the tidal analysis. As stated above, the analysis is done for every location and every calendar year separately. The quality of the reconstruction, quantified by the adjusted coefficient of determination, is presented first. Thus, I identify poor reconstructions before drawing any conclusions on sea level and tide.

Subsequently, I present mean sea level, amplitude of the lunar and solar semidiurnal tide and year-averaged wind effect as they follow from the analysis.

4.2 Quality of the reconstruction

The tidal analysis was run for the six locations and for all individual years separately. Results are presented per location and plotted as a function of the year. I judge the quality of the reconstruction by inspecting the adjusted explained variance $R^2_{adj;k}$. Figure 3 shows the values.

Calculating the adjusted coefficient of determination for a tidal reconstruction appears unusual, but is of great value. Tidal reconstruction is essentially a fit procedure using linear regression with the regression model consisting of a linear combination of a set of tidal constituents (Doodson, 1921; Pugh & Woodworth, 2014). Hence, standard statistical tools based on the standard error of the residuals apply, leading to the result shown in the graph.

Deviations of the astronomic tide are driven by wind (Pugh & Woodworth, 2014; Voortman, 2003; Vrijling et al., 1980) and therefore water levels deviating from the astronomic tide are to be expected. These deviations are reflected in a statistical measure for goodness-of-fit, such as the adjusted coefficient of determination. Nevertheless, the values are satisfactory for all locations.

The reconstruction is a better description of the actual water levels if the tidal amplitude is large, such as in Delfzijl and Vlissingen, in comparison to stations with a smaller tidal amplitude such as Harlingen and Den Helder. This is explained from the fact that wind effects are proportional to the squared wind velocity (Voortman, 2003; Vrijling & Bruinsma, 1980; Webbers et al., 2003), and in the relatively small North Sea this implies that daily wind effects will be of the same order of magnitude on all locations. In case of large tidal amplitude, the same wind deviation is smaller relative to the tide, leading to a higher coefficient of determination.

Harlingen, Den Helder, IJmuiden and Hoek van Holland show a decrease of the coefficient of determination between 1925 and 1950. At all stations except Delfzijl, data acquisition changed from a registration of high and low water to a registration of water level eight times a day[1]. The decrease of the coefficient of determination coincides with this change in registration strategy. The graph suggests that the fits worsen if more data is available. A better interpretation is that the coefficient of determination for the older data is too optimistic.

The introduction of hourly data acquisition in the early 1970s is not visible in the values of the coefficient of determination, indicating that data acquisition on three hour intervals is sufficient for a tidal analysis. As explained above, the increase of data acquisition to 10-minute intervals in the 1980s was neglected in this study and hourly data was used from the early 1970s to 2021 (the last year in the set).

The Dutch coast has seen major changes over the years such as the closure of estuaries, the construction of a number of locks and barriers and the artificial deepening of channels (Thijsse, 1972; Van de Ven, 2004), which are expected to influence the shape of the tide (Elias et al., 2012; Pugh & Woodworth, 2014; Stuur, 2022; Winterwerp et al., 2013; Winterwerp & Wang, 2013). Because my method reconstructs the tide for individual years, such changes are *not* reflected

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[1] In Delfzijl this method is present in the whole record

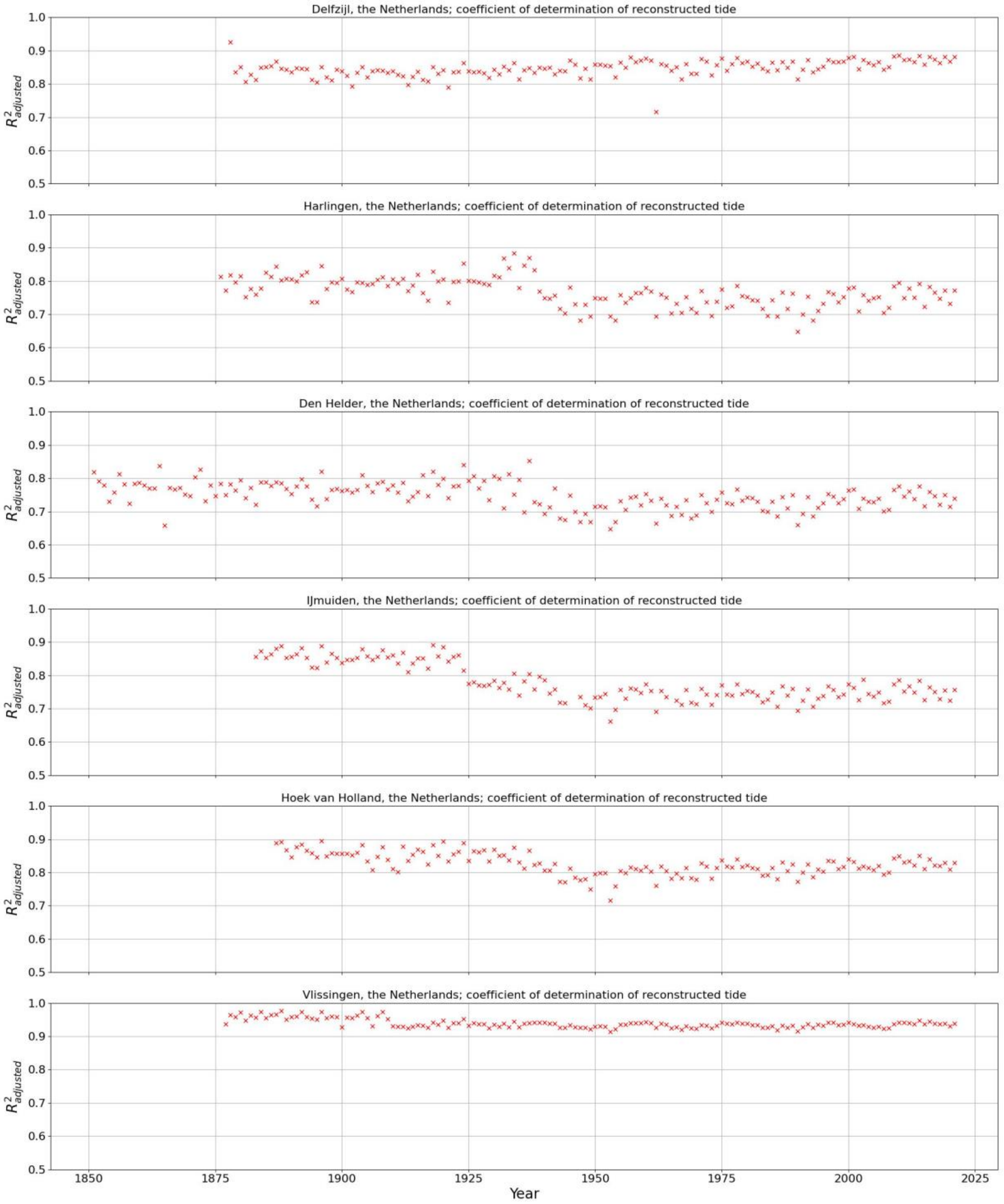

Figure 3: coefficient of determination of reconstructed tide per location and per year

in the values of the coefficient of determination presented here. The coefficient of determination only provides an objective check on the validity of the reconstructed tide in any given year.

4.3 Mean sea level

I identified two methods for determining MSL in section 3.2.1. Both methods are applied and the results are compared with each other and with the data provided by PSMSL in Figure 4.

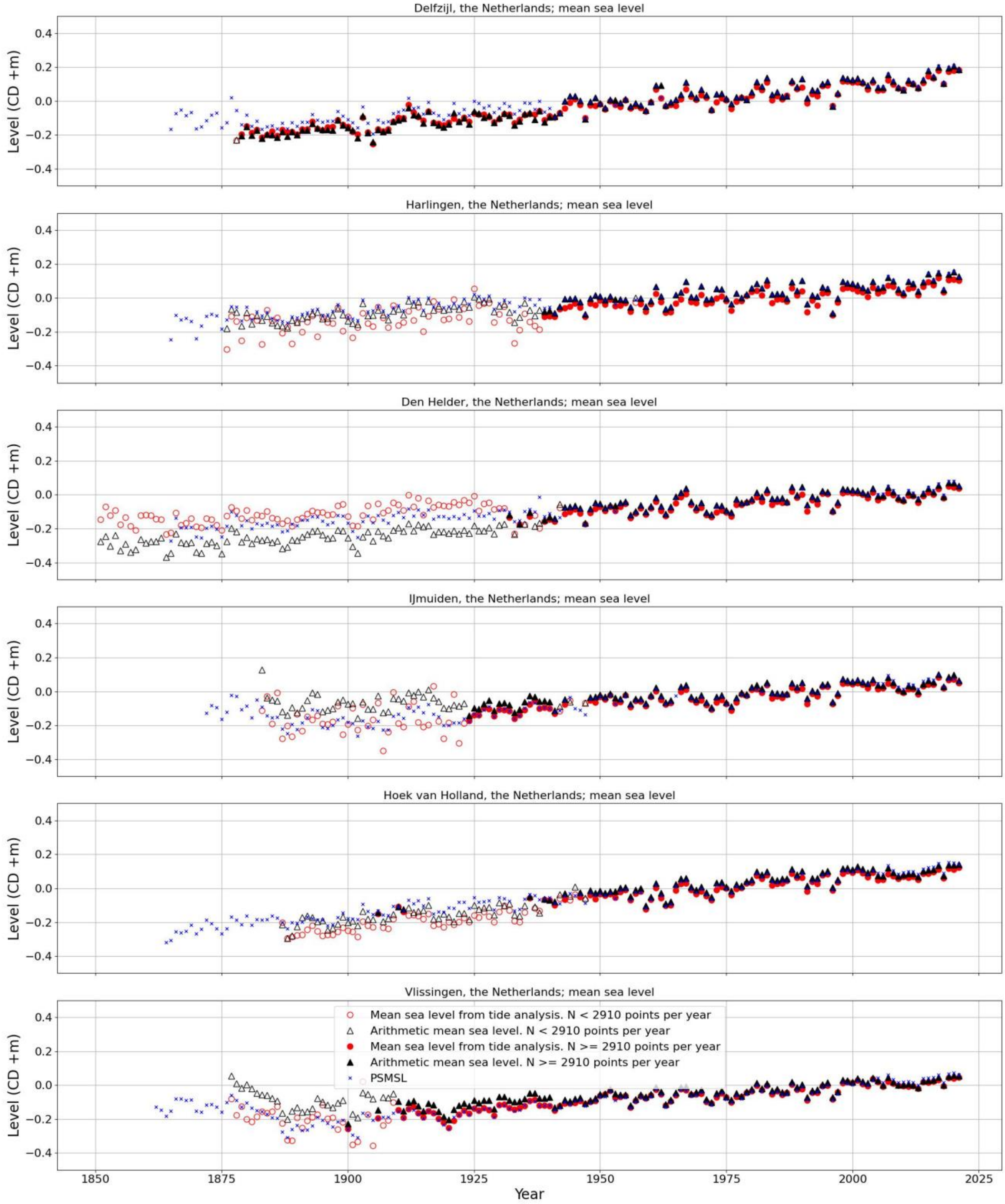

Figure 4: mean sea level from tidal analysis, arithmetic mean sea level and PSMSL data for six Dutch stations. Registration 8 times a day corresponds to 2920 observations per year. The limit of 2910 allows for a small percentage missing data

The closed symbols indicate that the water level was registered at least eight times a day at fixed intervals. Open symbols indicates registration of high and low water only. Starting in the modern part of the record (in Hoek van Holland starting in 1945; other locations earlier) all datasets are in good agreement with each other and the choice of method to determine MSL is of little influence on the result. A small systematic difference exists between the arithmetic mean water level and the astronomically determined MSL, most likely reflecting the effect of wind setup which was also found by Baart et al. (2012).

Also shown in Figure 4 is the annual mean sea level as stored by PSMSL (Holgate et al., 2013). Again differences with the local data are found. In Delfzijl, PSMSL is consistently higher than the local data prior to 1940. For the other stations, deviations are found in the early parts of the dataset where the sampling frequency is limited. There is no single parameter with which the PSMSL-data tends to match. In Harlingen PSMSL roughly matches the arithmetic mean sea level, in Den Helder the mean level taken from tidal analysis and in IJmuiden neither. The cause of the differences is unclear. Some PSMSL records are very old and it is virtually impossible to reconstruct what data was delivered to PSMSL and whether changes occurred later in the series either at PSMSL or at the source. As an aside: Rossiter (1967) uses PSMSL data from IJmuiden to illustrate the presence of non-linear trends and illustrates that with a marked drop of sea level between 1880 and 1910. That drop is still present in the PSMSL data today but is diminished when a tidal analysis is used to derive MSL.

The method used for sampling the water levels has dominant influence on the estimate of mean sea level. The mean derived from a series of high and low water is called "half-tide" and differs from mean sea level, defined as the mean of series of water level observations at fixed times. A fact known to Van Veen (1945) but apparently forgotten in recent times. To illustrate the effect, I took the data of 2020 (sampled at 10 minute intervals) and derived the tidal and arithmetic mean using four different sampling methods.

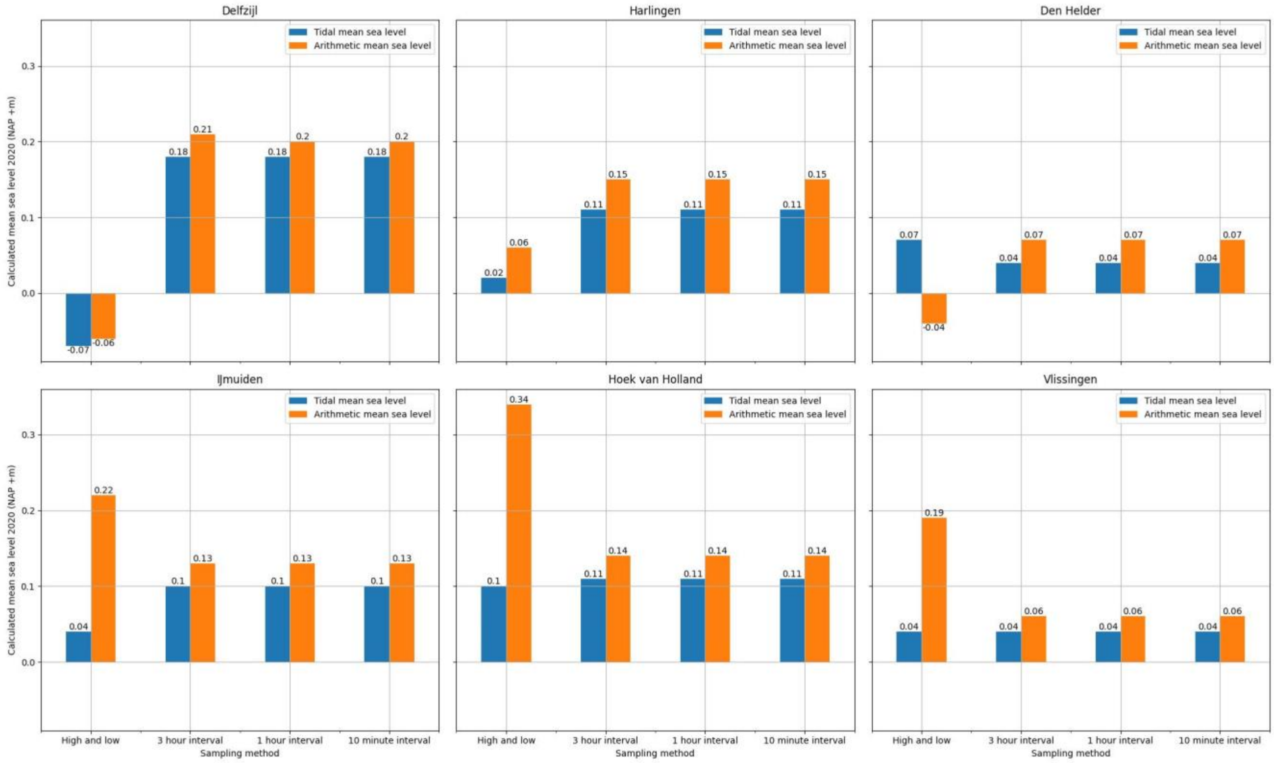

Figure 5: mean sea level in 2020 at six Dutch tide stations using four different sampling methods

Characteristic for the Dutch tides is the presence of short period constituents such as *M4* and *MS4*. Depending on their phase, these constituents "flatten" either the high water phase (e.g. Den Helder) or the low water phase (e.g. Hoek van Holland). Such tidal asymmetry distorts the estimate of mean sea level if the sampling frequency is too low. Figure 5 shows that sampling at intervals of 3 hours or less is sufficient to capture the asymmetries; the calculated mean sea level is the same for sampling on 3 hour, 1 hour and 10 minute intervals.

Sampling only the high and low water levels leads to inconsistent estimates of mean sea level; per station with the other three methods and among the respective stations. Especially the arithmetic mean sea level is erratic. The tidal mean sea level is more stable and in three (of six) cases quite close to the result when a higher sampling frequency is used.

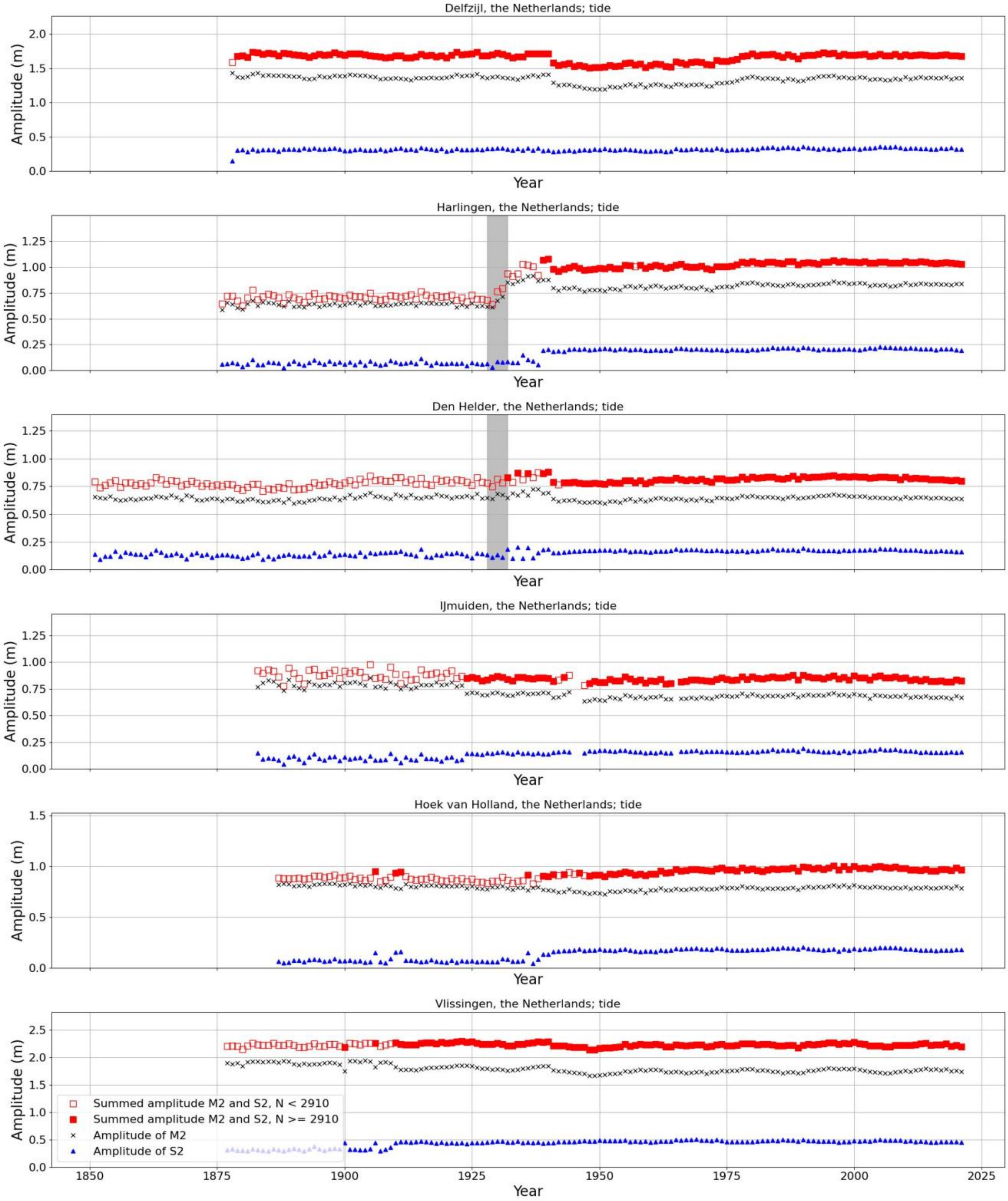

Figure 6: Amplitudes of M2 and S2 and their sum; changes in sampling method are only indicated for the sum

4.4 Amplitudes of M2 and S2

The North Sea shows semidiurnal tides with the lunar component *M2* and the solar component *S2* as the most important constituents (Pugh & Woodworth, 2014; Quante & Colijn, 2016). For structures, two important characteristics of the tide can be calculated from the amplitudes of these two constituents. The mean tidal water level at spring tide (Mean

Figure 7: development of the port of Delfzijl between 1908 and 1993. Years shown are years of publication of the topographical map (maps reproduced from www.topotijdreis.nl). The red dot is the approximate location of the tide station

High Water Spring, or MHWS) is calculated as the sum of the amplitudes of *M2* and *S2* and MSL. It is input for the design water level for flood retaining structures (Voortman, 2003; Vrijling & Bruinsma, 1980; Webbers et al., 2003).

Regulators discharge water to the sea at low tide and need to do so at spring tide as well as at neap tide (Lely, 1892; Thijsse, 1972; Voortman & Van der Kolk, 2013). For analyzing the changes of discharge capacity over time the changes over time of low water levels at both spring and neap tide are therefore important. The change in low water over a full spring-neap cycle is equal to twice the amplitude of *S2*. Figure 6 shows he amplitudes of *M2* and *S2* and their sum calculated in this study.

The changes in sampling strategy explained previously have little effect on the calculated tidal amplitude. Total tidal amplitude shows little to no trend. In the North, the closure of the “Zuiderzee” estuary took place between 1928 and 1932. Effects of this closure are expected to show up in Harlingen and Den Helder and therefore, the construction period has been marked in the graph of these two locations. Indeed, the effect of the closure is clearly visible in a marked increase of the tidal amplitudes in Harlingen and similar but smaller in Den Helder. The effects are consistent with the forecasts by Lorentz (1926) and the empirical findings of Jänicke (2022) and Thijsse (1972).

Eight years after the closure the total tidal amplitude in Den Helder shows a small but marked drop that appears to be caused by a similar drop in the amplitude of *M2* with the amplitude of *S2* virtually unchanged. In Harlingen, a similar drop in amplitude of *M2* is visible with a marked increase of the amplitude of *S2* at the same time, leaving the total amplitude virtually unchanged. In the preparation of the works, an eastward shifting tidal divide was expected (Lorentz, 1926; Stuur, 2022) and the divide reaching Harlingen would explain the sudden change, although the divide should be considered a zone rather than a line (Cleveringa, personal communication). But I can offer no explanation for the sudden change that occurs in Den Helder at the same time.

Figure 8: the harbour of Ijmuiden on the topographical maps of 1923 (left) and 1924 (right). Maps taken from www.topotijdreis.nl.

Other works than the Zuiderzee closure in time also correspond to calculated changes of the tidal amplitudes, although less pronounced. In Delfzijl, tidal amplitude drops in 1940, remains virtually unchanged until 1973 and then rises until 1980. These changes are consistent with modifications to the harbor basin. Figure 7 shows topographical maps of the Delfzijl port at six points in time.

The harbor basin in Delfzijl gradually expanded between 1908 and 1971. For the same tide at the harbour mouth, hydrodynamics requires the tidal amplitude to decrease if the area of the harbour basin increases with the entrance remaining the same size (Battjes & Labeur, 2017; Führböter, 1989). Somewhere between 1971 and 1982 a new and much larger harbor entrance was constructed. The increase of the tidal amplitude in the same period is consistent with that change. Finally, the map of 1993 shows that the original entrance is closed; only the new entrance remains. The loss of

Figure 9: harbour basins in Rotterdam on the map of 1907 (left) and 1939 (right). The tide station Hoek van Holland is 30 km west of Rotterdam at the river mouth. Maps taken from www.topotijdreis.nl.

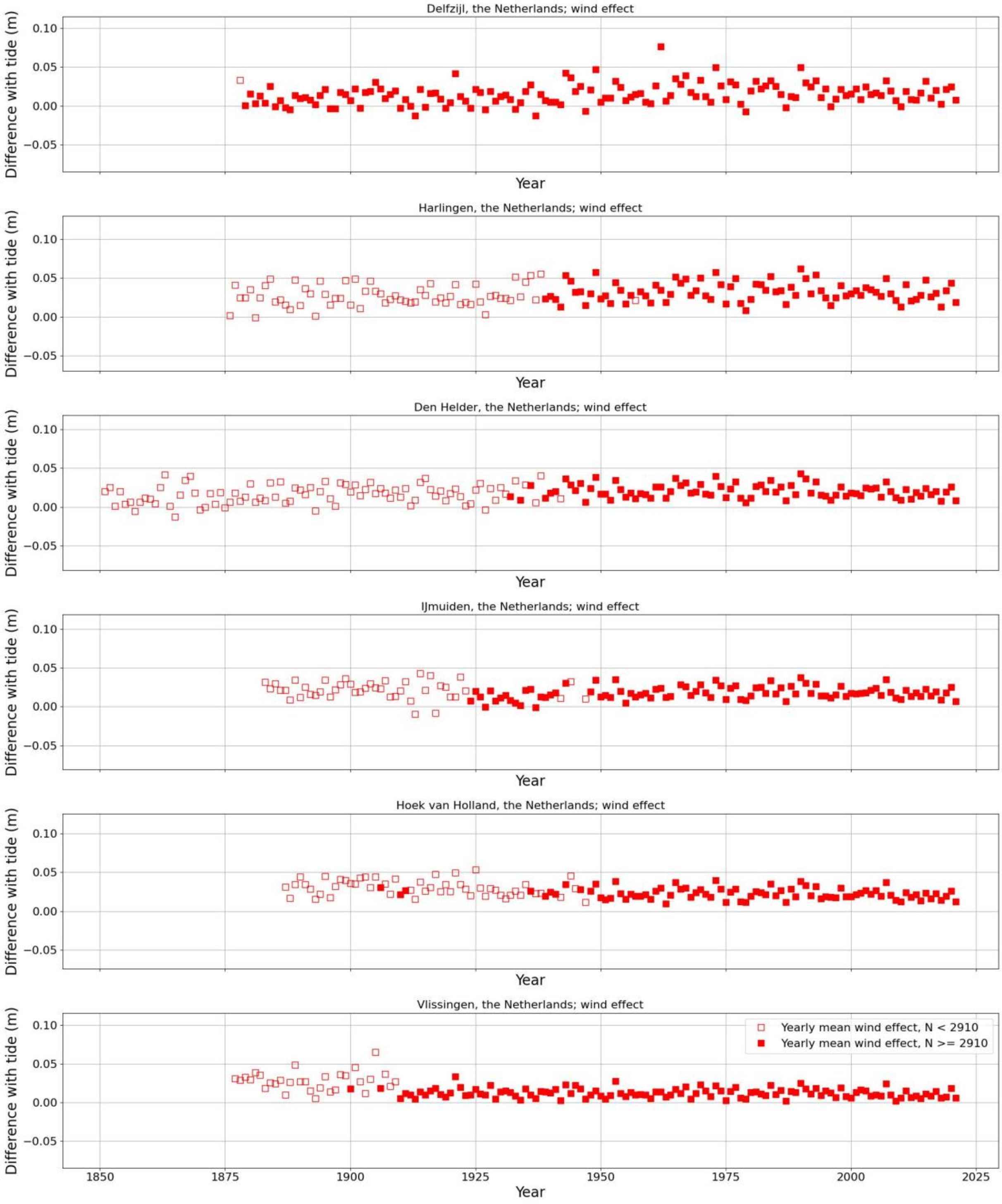

Figure 10: yearly mean wind effect, calculated as the difference of the observed water level with the calculated astronomic water level

the old entrance does not reveal itself in the tidal amplitude, possibly because the old mouth was much smaller than the new one.

The harbor basin in IJmuiden was expanded considerably during the 1920s (Figure 8), coupled to the construction of the North Lock. A marked drop of the amplitude of M2 with a slightly smaller increase in amplitude of S2 occurs around the same time. The total amplitude is slightly reduced, consistent with the hydrodynamic response of the tide to an enlarged harbor basin (Battjes & Labeur, 2017; Führböter, 1989). In this case, the water level registration changes at the same time and I cannot exclude that the effect is partly due to that change.

In Hoek van Holland, the tidal amplitude is relatively constant. However, inspection of the underlying amplitudes in the 1930s reveals a drop of the *M2* amplitude of 0.15 m, compensated by a similar increase of amplitude of *S2*. In time this coincides with the construction of a large harbour basin west of Rotterdam, 30 km east of the tide station (Figure 9).

4.5 Wind effect

The harmonic method enables the calculation of tidal water level for every observation in the dataset. With that result, the wind effect in every observation can be calculated without information about the wind itself. The wind effect (wind setup or set down) is defined as the difference between the calculated astronomical water level and the observed level (Pugh & Woodworth, 2014). The result is averaged per year and the average is shown in Figure 10. The yearly averaged wind effect is small (less than 5 cm) and positive on all locations. There is no visible trend in the yearly mean wind effect.

5 Empirical descriptions of mean sea level in time

5.1 Approach

One of the results of the previous section is six time series of yearly mean sea level. In this section, I analyze these time series further for rate of rise, acceleration of the rate of rise and long-period cycles. To that end, regression is performed using the following regression model:

$$z_0(t) = \begin{cases} p_0 + p_1 t + \sum_{n=0}^{1} A_n \cos(\omega_n t + \varphi_n) \ \ if\ t \leq t_0 \\ p_0 + p_1 t + \frac{1}{2} p_2 (t - t_0)^2 + \frac{1}{6} p_3 (t - t_0)^3 + \sum_{n=0}^{1} A_n \cos(\omega_n t + \varphi_n) \ \ if\ t > t_0 \end{cases}$$

Where p_i are the parameters of the trend and acceleration of the sea level and A_i and φ_i the amplitude and phase of the perigean and nodal cycles.

The model combines insights from tidal analysis and contemporary investigations of sea level projections (Fox-Kemper et al., 2021). The gradual rise of mean sea level in the North Sea is a long-known fact (Deltares, 2023; Van Veen, 1945). The perigean tide (period 8.85 years) and the nodal cycle (period 18.61 years) are included in the model. There is some debate regarding the added value of including long-period tides in projections of mean sea level. Houston and Dean (2011) and Baart et al (2012) include the nodal cycle but not the perigean cycle. Haigh et al (2011) use both.

Woodworth (2012) argues that long-period tides should not be calibrated but taken equal to their equilibrium values or even be ignored. But Woodworth points to shelf areas as a possible exception where long-period signals may be found, although he explains that these are not tides in the strict sense. Woodworth's suggestion to use the equilibrium tide for the nodal cycle is followed by several authors studying sea level in the North Sea (Keizer et al., 2022; Steffelbauer et al., 2022), failing to recognize that the North Sea is a shallow shelf sea. I follow Woodworth in a different way. Recognizing the shallowness of the North Sea, I assume the possibility of long-period signals in the data but I will refrain from calling them tides. Further, I will not enforce the phase of the long-period cycles (as suggested by Woodworth) but allow them to follow from the regression. I will judge the resulting phase of the long-period oscillation graphically, expecting the phase over the six locations to coincide.

Several authors point to the possibility that sea level rise in the North Sea will accelerate and that the acceleration may increase over time (Houston & Dean, 2011; Keizer et al., 2022; Steffelbauer et al., 2022; Watson, 2017). The acceleration is assumed to be a consequence of anthropogenic climate change and is therefore expected to emerge at some unknown point in time after 1950 (Fox-Kemper et al., 2021; Keizer et al., 2022; Slangen et al., 2022; Steffelbauer et al., 2022). In my model the starting point of acceleration is denoted t_0 and is treated as a fit parameter. Recognizing the still existing uncertainty regarding the starting point of acceleration, I allow a wide interval around published values. The parameter t_0 is bounded between 1960 and 1995, forcing the regression procedure to find the value between these bounds.

Acceleration and change of acceleration is described by the arguments in the second and third power of time. Consistent with the assumed effect of climate change on sea level (Fox-Kemper et al., 2021), acceleration and its change are bounded to non-negative values. I call this the “long-term” acceleration of sea level rise as it plays out over timescales of multiple decades.

On the timescale of years to two decades sea level rise accelerates and decelerates as well; I call this the “short-term” acceleration of sea level rise. Previous studies attempted to describe the pattern of acceleration and deceleration by fitting overlapping linear trends (Albrecht et al., 2011; Church et al., 2008; I. Haigh et al., 2009; Wahl et al., 2011). Here, I assume the short-term acceleration to be driven by the multi-year tide-driven cycles, which could be considered an alternative to the approach of overlapping linear trends.

The full model is compared to a reduced model using an *F*-test, explained in section 3.2.2 and by Visser et al (2015). The test involves comparing the full model to a reduced model. The reduced model assumes the anthropogenic climate signal (expressed in the 2nd and 3th order terms) to be negligible (or: the long-term rate of sea level rise to be constant) and thus reads:

$$z_{0;reduced}(t) = p_0 + p_1 t + \sum_{n=0}^{1} A_n \cos(\omega_n t + \varphi_n)$$

The comparison of the two models for the six datasets is executed as six separate *F*-tests. For the set of six, I choose a rejection level of 5% from this I achieve a rejection level for an individual test of 0.8% by applying the Bonferroni inequality (Bonferroni, 1936; Ott & Longnecker, 2016, p. 455).

5.2 Mean relative sea level

I use the data on mean sea level from 1887 onwards. The starting point is taken equal for all stations to ensure equal length of all records. Hoek van Holland, the shortest record, starts in 1887 and decides therefore the starting point of the selected data. The graph below shows the data, the full model and the reduced model.

Sea level is clearly rising in all six locations which is in line with earlier investigations (see section 2.3). The long-period cycles are clearly visible and are in phase over the six locations, which is consistent with the driving force of the long-period cycles being external. The nodal cycle takes a minimum close to 1923, consistent with Pugh & Woodworth (2014, p. 261) at a latitude of 52°N.

There is very little difference between the full and the reduced model. This is confirmed by the calculated coefficient of determination R^2_{adj} which differs at maximum a few percent between the two models. In a few cases the reduced model performs slightly better than the full model. The rapid changes of MSL in Den Helder and Harlingen during the Zuiderzee closure are clearly visible, giving a poor quality of the fit in part of the record. In Den Helder this also leads to a poor value of the coefficient of determination. In an *F*-test, the null hypothesis is rejected for Den Helder but in view of the poor fit, this result is of little value.

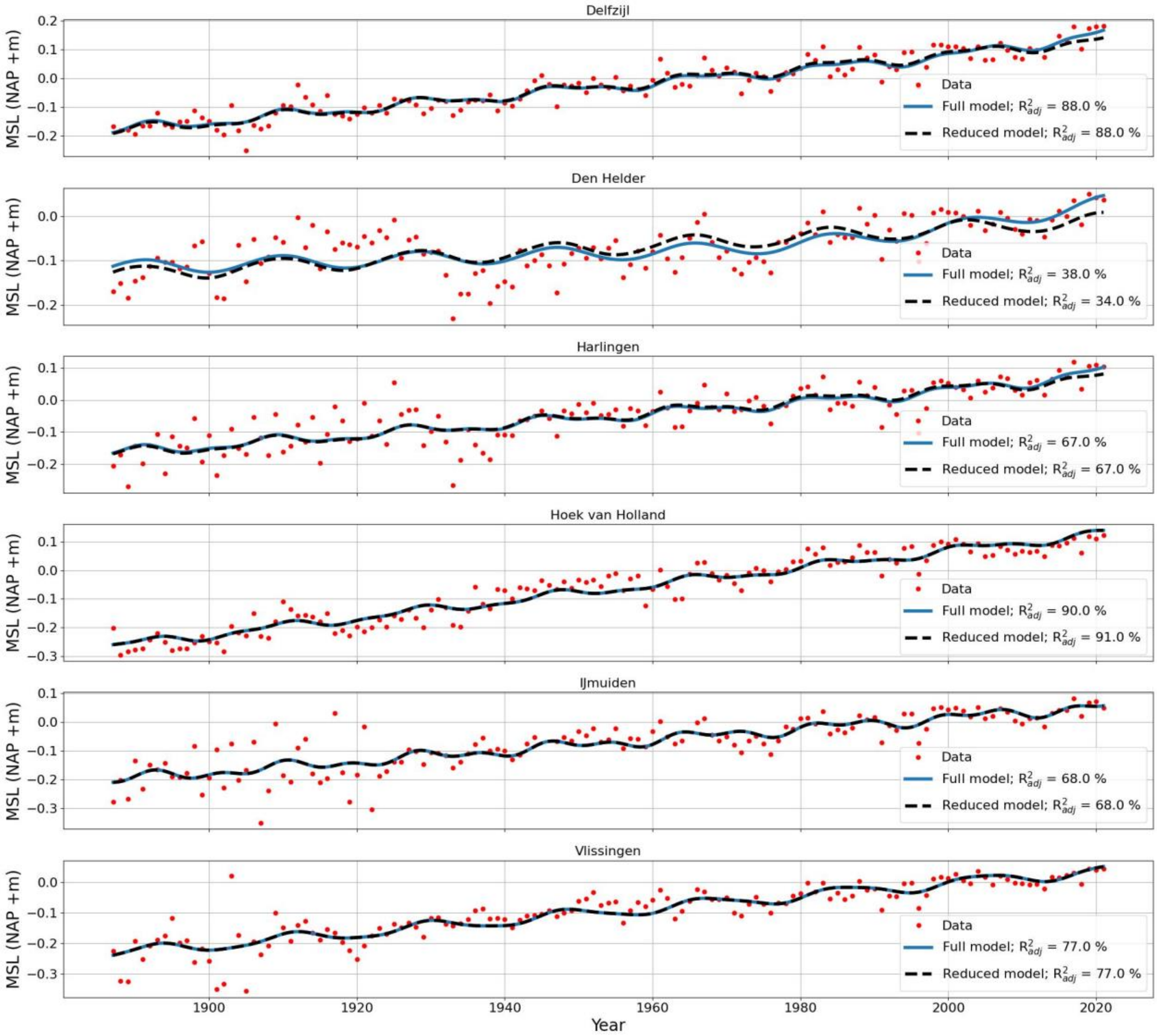

Figure 11: Mean sea level 1887 – 2021 with two regression models

To avoid the effect of the Zuiderzee closure on the results, the procedure is repeated using only data of 1945-2021. In this case, the null hypothesis is never rejected. The calibrated values of the parameters of the reduced model for the two periods are shown in Table 3.

Table 3: calibrated values of the parameters of the reduced regression model and the coefficient of determination for two selected time periods

Station	Period	Rate (mm/century)	Amplitude perigean cycle (mm)	Amplitude nodal cycle (mm)	R^2_{adj} (%)
Delfzijl	1887-2021	238	7	16	88
	1945-2021	241	8	19	72
Den Helder	1887-2021	93	1	18	41
	1945-2021	169	2	18	60
Harlingen	1887-2021	179	6	15	68
	1945-2021	175	6	13	53
Hoek van Holland	1887-2021	294	6	14	91
	1945-2021	232	4	13	72
IJmuiden	1887-2021	191	11	14	68
	1945-2021	156	5	21	61
Vlissingen	1887-2021	203	3	18	78
	1945-2021	162	5	14	68

Den Helder is clearly affected by the nearby Zuiderzee closure. The rate of rise since 1945 is considerably higher than the rate taken over the full period. But also Hoek van Holland, IJmuiden and Vlissingen show clear differences between the two periods, potentially reflecting harbor modifications and dredging. All are active harbors and Vlissingen borders the Western Scheldt, the access to Antwerp and hence considerably deepened by dredging over the years.

5.3 Comparison to projected rates of sea level rise

As part of the latest assessment report of the Intergovernmental Panel on Climate Change, projections of relative sea level for a number of locations in the world were published (Fox-Kemper et al., 2021; Kopp et al., 2014). The projections are available on the *Sea level projection tool* (NASA, 2023). Projections are available for all six locations considered in this study. The projections provide tables of relative sea level, tables of the individual contributors *and* the projected rate of rise (or first derivative in time). The start year of the projections is 2005 and the earliest year reported is 2020. For two scenarios, the medium rate as published by NASA (2023) is shown below. Following guidance in Chen et al (2021, p. 238) and Hausfather & Peters (2020) I selected the pathways ssp1-2.6 and ssp2-4.5. The long-term rate found in this study is included for comparison.

The empirical rates are in line with earlier studies into sea level rise in the North Sea (Dangendorf et al., 2014; Deltares, 2023; Frederikse et al., 2016; Frederikse & Gerkema, 2018; Führböter, 1989; Führböter & Jensen, 1985; Jänicke et al., 2021; Quante & Colijn, 2016; Wahl et al., 2013). The contemporary projections by Fox-Kemper et al (2021), Kopp et al (2023) and NASA (2023) appear to systematically over-estimate the rate of sea level rise in 2020.

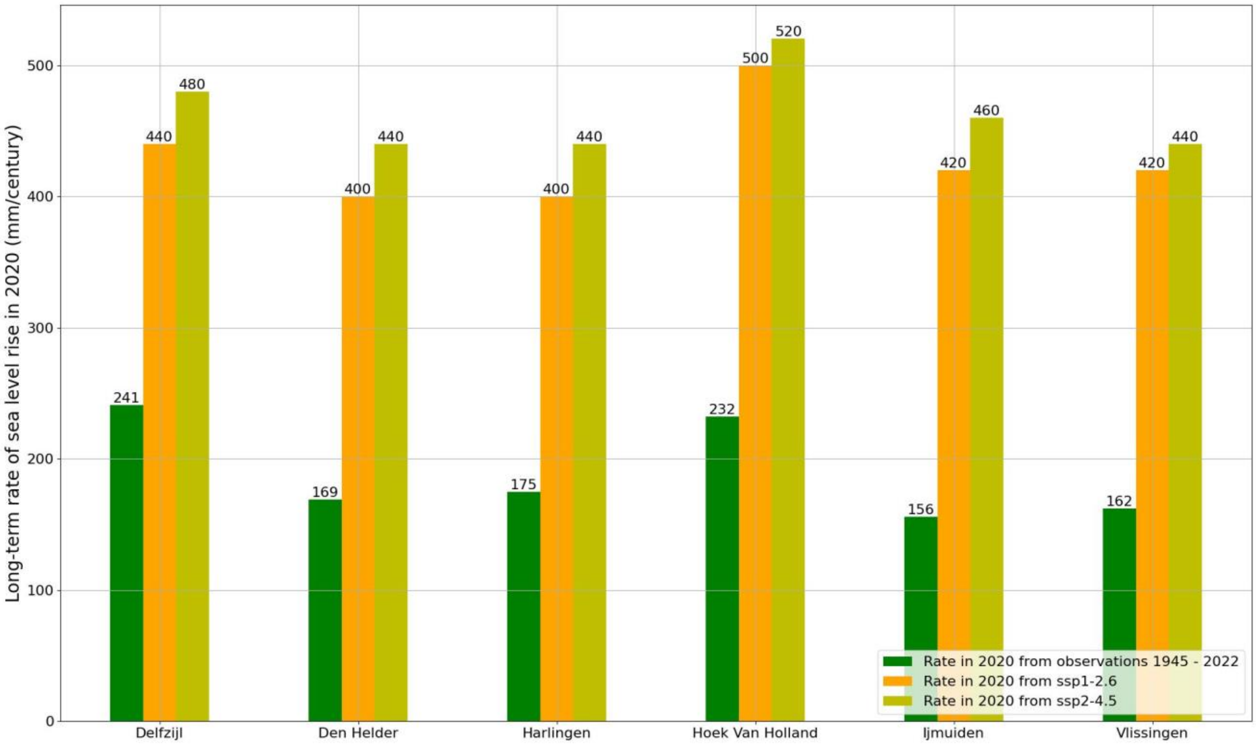

Figure 12: Long-term rates of sea level rise in 2020 for six Dutch tide stations. The rate from observations is the long-term rate based on the period 1945-2022 as explained previously. The rates for ssp1-2.6 and ssp2-4.5 are the medium rates as reported by NASA (2023).

6 Discussion

6.1 Harmonic analysis

I developed an automated procedure for analyzing large sets of sea level data, giving mean sea level and the amplitudes of tidal constituents for individual years and location. I applied this procedure successfully to over 130 years of sea level observations on six locations in the Dutch North Sea. The method provides empirically supported estimates of Mean Sea Level (MSL), tidal amplitudes and wind effects; vital information for the design of structures in the coastal zone. The estimate of MSL can be considered an estimate corrected for the effects of wind. The method is more straight-forward and requires less data than corrections relying on wind information (Deltares, 2023; Keizer et al., 2022; Steffelbauer et al., 2022).

Studies into mean sea level tend to use the arithmetic mean sea level as an estimate for MSL. My results show that that estimate deviates from the astronomical estimate depending on the shape of the tide. The difference occurs for old datasets where only high and low water was registered. If water levels are registered eight times per day or more on fixed times, the difference disappears.

The estimates of mean sea level were compared to the data stored in the PSMSL database. In the oldest parts of the data, when only high and low water was registered, PSML data differs from both the astronomic estimate and from the arithmetic mean water level. These differences remain unexplained. Differences disappeared once the sampling of water levels was executed at least eight times a day.

Long term records of sea level such as those kept by PSMSL and Rijkswaterstaat are invaluable for investigating the development of sea levels over the years. Nevertheless, the unexplained variations in the oldest records are an important warning for all investigating long-term trends of sea level. It appears that to date most researchers use PSMSL data indiscriminately.

The tidal amplitudes were found to show jumps and dramatic changes in trends. And also MSL showed periods of sudden change. In part these changes can be explained from coastal works in the vicinity of the tide station in the same period. Without exaggerating, the Dutch coast can be assumed to be in a continuous state of construction and it seems reasonable to assume that several smaller changes go unnoticed. In this study, the trends and cycles of MSL were analyzed for two different time periods and that reveals radically different rates of rise in multiple locations. A few can be explained from nearby estuary closures. Again, this shows that coastal works should be accounted for when selecting an analysis period. A fact that appears to be overlooked by most studies of mean sea level. To be sure, I cannot guarantee that my shortest period (1945-2021) sufficiently excludes these effects. Further investigation is warranted but is outside the scope of the current paper. At the very least, this study shows that estimates based on the indiscriminate use of PSMSL data for periods including major changes to the coast should be used with caution.

6.2 Acceleration of MSL in the North Sea?

6.2.1 General

My regression model incorporates known characteristics of the sea level in time (such as long-period oscillations) and contemporary insights into the effect of anthropogenic climate change. Anthropogenic climate change is modelled as an increasing acceleration of the rise mean sea level, mathematically corresponding to second degree and third degree terms in time. Regression was applied to find the parameters of the model, including the year of onset of acceleration bounded to values consistent with contemporary insights in the effects of climate change (Fox-Kemper et al., 2021).

Statistical testing shows that the higher order terms are not significant. This result is consistent over the two analysis periods used. Baart et al (2012) reached the same conclusion using a less formal method of testing. Recent work by Keizer et al (2022), Steffelbauer et al (2022) and Deltares (2023) argued that an acceleration was significant but masked by wind effect.

My method relies on the assumption that tidal water levels can be accurately estimated by harmonic analysis. This opens the possibility to use the difference between (calculated) tidal water level and observed water level as an estimate of the wind effect. Thus, the wind effect is calculated *without* the use of observed or re-analyzed wind data. Taking the yearly mean of the thus calculated wind effect reveals that the water level along the Dutch Coast is consistently a few cm's above the astronomical value. This is consistent with the dominance of wind setup by Westerly and North-Westerly wind (Voortman, 2003; Vrijling & Bruinsma, 1980; Webbers et al., 2003).

I arrive at estimates of the wind effect that are small and trendless, disproving the hypothesis that the wind effect masks an acceleration of sea level rise. Hence, the acceleration is either not there or masked by another, as yet unknown, factor. In the next section, I study this aspect of Keizer et al. and Steffelbauer et al. more closely. Deltares (2023) rests heavily on these two studies, so any comments extend to that study as well.

6.2.2 Wind effect

Keizer et al. (2022) and Steffelbauer et al. (2022) start from time-averaged data (monthly or yearly) obtained from PSMSL. This data is justly assumed to include a wind effect of unknown magnitude. The starting point of Keizer et al. and of Steffelbauer et al. is that the wind effect needs to be filtered out to reveal the "real" sea level over time. Keizer et al. explicitly state that they expect to find an acceleration but that it is masked by the wind effect.

Both studies correct the observations for the wind, referring to equation 4 in Frederikse & Gerkema (2018). The source of that equation is Pugh & Woodworth (2014, p. 156). Pugh & Woodworth give their equation in an explanation how wind shear stress is taken into account in the depth-averaged equations of water motion. Their formula is a correct description of the water level gradient due to wind *in a point*. Numerically solving the shallow water equations including wind can provide accurate estimates of the water level. In this context, see also Battjes & Labeur (2017).

Frederikse & Gerkema (2018) use the same formula to correct sea level observations for wind and apparently overlook the necessity to solve the shallow water equations to be accurate. Vrijling & Bruinsma (1980) and (based on them) Voortman (2003) analyzed water level statistics in the North Sea and showed a clear dependence of wind setup on the wind direction, caused by the shallowness and irregular shape of the basin. The correction of the sea level for wind by Frederikse & Gerkema is therefore on theoretical and empirical grounds invalid. Further, Frederikse & Gerkema take the drag coefficient from Pugh & Woodworth, but omit a factor 10^{-3}, rendering their drag coefficient a factor 1000 too high and of order 1. This has not yielded clearly erroneous results, probably because the fitting procedure yields values of the parameters compensating for this error, *or* the error is in their paper but not in their source code.

Steffelbauer et al. indiscriminately use the invalid procedure proposed by Frederikse & Gerkema and simplify further by omitting the wind speed dependent drag coefficient altogether. North Sea conditions typically show wind speeds up to 30 m/s and omitting the wind dependent drag gives a difference in wind shear stress up to more than a factor three. An effect on Steffelbauer's trends is expected but outside the scope of this paper.

Keizer et al. finally neglect the meridional wind, explaining that the two wind components are highly correlated and that Frederikse & Gerkema showed the meridional wind to be less important. In the light of my findings regarding that paper, this assumption by Keizer et al. is in serious doubt. And ignoring the meridional wind contradicts empirical facts, with the disastrous storm surge of 1953 as a dramatic example of the importance of meridional wind.

Setting aside the objections against the methods used, it remains unclear how the authors concluded that the wind was masking an acceleration. For an accelerating sea level to show up as a linear trend, it is necessary that the wind effect is equally accelerating with an opposite sign. The results shown in Steffelbauer et al. (2022, fig. 2) and Keizer et al. (2022, fig. 3a) do not reveal that required pattern.

6.2.3 Long-period cycles

On empirical grounds, I find an amplitude of 15 to 20 mm for the nodal cycle and an additional 5 to 8 mm for the perigean cycle, giving a total amplitude of approximately 30 mm in times when the two cycles are in phase. Frederikse et al. (2016) and Frederikse & Gerkema (2018) use the nodal cycle only and report that they derive the amplitude from the self-consistent long-period tide proposed by Woodworth (2012). Accounting for the difference in approach, these results are in reasonable agreement. Keizer et al. (2022) however report the self-consistent tide to be too small and therefore choose to derive the amplitude of the nodal cycle on empirical grounds. A strange conclusion *if* the estimates of the nodal cycle are in agreement.

I am not able to fully explain this finding of Keizer et al. but a closer inspection of the code repository of Steffelbauer (2022) gives some insight. There, I find a data file *"nodal.nc"* that gives the amplitude of the nodal cycle. Testing the code shows the nodal cycle to be in the order of 6 mm, or a factor 5 too small in comparison to either the self-consistent tide *and* to empirical estimates. When asked, Steffelbauer indicated that the source of the file was Frederikse & Gerkema (Steffelbauer, personal communication on Github; May 2023), but in that paper 30 mm is reported. Within the scope of this paper, it was not possible to find whether Frederikse & Gerkema are also in error or that between 2018 and today the file got corrupted. The source code further indicates that Steffelbauer used the wrong sign of the nodal cycle, producing peaks where there should be troughs and vice versa.

Underestimating the amplitude of the long-period oscillations *and/or* using the wrong sign, easily leads to unwarranted detection of acceleration. I will illustrate this with a worked example. A perigean oscillation with 5 mm amplitude gives an acceleration of 2.5 mm/yr^2 (calculated as the second derivative of the perigean oscillation). A nodal cycle with an amplitude of 20 mm gives an acceleration of 2.3 mm/yr^2. When the two cycles are in phase, an acceleration of 4.8 mm/yr^2 occurs during a brief period. To put this abstract number in perspective: sustained over 100 years that acceleration alone would give 24 m of sea level rise. If cycles go unnoticed they may easily be picked up as accelerations.

It is realistic to assume that this is what happened in Steffelbauer et al. (2022) and the *Zeespiegelmonitor* (2023). Both take 1993 as the breakpoint of the bi-linear model, taking a higher rate of rise after 1993. That year is a minimum of the long-period cycles *at this latitude*. Both in theory (P. L. Woodworth, 2012) and empirically (Baart et al. (2012) and the present study).

6.2.4 Statistical testing

Both Keizer et al. and Steffelbauer et al. appear to statistically compare slopes of trends on two sides of a breakpoint. Their method is not fully clarified, but resembles a *t*-test (Ott & Longnecker, 2016). The well-known test by Chow (1960) is not used, despite the fact that it is specifically aimed at detecting breakpoints in datasets. This affects the conclusions because the Chow-test (being a special case of the *F*-test) penalizes for model complexity and a comparison of slopes does not. Statistics aside, previously I explained that there is no plausible physical process that would reveal itself in a piecewise linear development of sea level.

Deltares selects the bilinear model on the basis of a better score of the Akaike Information Criterion or AIC (Akaike, 1974; Ott & Longnecker, 2016, p. 722) than other models. The AIC is equivalent to the adjusted R^2 value, uses the same information and likewise penalizes for model complexity. But like comparing adjusted R^2-values, comparing AIC values neglects the uncertainty in the test-statistic. Too much value may therefore be attached to very small differences in AIC. Closer inspection of annex I of Deltares (2023) indicates that this has happened in the *Zeespiegelmonitor*.

Deltares tests several other regression models, one of which resembles the regression models used in the present study. Deltares reports that under that model and based on a comparison of AIC, no acceleration has been found. That conclusion is consistent with the findings in the current paper.

6.3 Comparison to contemporary sea level projections

Based on my method, an empirical estimate of the *rate* of sea level rise in 2020 can be given. That rate can be compared the rate in contemporary sea level projections (Fox-Kemper et al., 2021; NASA, 2023). For the comparison, I selected the emission paths ssp1-2.6 and ssp2-4.5, in connection to recent developments in global energy use (Chen et al., 2021; Hausfather & Peters, 2020). The projected rates of rise under the emission pathways ssp1-2.6 and ssp2-4.5 are close to a factor two higher than the empirical estimate for the location Delfzijl and more than a factor two higher for the other five locations. Further acceleration is implied in the projections (Figure 13).

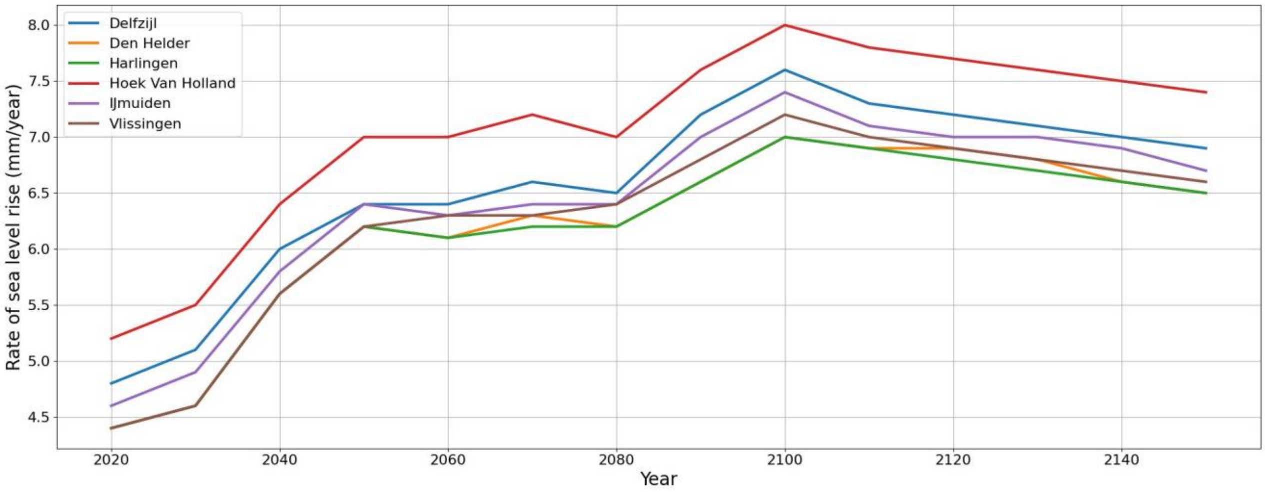

Figure 13: rate of sea level rise in time under the ssp2-4.5 emission pathway as reported in the Sea Level Projection Tool (NASA, 2023)

Structures are designed for a reference period of 50 to 100 years. The current values of rate and acceleration determine the projected outcome in the reference period. The current study indicates that contemporary projections are too high and not empirically supported, both in terms of current rate and current acceleration of sea level rise.

There is an economic case to be made for adopting conservative estimates of future sea levels in the design of structures (Voortman & Veendorp, 2011) but overly conservative estimates lead to an excessive and unnecessary burden on society. Regional sea level projections should always be validated against local observations so that informed decisions for design can be made.

7 Conclusions

Changes of sea level, tide and wind setup are important for design and assessment of coastal structures, such as regulators and levees. I presented a practical method to analyze historical records of observed sea levels, based on harmonic analysis of the water levels. The method “weeds out” the tidal part of the observed water levels. From that, estimates of Mean Sea Level, tidal amplitudes and wind effect for every year in the record are found; vital information for the design and safety assessment of structures in the coastal zone.

I applied the method to six locations in the Dutch North Sea, all with a sea level record of at least 130 years. Local data was used. The analysis reveals that in the Dutch North Sea, changes of tidal shape have occurred. The major changes were associated with estuary closures and harbor modifications. Other than that, tides appear to be rather stable.

Mean sea level is calculated from the data and the estimate turns out to be sensitive to the method used if less than eight datapoints per day are available. I show that for that reason, in the older parts of the record, differences occur with the well-known dataset maintained by PSMSL. The actual difference is shown to be determined by the shape of the tide. Mean sea level was shown to rise consistently in all six locations, with short-term accelerations and decelerations consistent with multi-year tidal drivers. Higher-order terms in time, expressing acceleration of the rate of rise, were found to be insignificant in a formal statistical test.

The wind effect, calculated as the difference between observed and calculated tidal water level, was found to be slightly positive over the full record. This shows that the wind consistently raises the water levels a few cm’s above astronomical levels. The wind effect showed no trend in the 130 year record. This invalidates the assumption that changes of the wind effect over time mask an acceleration of sea level rise in the North Sea.

The long-period oscillations of mean sea level were found at periods and phases corresponding to the oceanic (equilibrium) perigean tide and nodal cycle. Combined and in phase, the two cycles can cause accelerations of close to 5 mm/yr^2. Such a rapid rise is easily mistaken for a climate-driven acceleration of the rate of rise. It is therefore important to be aware of these cycles in every analysis of sea level. I analyzed my conclusions in relation to a few recent papers that reported an accelerated sea level rise in the North Sea. The difference could be explained by an erroneous correction for the wind effect and in a few cases by erroneous estimates of the multi-year tidal cycles.

Finally, I compared the rate of rise following from the present study with the contemporary projections of sea level rise; specifically the projected rate of rise in 2020. I found that in the North Sea, the projected rate of rise overestimates the empirical rate of rise by at least a factor two. The projections imply a further acceleration of the rate of rise, starting in 2005, that is in contradiction with my empirical findings, where no (statistically) significant acceleration was detected.

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Supplementary material

Processed data and methods are available at https://github.com/HVEC-lab/JCHS_sea_level. Raw sea level data is available on https://waterinfo.rws.nl.

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