How to improve estimates of real-time acceleration in the mean sea level signal

Author: Watson, Phil J.

Source: Journal of Coastal Research, 75(sp1) : 780-784

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/SI75-157.1

Journal of Coastal Research	SI	75	780-784	Coconut Creek, Florida	2016

How to improve estimates of real-time acceleration in the mean sea level signal

Phil J. Watson[†]

[†]School of Civil and Environmental Engineering,
University of New South Wales,
Kensington, NSW, Australia.

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Watson, P.J., 2016. How to improve estimates of real-time acceleration in the mean sea level signal. *In:* Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds.), *Proceedings of the 14th International Coastal Symposium* (Sydney, Australia). *Journal of Coastal Research*, Special Issue, No. 75, pp. 780-784. Coconut Creek (Florida), ISSN 0749-0208.

One of the most critical environmental issues confronting mankind into the foreseeable future remains the ominous spectre of climate change, in particular the pace at which impacts will occur and our capacity to adapt. Sea level rise is one of the key artefacts of climate change that will have profound impacts on global coastal populations. Although extensive research has been undertaken into this issue, there remains considerable conjecture and scientific debate about the temporal changes in mean sea level and the climatic and associated physical forcings responsible for them. Over recent years, significant debate has centered around the issue of a measurable acceleration in mean sea level, a feature central to projections based on the current knowledge of climate science. To reduce this uncertainty, it is necessary to determine the better performing analytical approaches for isolating the mean sea level signal from long, individual ocean water level time series with improved temporal resolution. This paper summarises the testing and development of an analytical tool designed specifically to enhance real-time estimates of velocity and acceleration in mean sea level derived from contemporary ocean water level data sets. The long ocean water level record at San Francisco, USA has been used to highlight the application and utility of the improved approach.

ADDITIONAL INDEX WORDS: *Mean sea level, acceleration, improved analytical tool.*

INTRODUCTION

One of the most critical environmental issues confronting mankind into the foreseeable future remains the ominous spectre of climate change, in particular the pace at which impacts will occur and our capacity to adapt. Sea level rise is one of the key artefacts of climate change that will have profound impacts on global coastal populations (Nicholls and Cazenave, 2010).

Although extensive research has been undertaken into sea level rise, there remains considerable conjecture and scientific debate about the temporal changes in mean sea level and the climatic and associated physical forcings responsible for them (Watson, 2015a). Of keen interest is whether there is a measurable acceleration in ocean water level records (*e.g.*, Baart, Van Koningsveld, and Stive, 2011; Donoghue and Parkinson, 2011; Houston and Dean, 2011a; Houston and Dean, 2011b; Rahmstorf and Vermeer, 2011; Visser, Dangendorf, and Petersen, 2015; Watson, 2011], a feature central to projections based on the current knowledge of climate science (Stocker *et al.*, 2013). In particular, the published works of Watson (2011) and Houston and Dean (2011a) generated extensive political, social and media debate around the issue.

Much of the professional debate concerns the manner in which acceleration is estimated. Almost exclusively, estimates of acceleration in global or basin scale mean sea level studies have been derived from the ubiquitous simplicity afforded by doubling the quadratic coefficient after fitting a second order polynomial function (*e.g.*, Church and White, 2006; 2011; Douglas, 1992; 1997; Hay *et al.*, 2015; Houston and Dean, 2011a; Jevrejeva *et al.*, 2006; 2008; 2014).

Other techniques applied infer acceleration as a change in the average velocity between differing time slices (*e.g.*, Bindoff *et al.*, 2007; Calafat and Chambers, 2013; Hansen, Aagaard, and Binderup, 2012; Kemp *et al.*, 2009; Merrifield, Merrifield, and Mitchum, 2009). Both techniques are comparatively limited, especially the fitting of a second order polynomial whose acceleration term assumes a constant rate of acceleration applies over the course of the record.

It's well understood that long records and global mean sea level reconstructions contain well recognized signatures of positive and negative "inflexions" (Woodworth *et al.*, 2009) as well as key influences driven ostensibly by climate modes (Cazenave *et al.*, 2012; Fasullo *et al.*, 2013; Hamlington *et al.*, 2013).

As a result, acceleration determined through simple quadratic fits are likely to be unduly influenced by the particular time slice chosen (Rahmstorf and Vermeer, 2011). These comparatively simple approaches work well at a coarse scale where real-time changes in these key characteristics are unimportant.

However, the importance of mean sea level acceleration and its intrinsic linkages to climate change science, demand more sophisticated measures and tools. Improving knowledge of acceleration in mean sea level lies principally with improving

DOI: 10.2112/SI75-157.1 received 15 October 2015; accepted in revision 15 January 2016.
*Corresponding author: philwatson.slr@gmail.com

the temporal resolution of the trend signal. This is no trivial task given that ocean water level records are a complex composite of numerous dynamic influences of largely oceanographic, atmospheric or gravitational origins operating on differing temporal and spatial scales, superimposed on a comparatively low amplitude signal of sea level rise driven by climate change influences (Watson, 2015a).

The mean sea level (or trend) signal results directly from a change in volume of the ocean attributable principally to melting of snow and ice reserves bounded above sea level (directly adding water), and thermal expansion of the ocean water mass. This low amplitude, non-linear, non-stationary signal is quite distinct from all other known dynamic processes that influence the ocean water surface which, are considered to be stationary; that is, they cause the water surface to respond on differing scales and frequencies, but do not change the volume of the water mass.

Improved real-time knowledge of velocity and acceleration rests entirely with improving the temporal resolution of the mean sea level signal. Therefore it is essential to use enhanced time series analysis techniques to better isolate noise and remove the key contaminating signals that influence such records at inter-annual to decadal (and longer) timescales, revealing a more "refined" trend signal.

From this improved signal, the first and second differences provide real-time estimates of velocity and acceleration that are far more instructive in readily identifying key physical changes in mean sea level over time.

Background

Watson (2015b) provided the most extensive appraisal yet of time series analysis techniques for their utility to isolate the trend with improved temporal accuracy from conventional, long, individual ocean water level data sets. A broad range of analytical techniques were tested including linear and polynomial regression, LOESS smoothing, smoothing splines, moving averages, structural models, digital filters, singular spectrum analysis (SSA), empirical mode decomposition, wavelets and their respective derivatives. Sensitivity testing around key parametrization was undertaken to optimize performance of each of the analytics specifically for application with conventional ocean water level data.

In total some 1450 separate analyses were applied to a complex synthetic data set (Watson, 2015a), resulting in 21 million individual time series analyses. Key findings from this analysis were that enhanced accuracy in resolving the temporal resolution of the trend were achieved through the use of longer, annual average data, coupled with the use of so called "data adaptive" analytics, in particular, SSA and multi-resolution wavelet decomposition. SSA is more instructive and convenient for the process in hand given the techniques enhanced capability to seperate key harmonic components of the time series.

SSA is a powerful data adaptive technique capable of decomposing the observed time series into the sum of interpretable components with no a priori information about the time series structure (Alexandrov *et al.*, 2012; Golyandina and Zhigljavsky, 2013). Based upon detailed analysis of numerous long records in the Permanent Service for Mean Sea Level (PSMSL) data holdings (Holgate *et al.*, 2012), Watson has optimized the parameterization and performance of SSA to isolate the mean sea level (or trend) signal from long ocean water level data sets with improved accuracy.

The long annual average record at San Francisco, USA has been used to highlight the application and utility of the analytical approach within this paper.

METHODS

There are 4 key steps involved in isolating the trend signal from long individual ocean water level records with improved temporal resolution and improving estimates of the associated real-time (or instantaneous) velocity and acceleration.

Step 1: Gap Filling. In order to perform SSA, the time series data under consideration must be complete. Thus the initial step in the process involves filling any gaps in the annual average time series record under consideration. Although the San Francisco record used in this paper is one of the longer, more complete records available world-wide, there is a small gap in the time series for 2012. Numerous methods are available for gap filling time series data however, for ocean water level records it is recommended to fill the gaps using SSA and recurrent forecasts from complete parts of the record (Golyandina and Osipov, 2007). This process has been undertaken for the San Francisco record by reconstructing the gap from the combination of SSA components in which the peak spectral energy is ≤ 0.2 (alternatively, corresponding to peak periods ≥ 5 years). With this approach, the principal spectral structures evident in the complete parts of the record can be used to forecast with greater precision across the data gap.

Step 2: Isolating Trend Using SSA. Once gap filling has been completed, the time series is then decomposed using 1D-SSA via the "Rssa" Package in R (Golyandina *et al.*, 2015). The main step of the SSA method is the singular decomposition of the so-called series trajectory matrix. The time series is decomposed into a series of components of slowly varying trend, oscillatory components with variable amplitude and a structureless noise (Golyandina, Nekrutkin, and Zhigljavsky, 2001), with components ranked in order of their contribution to the original time series.

The trend can be isolated by reconstructing only the components that possess distinctly "trend-like" characteristics. Analysis of numerous long ocean records in the data holdings of the PSMSL demonstrate trend components are isolated effectively when a contribution threshold of $\geq 75\%$ is contained within a frequency bin of ≤ 0.01. The grouping of relevant components can be automatically detected (Alexandrov and Golyandina, 2005) and reconstructed via the Rssa Package. In the case of the gap-filled San Francisco time series, the first and second components of the SSA decomposition form the trend (or relative mean sea level) signal (Figure 1).

Step 3: Estimating Real-Time Velocity and Acceleration. A cubic smoothing spline is then fitted to the trend determined in Step 2 to estimate the real-time or instantaneous velocities and accelerations corresponding to each data point in the original time series. As the trend by definition is comparatively smooth, the fitted smoothing spline has been limited to 1 degree of freedom for every 8 data points. The coefficient of determination (R^2) between the SSA derived trend and the fitted cubic smoothing spline for the San Francisco record exceeds 0.9999, representing a near mathematically perfect model fit.

The instantaneous velocity and accelerations can be readily estimated from the first and second derivatives of the fitted smoothing spline, respectively. However, care is required in fitting smoothing splines and deriving second derivatives near the end of the time series. The reason for this is that the knots at the end of a fitted cubic smoothing spline are fixed in order to be differentiable, resulting in a second derivative at the ends which must converge to zero. For this reason, the first and last three derived acceleration points on the time series will likely have reduced accuracy and should not be included in the analysis.

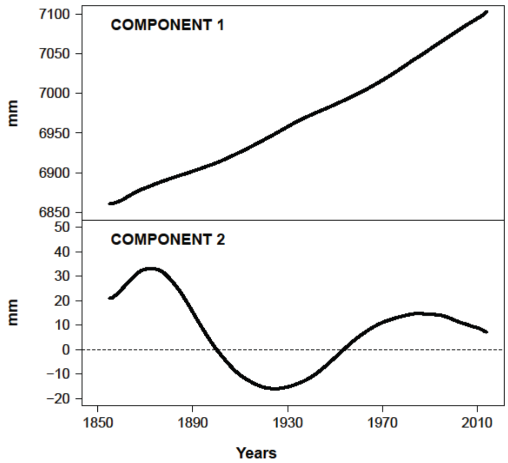

Figure 1. Components of the SSA decomposition of the San Francisco record which form the trend signal.

Step 4: Calculation of Errors. Errors in estimating the trend and associated instantaneous velocity and accelerations have been determined using block bootstrapping techniques with 10,000 iterations. This process initially involves fitting an autoregressive time series model to remove the serial correlation in the residuals between the SSA derived trend and the gap filled time series (Forster and Brown, 2015).

The uncorrelated residuals are then tested to identify change points in the statistical variance along the time series using the "Changepoint" Package in R (Killick and Eckley, 2014). A changepoint was not detected for the San Francisco record. However, in a time series where there is a changepoint detected in the variance, the recommended procedure involves block bootstrapping of residuals quarantined between identified variance change points and then adding the sections to the SSA derived trend prior to running steps 2 and 3 some 10,000 times. The standard deviations are then readily calculated for the trend and associated velocity and accelerations from which to directly derive confidence intervals (CI).

RESULTS

The application of the advised methodology to the long San Francisco tide gauge record is graphically depicted at Figure 2.

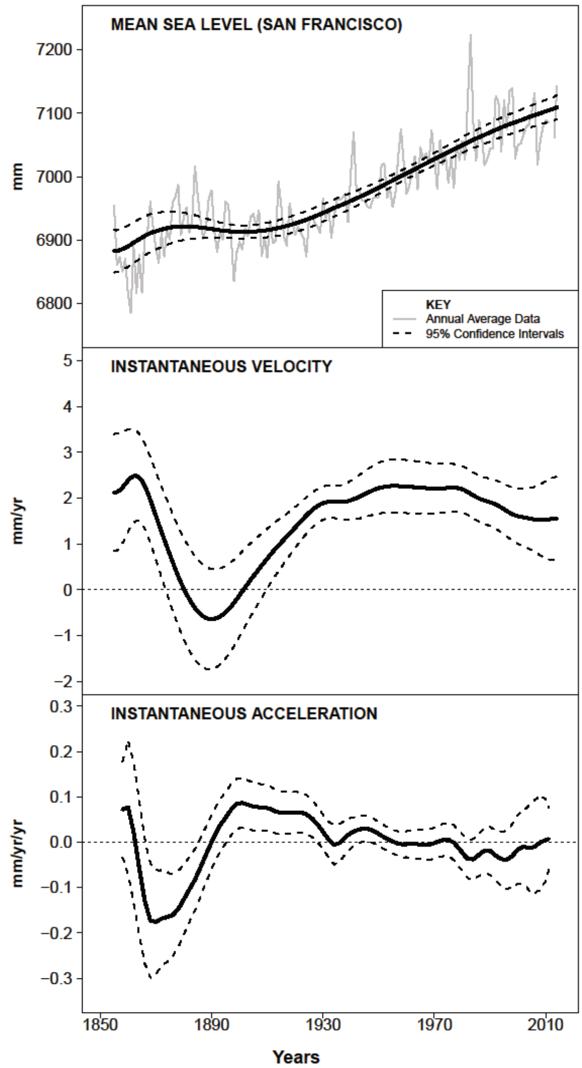

Figure 2. Refined trend and associated real-time velocity and acceleration for relative mean sea level at San Francisco, USA. Annual average data obtained from Permanent Service for Mean Sea Level (UK).

Whilst the record provides very clear evidence of significant relative sea level rise, of the order of 189 ± 52 mm (95% CI) over the course of the historical record, it is clear that the rate at which relative mean sea level has risen has fluctuated substantially over this period. Despite this rise, there is evidence of a fall in the mean signal of the order of around 9 mm between 1880 and 1901.

Interestingly the peak instantaneous velocity of 2.5 ± 1.0 mm/yr (95% CI) occurred early in the record (1863). The second highest velocity of 2.3 ± 0.6 mm/yr (95% CI) occurred in a block between 1950 and 1980, falling moderately to present day (2014) where the velocity is currently 1.6 ± 0.9 mm/yr (95%

CI). Another interesting artefact of the velocity time series is that the last time the mean velocity was as low as present was in 1922.

The peak instantaneous acceleration of 0.09 ± 0.03 mm/yr^2 (95% CI) occurred in 1901. However, over the period from 1928 to present, the instantaneous acceleration has not been statistically different to zero at the 95% confidence level.

DISCUSSION

The methodology advised in this paper and "road-tested" against the long San Francisco record, highlight the enhanced level of information which can be gleaned from the real-time (or instantaneous) velocity and acceleration derived from more accurate isolation of the relative mean sea level signal.

In reality the search for acceleration in any particular record need not be restricted to inspection of the instantaneous accelerations alone. Although this provides some instruction, an acceleration might also be inferred by considering whether or not peaks in the instantaneous velocity time series are increasing, becoming more sustained or abnormal over time in the context of the historical record. The decomposition of the San Francisco record highlights the virtue of considering acceleration from this new perspective, particularly when the mean sea level signal is dynamically changing over time.

Although this methodology provides enhanced levels of temporal understanding of the mean sea level trend signal, caution should be exercised in interpreting results as the quality of the data sets generally degrades (and in some cases substantially) back through time due to numerous factors that include technology and record keeping. Although the technique is based on relative mean sea level changes, the information gleaned could be further enhanced through consideration of land form movements (where relevant), particularly as the length of collocated continuous GPS measurements increases.

CONCLUSION

Based on extensive testing of time series analytics against the variety of complex signals and noise embedded within ocean water level data sets, SSA has proved an optimum choice for resolving the trend component with improved temporal precision for long, individual records (Watson, 2015a; 2015b).

These improved techniques are far more instructive than traditional methods used to date and provide a refreshing pathway forward to resolve some of the considerable ongoing professional debates over measures of acceleration in mean sea level records. This procedure is currently being developed into an analytical package for sea level researchers and is scheduled for release in 2016 as part of the R Project for Statistical Computing (R Development Core Team, 2015).

By enhancing the temporal resolution of the mean sea level signal, researchers can be more confident of identifying real changes to this signal at the earliest possible point in time which in turn might indicate the realisation of key climate change thresholds. These techniques will improve understanding of regional (and more localised) scales of sea level rise influence to better inform adaptation planning for this threat around the coastlines of the world.

ACKNOWLEDGMENTS

The genesis of this research initiative to improve measures of acceleration in mean sea level records has benefited significantly through encouragement from the late Professor Bob Dean (amonst others). The author also acknowledges the guidance and advice provided by Associate Professor Nina Golyandina (Department of Statistical Modelling, Saint Petersburg State University, Russia) in relation to the Rssa Package and SSA.

LITERATURE CITED

Alexandrov, T. and Golyandina, N., 2005: Automatic extraction and forecast of time series cyclic components within the framework of SSA. *Proceedings of the 5th St.Petersburg Workshop on Simulation* (St.Petersburg State University, St.Petersburg), pp. 45–50.

Alexandrov, T.; Bianconcini, S.; Dagum, E.B.; Maass, P. and McElroy, T.S., 2012. A review of some modern approaches to the problem of trend extraction. *Econometric Reviews*, 31(6), 593-624.

Baart, F.; Van Koningsveld, M. and Stive, M., 2011. Trends in sea-level trend analysis. *Journal of Coastal Research*, 28(2), 311-315.

Bindoff, N.; Willebrand, J.; Artale, V.; Cazenave, A.; Gregory, J.; Gulev, S.; Hanawa, K.; Le Quéré, C.; Levitus, S. and Nojiri, Y., 2007. *Observations: in Climate Change and Sea level, Climate Change 2007: The Physical Science Basis.* Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Calafat, F. and Chambers, D., 2013. Quantifying recent acceleration in sea level unrelated to internal climate variability. *Geophysical Research Letters*, 40(14), 3661-3666.

Cazenave, A.; Henry, O.; Munier, S.; Delcroix, T.; Gordon, A.; Meyssignac, B.; Llovel, W.; Palanisamy, H. and Becker, M., 2012. Estimating ENSO influence on the global mean sea level, 1993–2010. *Marine Geodesy*, 35(sup1), 82-97.

Church, J.A. and White, N.J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, 33(1).

Church, J.A. and White, N.J., 2011, Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics*, 32(4-5), 585-602.

Donoghue, J.F. and Parkinson, R.W., 2011. Discussion of: Houston, J.R. and Dean, R.G., 2011. Sea-Level Acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses. *Journal of Coastal Research*, 27 (3), 409-417, *Journal of Coastal Research*, 27(5), 994-996.

Douglas, B.C., 1992. Global sea level acceleration. *Journal of Geophysical Research: Oceans* (1978–2012), 97(C8), 12699-12706.

Douglas, B.C., 1997. Global sea rise: a redetermination. *Surveys in Geophysics*, 18(2-3), 279-292.

Fasullo, J.T.; Boening, C.; Landerer, F.W. and Nerem, R.S., 2013. Australia's unique influence on global sea level in

2010–2011. *Geophysical Research Letters*, 40(16), 4368-4373.

Foster, G. and Brown, N., 2015. Time and tide: analysis of sea level time series. *Climate Dynamics*, 45, 291–308.

Golyandina, N.; Korobeynikov, A.; Shlemov, A. and Usevich, K., 2015. Multivariate and 2D Extensions of Singular Spectrum Analysis with the Rssa Package. *Journal Of Statistical Software*, 67(2), 1-78.

Golyandina, N.; Nekrutkin, V. and Zhigljavsky, A.A., 2001. *Analysis of time series structure: SSA and related techniques*. CRC press.

Golyandina, N. and Osipov, E., 2007. The "Caterpillar"-SSA method for analysis of time series with missing values. *Journal of Statistical Planning and Inference*, 137(8), 2642–2653.

Golyandina, N. and Zhigljavsky, A., 2013. *Singular Spectrum Analysis for time series*, Springer Science & Business Media.

Hamlington, B.; Leben, R.; Strassburg, M.; Nerem, R. and Kim, K.Y., 2013. Contribution of the Pacific Decadal Oscillation to global mean sea level trends. *Geophysical Research Letters*, 40(19), 5171-5175.

Hansen, J.M.; Aagaard, T. and Binderup, M., 2012. Absolute sea levels and isostatic changes of the eastern North Sea to central Baltic region during the last 900 years. *Boreas*, 41(2), 180-208.

Hay, C.C.; Morrow, E.; Kopp, R.E. and Mitrovica, J.X., 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, 517(7535), 481-484.

Holgate, S.J.; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamisiea, M.E.; Bradshaw, E.; Foden, P.R.; Gordon, K.M.; Jevrejeva, S. and Pugh, J., 2012. New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, 29(3) 493-504.

Houston, J.R. and Dean, R.G., 2011a. Sea-level acceleration based on US tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research*, 27(3), 409-417.

Houston, J.R. and Dean, R.G., 2011b. Reply to: Rahmstorf, S. and Vermeer, M., 2011. Discussion of: Houston, JR and Dean, RG, 2011. Sea-Level Acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses. *Journal of Coastal Research*, 27 (3), 409-417, Journal of Coastal Research, 27(4), 788-790.

Jevrejeva, S.; Grinsted, A.; Moore, J. and Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. *Journal of Geophysical Research: Oceans* (1978–2012), 111(C9).

Jevrejeva, S.; Moore, J.; Grinsted, A. and Woodworth, P., 2008. Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters*, 35(8).

Jevrejeva, S.; Moore, J.; Grinsted, A.; Matthews, A. and Spada, G., 2014. Trends and acceleration in global and regional sea levels since 1807. *Global and Planetary Change*, 113, 11-22.

Kemp, A.C.; Horton, B.P.; Culver, S.J.; Corbett, D.R.; van de Plassche, O.; Gehrels, W.R.; Douglas, B.C. and Parnell, A. C., 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology*, 37(11), 1035-1038.

Killick, R. and Eckley, I., 2014. Changepoint: An R package for changepoint analysis. *Journal of Statistical Software*, 58(3), 1-19.

Merrifield, M., S. Merrifield, and G. Mitchum (2009), An anomalous recent acceleration of global sea level rise. *Journal of Climate*, 22(21), 5772-5781.

Nicholls, R.J. and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, 328(5985), 1517-1520.

R Development Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Rahmstorf, S. and Vermeer, M., 2011. Discussion of: Houston, J.R. and Dean, R.G., 2011. Sea-Level Acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses. *Journal of Coastal Research*, 27 (3), 409-417, *Journal of Coastal Research*, 27(4), 784-787.

Stocker, T.; Qin, D.; Plattner, G,; Tignor, M.; Allen, S. and Boschung, J., 2013. Summary for Policymakers in Climate Change 2013: The physical science basis, contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, edited, Cambridge University Press, Cambridge, New York, USA.

Visser, H.; Dangendorf, S.and Petersen, A.C., 2015. A review of trend models applied to sea level data with reference to the "acceleration-deceleration debate". *Journal of Geophysical Research: Oceans*, 120(6), 3873-3895.

Watson, P.J., 2011. Is there evidence yet of acceleration in mean sea level rise around mainland Australia? *Journal of Coastal Research*, 27(2), 368-377.

Watson, P.J., 2015a. Development of a Unique Synthetic Data Set to Improve Sea-Level Research and Understanding. *Journal of Coastal Research*, 31(3), 758-770.

Watson, P.J., 2015b. Identifying the best performing time series analytics for sea-level research: in *Contributions to Statistics*, Springer Science & Business Media (in press).

Woodworth, P.; White, N.J.; Jevrejeva, S.; Holgate, S.; Church, J. and Gehrels, W., 2009. Evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology*, 29(6), 777-789.