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DISCUSSION

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ABSTRACT

Schmith, T.; Thejll, P., and Nielsen, J.W., 2016. Discussion of: Hansen, J. M., Aagaard, T. and Kuijpers, A., 2015. Sea-level forcing by synchronization of 56- and 74-year oscillations with the Moon's nodal tide on the northwest European shelf (eastern North Sea to central Baltic Sea). *Journal of Coastal Research*, 31(5), 1041–1056. *Journal of Coastal Research,* 32(2), 452–455. Coconut Creek (Florida), ISSN 0749-0208.

We criticize important aspects of the analysis presented in Hansen, Aagaard, and Kuijpers (2015) (hereafter "HAK") and thereby cast doubt on their conclusions. HAK claim that 18.6-year variations in sea level are supported by tidal theory, but this is not the case; therefore, the existence of such variations must be explicitly shown. We calculated the amplitude spectrum of the annual sea level by harmonic analysis and found no significant peaks at the periods claimed by HAK. Next, we used results given by HAK to reconstruct their decomposition and formed the residuals by subtracting the decomposition from the original data. We found that the variability near 18.6 years is present in the residuals, showing that the decomposition by HAK does not describe this variability. This motivated us to redo HAK's analysis, and we found a seven times lower amplitude for the 18.6-year periodicity than claimed by HAK. Finally, we discuss HAK's mode selection criteria, based on correlation coefficients of trending series, and find them invalid. Therefore, we performed a significance test based on a Monte Carlo technique and conclude that none of the modes identified by HAK are statistically significant.

ADDITIONAL INDEX WORDS: *Lunar nodal, spectral peak, residual, significance, sea-level rise.*

INTRODUCTION

Hansen, Aagaard, and Kuijpers (2015) (hereafter "HAK") present an analysis of annual mean sea level from the northwest European shelf in terms of the lunar nodal tide and its subharmonics. They combine 26 tide gauge records, corrected for glacio-isostatic adjustment (GIA), to form a common curve of annual average sea levels representing the region. We take the results from this work as given and proceed with analysis of the provided annual sea-level series (Hansen, *personal communication*).

HAK state that there must be an 18.6-year oscillation in the sea level due to the lunar nodal oscillation. Motivated by this, they apply a sine regression technique to identify the 18.6-year, and other, oscillatory components in addition to a long term trend. It is this analytical part of HAK's work that we find flawed: HAK has misunderstood tidal theory and there are statistical errors as well as an unnecessarily complex decomposition method.

In what follows, we describe each of our points of criticism in detail, each of which are independent, *i.e.* they do not assume the validity of any of the other points.

EXISTENCE OF THE 18.6-YEAR PERIODICITY IN ANNUAL SEA LEVEL

A pivotal point in the argumentation of HAK is the existence of a predominant 18.6-year periodicity in sea level due to the Moon's nodal tide. However, the astronomical tide forcing anticipates an 18.6-year periodicity in the *tidal range* (*e.g.,* Parker, 2007) or, in other words, a modulation of the tidal constituents, which causes no net transport of water, meaning no sea-level signal. This does not preclude the existence of an 18.6-year signal in the sea level regionally, as showed by Baart *et al.* (2012), but implies that the presence of the 18.6-year signal in the sea level must be explicitly demonstrated in each individual case.

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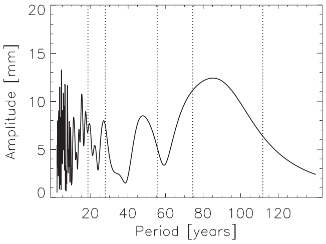

Figure 1. Amplitude spectrum of annual sea-level data from HAK, calculated by successive sine curve fitting on the linear detrended data. Vertical dotted lines indicate periods identified in HAK's analysis.

We therefore performed a harmonic analysis of the observed, GIA-corrected, annual sea-level data from the eastern North Sea to the central Baltic given in HAK (their Figure 2, lower panel, thin black curve). The resulting amplitude spectrum, calculated by the successive fitting of sine curves to the observed sea-level data, after removal of the linear trend is shown in Figure 1.

The spectrum does not show any outstanding amplitude near 18.6 years, nor at the other periodicities identified in the analysis by HAK, which are all marked on the plot. This casts severe doubt on focusing on exactly these periods as HAK do.

EXAMINING THE DECOMPOSITION GIVEN IN HAK

Examination of the residuals, here being the original annual sea-level series minus its decomposition, is good practice in any statistical decomposition of a time series (*e.g.,* von Storch and Zwiers, 1999). We therefore calculated the residuals by using the original data and the decomposition parameters (period, amplitude, and culmination) given in HAK (their Table 2b). The decomposition is shown in the upper panel of Figure 2. Inspecting this reveals no convincing correspondence between the original series and the decomposition apart from the trend.

To investigate this in more detail, we calculated the residuals, shown in the middle panel of Figure 2, and their autocorrelation function (ACF) shown in the lower panel of Figure 2.

We note that the ACF of the residuals appears cyclic with large positive values near 18.6 years and multiples of this value and large negative values in between. This means that the statistical decomposition in periodic components by HAK has not properly described any variability near 18.6 years. Therefore, we do not believe that the parameters (period, amplitude, and culmination) given by HAK (Table 2b) refer to a harmonic decomposition of the original annual sea-level series.

REDOING HAK'S METHODOLOGY OF DECOMPOSITION

Motivated by the findings described in the previous section, we redid HAK's iterative sine regression procedure to estimate phase (culmination) and amplitude of the oscillatory components. We limited ourselves to the version with HAK's five predefined periods fixed at the values in their Table 2b.

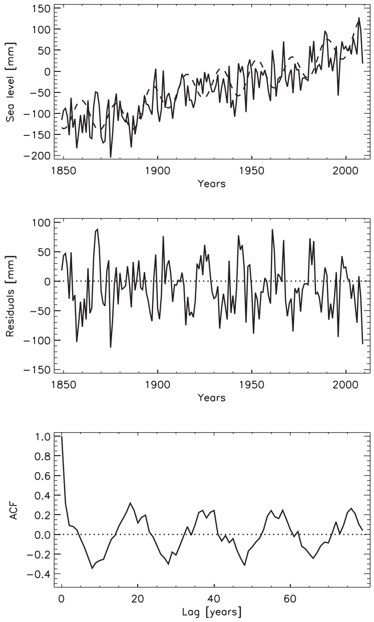

Figure 2. The decomposition given in HAK. Upper panel: Observed annual sea level, with decomposition as dashed line. Middle panel: Residuals equal observed annual sea-level data minus decomposition. Lower panel: Autocorrelation function of the residuals.

We note that by the harmonic addition theorem, we can rewrite a particular oscillatory component with period T and phase δ as

$$A \sin\left(\frac{2\pi t}{T} + \delta\right) = a \cos\left(\frac{2\pi t}{T}\right) + b \sin\left(\frac{2\pi t}{T}\right),$$

with

$$A = \sqrt{a^2 + b^2}.$$

The problem of estimating amplitudes and phases can thus be transformed to the linear problem of estimating the amplitudes of pairs of cosine and sine functions with zero phases. This is standard procedure in tidal analysis (*e.g.,* Parker, 2007). The linearity implies that multiple regression can be used giving explicit least-square estimates of the amplitudes and their uncertainties. Therefore the iterative procedure of HAK is unnecessarily complex, inviting accumulated round-off errors due to its iterative nature.

In Table 1, we give the fitted parameters and uncertainties found by our method using fixed periods from HAK (their Table 2b) and a linear trend.

By comparing amplitudes from Table 1 with corresponding values from HAK's Table 2b (repeated for convenience in our Table 1), we find agreement, inside uncertainties, with the important exception of the amplitude of the 18.6-year oscillation. Here we find an amplitude about seven times smaller than HAK. After acceptance of the present discussion paper we became aware of an analysis of the Stockholm sea-level series (Wroblewski, 2001) and its estimated amplitude of the 18.6-year nodal signal of 7.2 mm or 14.4 mm top to bottom. We take

Table 1. *Estimated model parameters by redoing the method of HAK using linear regression. For each period, we give amplitude by HAK and our amplitude estimate and its uncertainty. Then we give slope estimates by HAK and by us with uncertainty. Finally, we give root mean square error (RMSE) by HAK and by us.*

Period (y)	Amplitude[a] (mm) HAK[b]	Amplitude[a] (mm) This Paper	1-Sigma Uncertainty (mm)
18.6	70.0	10.9	8.2
74.4	35.5	28.9	12.7
55.8	22.7	17.7	10.2
111.7	8.0	0.5	12.5
27.9	8.5	18.3	8.4
Slope (mm/y)	1.2	1.1	0.1
RMSE (mm)	34.5	34.8	

[a] Top to bottom.

[b] From HAK's Table 2b.

this result as further support of our estimated amplitude of 10.9 mm of the 18.6-year component, as opposed to HAK's value of 70.0 mm, both top to bottom and given in Table 1.

From our estimated parameters we construct the corresponding decomposition (upper panel of Figure 3); generally, there is a larger degree of coincidence with the original data than in HAK's decomposition shown in the upper panel of Figure 2.

We also calculated the residuals from our fit of oscillatory components and the corresponding ACF. This is shown in the middle and lower panels of Figure 3. This ACF shows no periodicity (in contrast to the lower panel of Figure 2) but has low values for all lags except zero. This gives more confidence to our results compared with results based on HAK.

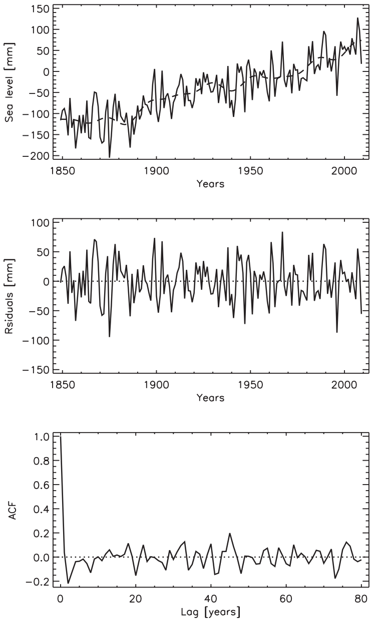

Figure 3. The decomposition estimated in this paper. Upper panel: Observed annual sea level, with decomposition as dashed line. Middle panel: Residuals equal observed annual sea-level data minus decomposition. Lower panel: Autocorrelation function of the residuals.

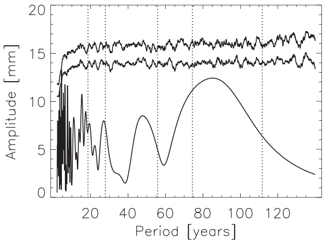

Figure 4. Selected upper percentiles (95% and 99%) of null hypothesis amplitudes as a function of period. See text for details. Also shown is the result of the harmonic analysis from Figure 1.

SELECTION OF COMPONENTS TO BE RETAINED

Finally, there is the question of test criteria for including the identified oscillatory components in the final decomposition. In HAK, this is based on testing the statistical significance of certain correlation coefficients specified therein. The problem with this approach is that the series contain trends, which will artificially inflate the calculated correlation coefficients. A more proper approach would have been to take the trend out of the data before calculating the correlation coefficients.

Next, HAK evaluate the confidence level of these correlation coefficients. It is not specified how this is done. A standard approach described in many textbooks is to calculate first the correlation coefficient r from the data and then the test statistics

$$t = |r|\sqrt{\frac{n-2}{1-r^2}},$$

where n is the number of data points, and compare t with critical values from the t distribution.

This approach, however, assumes stationarity of the data and may yield strongly misleading results when data, as in HAK's case, include trends.

We know of no parametric approach to evaluate confidence levels correctly with trending and cyclic data. Therefore, we resorted to a Monte Carlo approach. Repeatedly (3700 times), we generated surrogate time series with the same autocorrelation at lag 1 as the original detrended series. Each surrogate time series was normalized to have the same mean and variance as the original detrended series. Then, we swept for periods from 2 to 140 years in 0.1-year steps, and for each period, we fitted trigonometric functions to derive the amplitude at each period. Based on all 3700 sweeps, we finally calculated a histogram of amplitudes for each period. Figure 4 shows selected percentiles of these histograms as function of period, together with the result of the harmonic analysis from Figure 1. This enables us to compare the distribution of amplitudes of the surrogate series, which by construction have no spectral peaks, with the amplitude spectrum of the observed sea-level series.

If any of the peaks in the harmonic analysis shown in Figure 1 were statistically significant and not due to mere coincidence, the amplitude of that particular peak would exceed a high percentile based on the histogram of amplitudes of the surrogate series. But as we can see from Figure 4, even if some periodicities are prominent, notably the one near 80 years and a few at short periods, none of the longer periods are significant.

CONCLUSIONS

By documenting a misunderstanding of basic concepts of tidal theory combined with erroneous and/or irreproducible statistical analysis in HAK, we conclude that their claim of significant oscillatory components in the regional (eastern North Sea to central Baltic Sea) sea level remains unsupported. This leaves their considerations about synchronization as well as their sea-level prognosis in doubt.

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