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The Effect of the 18.6-Year Lunar Nodal Cycle on Regional Sea-Level Rise Estimates

Fedor Baart[†‡], Pieter H.A.J.M. van Gelder[†], John de Ronde[†‡], Mark van Koningsveld[†§], and Bert Wouters[††]

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[†]Department of Hydraulic Engineering
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1
2628 CN Delft,
The Netherlands

[‡]Department Marine and Coastal Systems
Deltares
P.O. Box 177, 2600 MH Delft,
The Netherlands

[§]Department of Environmental Engineering
Van Oord
P.O. Box 8574, 3009 AN
Rotterdam, The Netherlands

[††]Department of Climate Research and Seismology
Royal Netherlands Meteorological Institute
P.O. Box 201, 3730 AE De Bilt,
The Netherlands

ABSTRACT

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Sea-level rise rates have become important drivers for policy makers dealing with the long-term protection of coastal populations. Scenario studies suggest that an acceleration in sea-level rise is imminent. The anticipated acceleration is hard to detect because of spatial and temporal variability, which consequently, have become important research topics. A known decadal-scale variation is the 18.6-year nodal cycle. Here, we show how failing to account for the nodal cycle resulted in an overestimation of Dutch sea-level rise. The nodal cycle is present across the globe with a varying phase and a median amplitude of 2.2 cm. Accounting for the nodal cycle increases the probability of detecting acceleration in the rate of sea-level rise. In an analysis of the Dutch coast, however, still no significant acceleration was found. The nodal cycle causes sea level to drop or to rise at an increased rate; therefore, accounting for it is crucial to accurately estimate regional sea-level rise.

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ADDITIONAL INDEX WORDS: *Sea level, subsidence, decadal, tide, trend estimate.*

INTRODUCTION

The current and expected rates of sea-level rise are important drivers for policy makers dealing with the long-term protection of coastal areas and populations. An example of an area where sea-level rise is important is the Dutch coast. There are several measures planned to deal with the expected acceleration in sea-level rise, which will cost up to €1.6 billion y^{-1} until 2050 (Kabat *et al.,* 2009). The long history of tidal records and the economic value of the area below sea level make the Dutch coast an interesting case for analyzing sea-level measurements and scenarios and for comparing local estimates with global estimates.

LOCAL TRENDS

Sea-level changes are usually reported in the form of trends, often determined over a period of one or more decades. For The Netherlands, an important trend was reported after the 1953 flood, when a relative sea-level rise of 0.15 to 0.20 cm y^{-1} was estimated for the design of the Delta Works. The first Delta Committee report (Deltacommissie, 1960) referred to this change rate as "*relative land subsidence*". *Relative sea level,* the current term, is the sea-level elevation relative to the continental crust as measured by tide gauges. Absolute sea level is relative to a reference ellipsoid and is measured by satellites. A recent estimate (van den Hurk et al., 2007) showed that relative sea level rose at a rate of 0.27 cm y^{-1} during the period 1990–2005. The land subsidence at the Dutch coast varies around 0.04 ± 0.09 cm y^{-1} (mean ± standard error of the mean [SEM]; Kooi *et al.,* 1998).

Local Forecasts

Coastal policy is shifting from observation-based reactions to scenario-based anticipation (Ministerie van Verkeer en Waterstaat, 2009); it is, therefore, interesting to compare observed trends with predicted rates. Sea-level scenarios often predict not only a sea-level rise but also an accelerated rise. The earliest Dutch scenario, published after the 1953 storm, forecasted a rise of several meters due to Greenland ice melting over an unspecified period (Deltacommissie, 1960). Van Dantzig (1956) used a more concrete number of 70 cm for the next century in a related publication. The latest study by the Royal Netherlands Meteorological Institute (KNMI) (van den Hurk *et al.,* 2007; Katsman *et al.,* 2008) resulted in a low and a high scenario. The low scenario estimates a rise of 0.25 cm y^{-1} in the period 1990 through 2050 and 0.32 cm y^{-1} for the period

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2050 through 2100. The high scenario predicts 0.58 cm y^{-1} and 0.77 cm y^{-1} for the same periods. A high-end estimate of 2.02 cm y^{-1} was reported by the second Delta Committee in 2008, based on the Intergovernmental Panel on Climate Change (IPCC) A1FI scenario for the period 2050 through 2100 (Deltacommissie, 2008, see figure 4, page 24). This extreme scenario was used to assess the sustainability of the Dutch coastal policy.

Global Trends

The global measurement of relative sea level started in 1933 when the Permanent Service for Mean Sea Level (PSMSL) began collecting sea-level data from the global network of tide gauges (Woodworth and Player, 2003). Trends based on those measurements vary around 0.17 cm y^{-1}. For example, Holgate (2007) reported a 0.145 cm y^{-1} over the period 1954–2003 and Church *et al.* (2008) reported 0.18 cm y^{-1} over the period 1961–2003. With the launch of the TOPEX/Poseidon satellite in 1992, measurements of absolute sea level became available, with near global coverage and high resolution in time and space. Those measurements were used in the latest estimates, summarized in the IPCC report (Bindoff *et al.,* 2007), giving a 0.31 cm y^{-1} absolute sea-level rise over the period 1993–2003. Despite the apparent difference, tidal-station measurements compare well with satellite data when accounting for corrections, start of time window, and the geographical location (Prandi, Cazenave, and Becker, 2009).

Global Forecasts

Of the global scenarios for future sea-level rise, the most influential are the current model-based IPCC scenarios (Bindoff *et al.,* 2007). The estimated rise varies between 0.17 cm y^{-1} (lower B1) and 0.56 cm y^{-1} (higher A1FI) over the period 1980–1999 through 2090–2099 (Meehl *et al.,* 2007). All scenarios result in a most likely sea-level rise that is higher than the average rate of 0.18 cm y^{-1} over the period 1961 to 2003.

Detecting Acceleration

Even though sea-level rise acceleration was expected to become apparent in the early years of this century (Woodworth, 1990), there is presently no overall, statistically significant acceleration, other than that in the early 20th century (Church and White, 2006; Jevrejeva *et al.,* 2008). The probability of detecting an acceleration in sea-level rise is low because of the effect of decadal variations (Douglas, 1992; Holgate, 2007). Accounting for decadal variations can, therefore, enhance our ability to detect acceleration.

The Nodal Cycle

One such decadal variation is the lunar nodal cycle. The tide on the Earth is driven by six different forcing components with periods varying from 1 day to 20,940 years. The fifth component is the 18.6-yearly lunar nodal cycle (Doodson, 1921). The term *nodal cycle* is best explained while looking up from the Earth. Consider the node as the intersection of the ecliptic plane, which follows the path of the Sun, and the orbital plane, which follows the path of the Moon. This node moves westward, making a circle every 18.6 years.

The main effect of this cycle is that it influences the tidal amplitude (Woodworth, 1999; Gratiot *et al.,* 2008). There are indications that the 18.6 yearly cycle also influences regional mean sea level, for example, at the Dutch coast (Dillingh *et al.,* 1993) and at a collection of other tidal stations (Houston and Dean, 2011; Lisitzin, 1957). Global variation studies on tide gauges using spectral analysis by Trupin and Wahr (1990) and on satellite data using harmonic analysis (Cherniawsky *et al.,* 2010) also indicate a cycle in regional mean sea levels.

Observed tide is often compared with the equilibrium tide. The *equilibrium tide* is the tide that would exist if the earth were completely covered by water and if there were no friction. The equilibrium tide theory builds on the work of Doodson (1921), Cartwright and Tayler (1971), and Cartwright and Edden (1973).

Following Rossiter (1967), we used Equation (1) for the equilibrium elevation ζ and the resulting nodal amplitude A (in millimeters), with the M mass of the moon in kilograms, the E mass of the earth in kilograms, the e mean radius of the earth (in kilometers), the ρ mean distance between the earth center and the moon center (in kilometers), the λ latitude in radians, and the N longitude of the Moon's' ascending node (from '18°18′ to '28°36′). The phase ϕ is 0° for $|\lambda| \geq 35.3°$ and 180° for $|\lambda| < 35.3°$.

$$\begin{aligned}
&\zeta = \frac{9}{8}\frac{M}{E}e\left(\frac{e}{\rho}\right)^3\left(\sin^2\lambda - \frac{1}{3}\right)\cos N' \times 0.06552A = 26.3\left|\sin^2\lambda - \frac{1}{3}\right| \\
&M = 5.9736e24 \\
&E = 7.3477e22 \\
&e = 6{,}371{,}000 \\
&\rho = 384{,}403{,}000
\end{aligned} \tag{1}$$

Proudman (1960) showed that the nodal tide should follow the equilibrium tide for friction. The earth tide should also be taken into account. Rossiter (1967) corrected by a factor of 0.7 to allow for the effect of a yielding Earth. This is also the approach used by Pugh (1987) and Cherniawsky *et al.* (2010). The correction factor is based on the combined effect of the change in the height of the equilibrium level above the solid earth, given by the formula $1 - k - h(\Omega_p/g)$, where k and h are the Love numbers (Love, 1909). The elastic response of the earth has an amplitude of $h\Omega_p/g$, where h is a known elastic constant, Ω_p/g is the gravitational potential, and g is the gravity constant. When the tidal periods become longer, not only the elastic response but also the viscose response is important, and, therefore, the factor of 0.7 may not be appropriate (Pugh, 1987).

For regional sea-level rise estimates, the spatial variability of the nodal cycle is relevant. This spatial variability is also relevant for estimating the global mean sea level. The global mean sea level itself is not affected by this cycle, but trend estimates can be affected because both tide gauges and the satellites have limited coverage of the world. Tide gauges have higher coverage in the Northern Hemisphere, and the altimetry satellites only cover the area between −64° and 64°.

Examining the agreement with the equilibrium tide and the observed nodal cycle is relevant because it determines the best

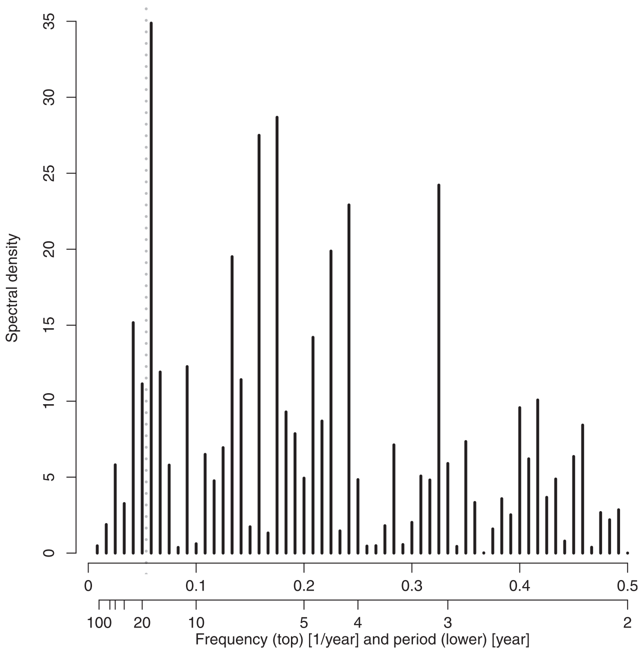

Figure 1. Spectral analysis of the mean of six tidal stations in the period 1890–2008. The dashed line marks 18.6 year.

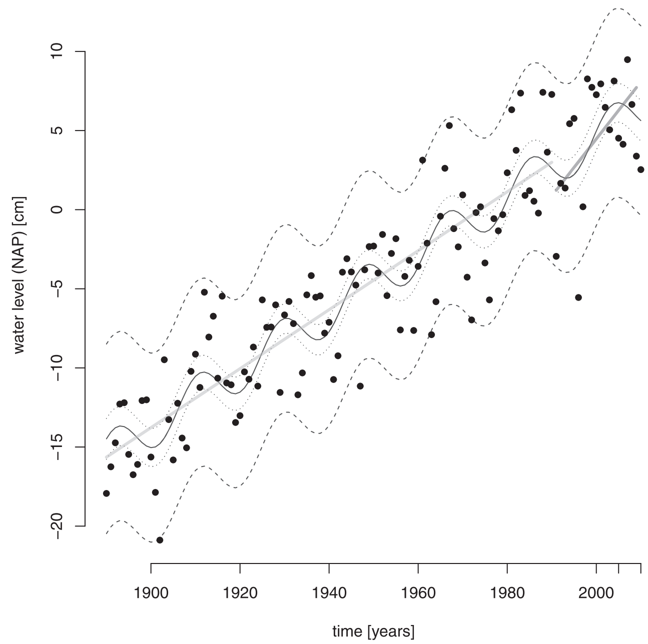

Figure 2. Annual mean sea level averaged over six Dutch tidal stations (black dots). Multiple linear regression with a nodal cycle (solid curve), with a confidence interval (dotted curve), and a prediction interval (dashed curve). Linear regression line through the period 1890–1990 (light gray). Linear regression line through the period 1991–2009 (dark gray).

method to estimate the local effects of the nodal cycle. Previous comparisons with the equilibrium tide (*e.g.,* Currie, 1976; Trupin and Wahr, 1990) have shown agreement.

Accounting for the nodal cycle should increase the probability of finding acceleration or deceleration in the rate of sea-level rise (Baart *et al.,* 2010; Houston and Dean, 2011). In this article, we determine whether accounting for the nodal cycle affects sea-level rise estimates locally and analyze how the nodal cycle varies across the globe.

METHODS

The phase and amplitude of the nodal cycle are estimated by multiple linear regression using Equation (2). Variable t is time in Julian years (365.25 d) since 1970, β_0 is the initial mean sea level (in centimeters), β_1 is the rise (centimeters *per* year), and a and b can be transformed into the amplitude $A = \sqrt{a^2+b^2}$ (in centimeters) and the phase ϕ = (arctan a/b) in radians. Acceleration is tested by comparing the regression model with the quadratic term β_2 (centimeters *per* year^2) with the regression model without the quadratic term.

$$h(t) = \underbrace{\beta_0}_{\text{mean level}} + \underbrace{\beta_1 t}_{\text{trend}} + \underbrace{(\beta_2 t^2)}_{\text{acceleration}} + \underbrace{a \sin\left(\frac{2\pi t}{18.6}\right) + b \cos\left(\frac{2\pi t}{18.6}\right)}_{\text{nodal cycle}}. \tag{2}$$

We used a spectral analysis only to determine whether the nodal cycle was the most dominant signal in the spectrum for cycles with a period greater than a year. The stacking method was not used because the ""detrending before fitting the cycle"" approach leads to an underestimate of the amplitude when the time-series length is not several times as long as the 18.6-year period. Therefore, we used the same harmonic analysis approach as Battjes and Gerritsen (2002) and Houston and Dean (2011).

RESULTS

Local Relative Sea Level

To determine the relevance of the nodal cycle at the Dutch coast, a spectral analysis was carried out on the yearly means of six main tidal gauges for the period 1890–2008. The data were corrected for atmospheric pressure variation using an inverse barometer correction. The spectral density shows a clear peak at the 18.6-year period (Figure 1). The multiple linear regression yields a sea-level rise (β_1) of 0.19 $\pm$ 0.015 cm y^{-1} (95%), an amplitude (A) of 1.2 $\pm$ 0.92 cm, and a phase (ϕ) of -1.16 (with 1970 as 0), resulting in a peak in February 2005 (Figure 2). No significant acceleration (inclusion of β_2) was found.

Probability of Acceleration Detection

The nodal cycle explains 9% of the variance in the detrended mean sea level. Explaining more variance has the advantage that other effects become clearer. We used this process to determine the change in the probability of detecting an acceleration in the rate of sea-level rise. This probability, the statistical power, is calculated for the lower and higher KNMI

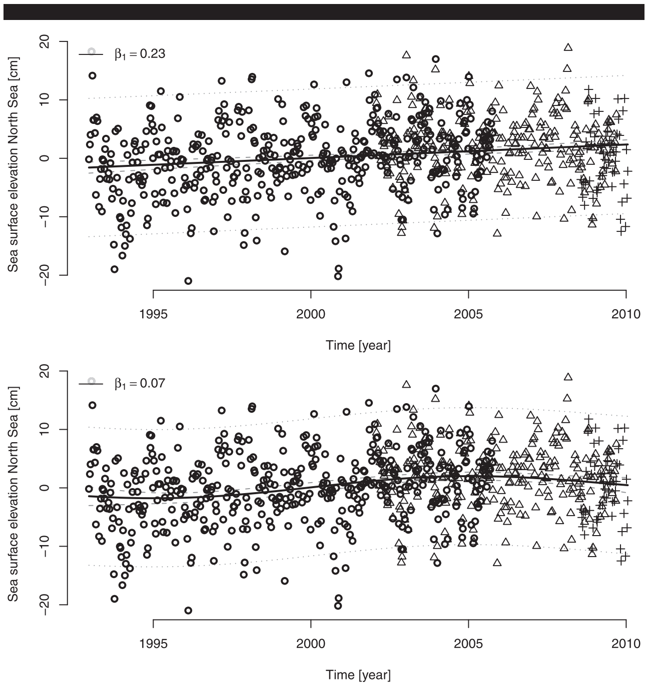

Figure 3. Absolute sea level in the North Sea. (Top figure) Linear regression fitted through corrected satellite observations for the North Sea from Topex (o), Jason1(△), and Jason2 (+). Dashed line represents the confidence interval; dotted line represents the prediction interval. (Lower figure) Seasonal regression (Equation 2) fitted through corrected satellite observations for the North Sea from Topex (o), Jason1(△), and Jason2 (+). Dashed line represents the confidence interval; dotted line represents the prediction interval.

scenarios (van den Hurk *et al.,* 2007) for the Dutch coast. The power was estimated using a simulation, with a generated data set, based on the broken linear trends from the scenarios in van den Hurk *et al.* (2007). In addition, the Dutch nodal cycle was imposed but with a random, uniform distributed phase, as well as a random, normal distributed error, based on the residuals after fitting the nodal cycle for the mean of the Dutch tidal station measurements. The simulation was performed with 200 samples per condition. The detection of the acceleration was done by comparing the linear-regression model with a model with an acceleration term included using an analysis of variance (ANOVA) with 1 degree of freedom. The probability of detecting sea-level acceleration for the lower scenario went up from 46% without the nodal cycle to 48% with the nodal cycle. The probability of detection in the high-end scenario went up from 82% without the nodal cycle to 84% with the nodal cycle included. Generally, 80% is considered an acceptable level. Thus, it can be concluded that, even without accounting for the nodal cycle, it is likely that the acceleration in the higher scenario, if it were present, would have been found.

Local Absolute Sea Level

Repeating the previous analysis on the North Sea satellite data yielded the same nodal cycle (Figure 3). By including the nodal cycle, the absolute sea-level rise lowers from 0.23 cm y^{-1} to 0.07 cm y^{-1} because, coincidently, the time window starts at the bottom and ends in the peak of the nodal cycle. This clearly shows how including the nodal cycle may affect estimates of sea-level rise.

Global Relative Sea Level

Now that it is known that the nodal cycle is important for estimates of local sea-level rise, the next question is how the nodal cycle varies across the globe. The variation in global relative sea-level was analyzed using the PSMSL tidal gauge data set. From the 1157 gauges, 511 were selected based on their recorded history of at least 57 (3×19) years. The analysis of the spectral densities at the tidal stations was skipped because it has already been performed in detail (Trupin and Wahr, 1990), showing a peak at 18.6 years.

Equation (2) was applied to the selected stations, in which 134 stations showed an amplitude (A) that was significantly different from 0. This confirms the global presence of the effect of the lunar nodal cycle, with a median amplitude of 2.2. The variation in global phase and amplitudes are shown in Figure 4.

Global Absolute Sea Level

The phases found at the tidal stations were compared with the phases found in nearby measurements from altimetry satellites for verification. This data set was obtained from the Commonwealth Scientific and Industrial Research Organisation web site and consists of sea surface heights with inverse barometer (IB) corrections, seasonal signals removed, and glacial isostatic adjustments corrected. Because satellite data are only available for one lunar nodal period, the results are susceptible to other influences and are not yet stable. The variation in global phase is plotted in Figure 4. Tidal gauge and satellite measurements show a reasonable correspondence in the Atlantic Ocean but not in the Pacific Ocean. The canonical correlation between the amplitude and the phases of stations and of the nearby satellites is 0.21, which is low yet statistically significant.

When to Include the Nodal Cycle

The two extra parameters, amplitude and phase, can result in a less-accurate estimate of the sea-level rise parameter. One way to approach this is by determining whether the variance explained by the combination of the two extra parameters is statistically significant (using an ANOVA with 2 degrees of freedom). An alternative is to use the Akaike information criterion.

Another simulation provides a general estimate of what would be a good period for including a nodal cycle in estimates of regional sea level. Here, we assumed a sea-level rise equal to 0.2 cm y^{-1}, a nodal amplitude of 2.2 cm, and a uniform distributed random phase and a random error of 2.5 cm. By varying the time period and comparing the root mean square error of the estimate of nodal fit and linear fit, we find that, with these conditions, it is useful to include the nodal cycle terms starting with periods of 14 years and longer. This period for which it is advisable to include the nodal cycle becomes longer because the ratio between them is a function of the random error and the amplitude of the nodal cycle increases. A

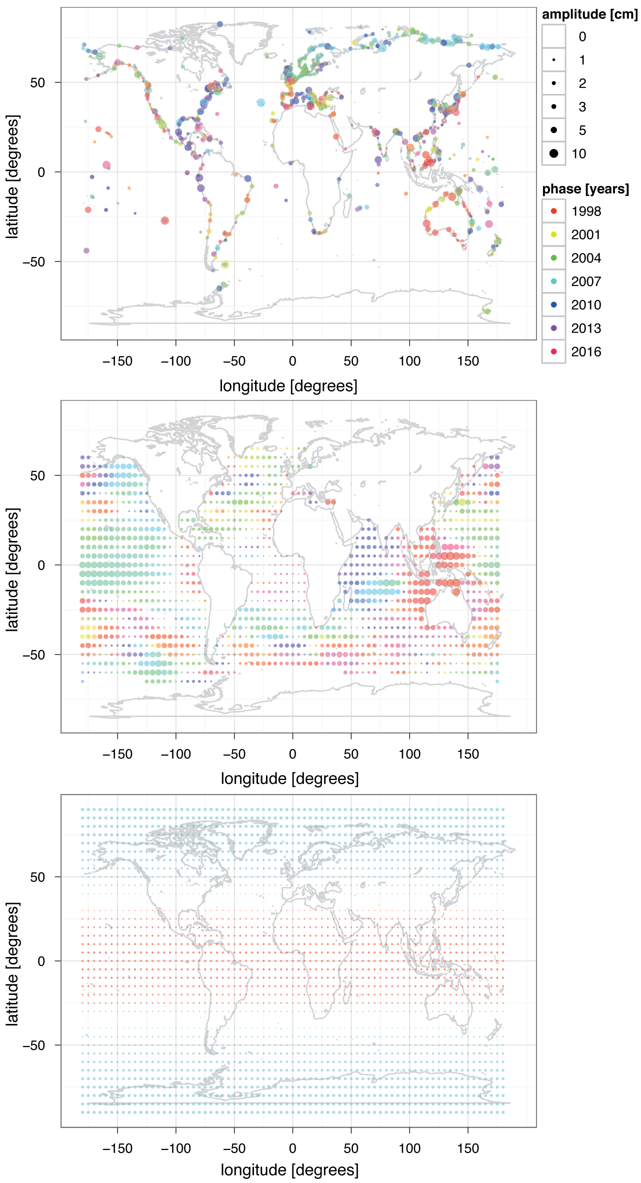

Figure 4. Nodal cycle, estimated using Equation (2). Amplitudes in cm (size of circles) and phases in years (color) of the lunar nodal cycle. (Top figure) Tide gauges with at least 57 y of measurements. (Middle figure) Altimetry satellites. (Bottom figure) Equilibrium.

similar discussion can be found in Blewitt and Lavallée (2002) for the comparable problem of fitting geodetic velocities.

If the goal is to develop an unbiased local estimate of the sea-level rise parameter, the simplest approach is to use time series of multiples of 18.6 + 9.3 years (integer plus a half). When the goal is to develop a good estimate of the level or acceleration, this approach cannot be used.

The goal of including the nodal tide is to fit the nodal cycle, not other decadal cycles. Therefore, the nodal cycle should only be incuded in the 18.6 year is within the modal frequency bin of the multi-year spectrum. In addition, it is advisable to check for the reliability of the fit, by, for example, splitting up the tidal signal into two separate parts, which should yield the same nodal cycle phase. If the estimate of the nodal cycle is based on satellite measurements, it should be verified using local tide gauges.

CONCLUSIONS

Coastal management requires estimates of the rate of sea-level rise. The trends found locally for the Dutch coast are the same as have been found in the past 50 years (Deltacommissie, 1960; Dillingh *et al.,* 1993). Even though including the nodal cycle made it more likely that the high-level scenarios would become apparent in the observations, no acceleration in the rate of sea-level rise was found. The higher, recent rise (van den Hurk *et al.,* 2007) coincides with the up phase of the nodal cycle. For the period 2005 through 2011, the Dutch mean sea-level is expected to drop because the lunar cycle is in the down phase. This shows the importance of including the 18.6-year cycle in regional sea-level estimates. Not doing so on a regional or local scale for decadal length projections leads to inaccuracies.

There is a difference between the nodal cycle phase expected from the equilibrium and the nodal cycle phase found in tidal records. This is inconsistent with the results from Trupin and Wahr (1990), possibly because of the difference between the stacking approach and the harmonic approach. The difference here is similar to the differences found by Cherniawsky et al. (2010). The cause for the difference between the observed nodal cycle and the equilibrium nodal cycle is not known. It could be a physical effect but could also be the result of the way our mean sea levels are measured and computed.

Whatever the cause, if there is a known decadal signal in the sea-level records, it should be taken into account. Doing so will provide better estimates of local sea-level rise, but only if it is determined that the nodal fit is clearly present.

Although the nodal tide does not affect the true global mean sea level, it can affect global mean sea level estimates. In sea-level trends from satellites, if one assumes the equilibrium nodal phase, one would expect a small nodal cycle in the mean because of the phase distribution in combination with the limited spatial coverage of the altimetry satellite. The sea-level trends based on tide gauges can also be affected by the nodal cycle because of irregular spatial sampling of the tidal gauges. The observed nodal cycle shows a pattern that is more E–W, rather than the equator–poles pattern of the equilibrium. The nodal cycle can thus be safely ignored for global mean sea-level estimates based on satellites. For global mean sea-level estimates based on tidal gauges, the distribution of nodal cycle phases could be checked for approximate, circular uniformness. Globally, the 18.6-year cycle is observable in one-fourth of the selected tidal stations, with a varying phase. The phases found, based on tidal records and satellite data, show a weak association, probably because of the short period of the satellite measurements. It is not yet possible to give an accurate estimate of the effect of the cycle across the globe. Just like a sea-level rise trend can be very sensitive to the window of observation, an estimate of a cycle is highly sensitive to peaks. Without removing such effects, for example, the El Niño–Southern Oscillation, short series like the satellite measurements are not very representative of the effect of the nodal cycle. A logical follow-up to this research would be to simulate the effect of the nodal cycle using a global tide model.

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