What tide gauges reveal about the future sea level

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Abstract

Purpose - There is no doubt, that climate change will cause changes of the mean sea level (MSL). In the research program KLIWAS (www.kliwas.de) of the Federal Ministry of Transport, Building and Urban Development, the Federal Institute of Hydrology determines individual values for the potential rise of the MSL for certain stretches of coastlines with the aim to assess the vulnerability of planning ports and coastal structures. This important information on regional changes can be derived from tide gauge measurements. The study shows, that the simple linear or non-linear extrapolation from the long-term series is inadmissible, because in addition to a significant climate signal of the rise of the MSL, a dominant superimposition of variability on different time scales is present.

Methods - We describe both, the quantitative and functional changes of the MSL observed by tide gauges. Fuzzy logic is used to extend several shorter time series of tide gauges. To determine functional changes we use modern spectral analysis and filtering techniques. Examples include the impact of the North Atlantic Oscillation (NAO) on the sea level at the German North Sea coast. We calculate the acceleration of the sea level rise and compare the rise and the acceleration with global estimates.

Findings - It is possible to reduce the stochastic part of the tide gauge measurements, so that the rise and the acceleration of sea level rise can be calculated with reasonable increase in accuracy. The secular sea level rise of the 20th Century was of 1.4 mm $a^{-1} \pm 0.2$ mm a^{-1}. We show that physical inherent fluctuations must be considered. An increase of the variability is indicated. The targeted removal of individual variations results in a non-linear trend which can be extrapolated to future states. We propose to integrate such scientific methods in monitoring and planning concepts, in order to take into account the uncertainty of future changes.

Originality – New methods to estimate the non-linear future regional MSL, based on quality controlled measurements, uncertainty analysis, uniform time scales, land-subsidence, and particularly with regard to physical inherent fluctuations.

Keywords regional sea level, sea level variability, non-linear sea level rise, spectral analysis

Introduction

"Sea level is not level" - This simple statement by Gehrels and Long (2008) goes to the heart of the challenge in the determination of the future sea level, as it is essential for a sustainable coastal zone management. The sea level undergoes fluctuations on almost all spatial and time scales. For example simple tidal motion: high-tide and low-tide occurs on every position on the earth with different phases and different amplitudes. However, we understand the governing processes sufficiently well, so we can predict the tides for almost every coastal region on the earth (e.g. Foreman, 1977; Godin, 1991). On the other hand, prediction of water levels fails for longer periods, like for the next 10 to 100 years.

Although there is progress in understanding the long-period changes in global mean sea level (gMSL), some of the processes can only be described roughly. In particular, the melting of the ice sheets has been not adequately monitored in the past. In addition, it is assumed that the global melt results in quite different effects in different regions (Mitrovica, 2001). Thus, if the polar ice melts, the gravity pull decreases, i.e. the impact of the ice gets bigger, the further a specific region is located away from the origin of the melting-source.

The Intergovernmental Panel on Climate Change (IPCC, 2007) provides in the fourth report predictions of the gMLS, which are separated into different emission scenarios. According to them the gMSL secular rise of the gMSL in the 21st Century will be in a span of 0.2 m to 0.6 m (2100 AD). This global numbers based on physical relationships like thermal expansion and ice sheet surface mass balance. However, the IPCC (2007) states also, that the ice dynamics may be underestimated. Therefore, in recent times so called "semi-empirical" models (i.e. Rahmsdorf, 2007; Vermeer and Rahmstorf, 2009) established. These models base on suspected, rather than real physical links, between global temperature and global sea level rise. It was shown that the correlation is open to doubt with these models, i.e. Schmith et al. (2007) show that estimation of the regression coefficient is not robust. For comprehension: specific numbers, that are calculated by the semi-empirical models, are in a range from 0.5 m to 2 m, i.e. significantly higher than in the IPCC report.

"How useful are these predictions in practice ?" - Gehrels and Long (2008) questioned with regard to the regional change of the mean sea level (rMLS). Here, we start our study about what tide gauges reveal about the future sea level. With one example region - the southern German Bright - we address this question. In this region, there are tide gauge measurements of a length in some cases more than one hundred years. Studies (Wahl, 2010, 2011) investigate into these gauges already in terms of historic linear long-term trends. However, we assume nonlinear future trends, so we have to look closer to the variability and to the acceleration of these time series. Therefore, we examine the inter-annual and decadal variations, to exclude their influence on the possible acceleration of long-term trends.

Methods & Data

In this study we investigate into a time varying sea level (ζ_t). A time-varying sea level is defined by a function of several processes:

$$\zeta_t = \overline{\zeta}_t + \alpha_t t + \beta t + \zeta Q_t + \zeta A_t + \zeta N_t + \zeta L_t \pm \zeta s_t \qquad (1)$$

In this formulation $\overline{\zeta}_t$ defined the theoretical null position of the water level, $\alpha_t t$ is the linear trend of the sea level, βt is a possible land subsidence, ζQ_t the atmospheric influence, ζA_t annual tides, ζN_t the Nodal tide, ζL_t long term periods and ζs_t are the stochastic residuals, which contains epistemic uncertainties as well works like a bad bank for not known inherent physical fluctuations.

Our study treats mainly the rMSL, which is defined as "the average height of the surface of the sea at a tide station for all stages of the tide over a 19-year period" (IHO, 1994). Hence, ζ_t is the monthly most likely sampled sea level by the tide gauges in this region, smoothed by a filter length of approximately 19 years. Additionally, this study addressed the parameter ζN_t and ζL_t to determine a better number for $\alpha_t t$. Land-subsidence is applied, the calculation procedure is an innovative one and will discussed later in the text. Atmospheric influence will be shown, but seen as aleatoric uncertainty and removed together with the annual tides into the bad bank.

Eight tide gauges provided by the Waterways and Shipping Administration of the Federal Government of Germany located in the southern German Bright are subject of this study: Emden Neue Seeschleuse, Norderney, Helgoland, Cuxhaven, Lt. Alte Weser, Wilhelmshaven, Bremerhaven and Husum. They are representative for the coastal region, a) due to their spatial extend and b) due to their distance to the coast-line. The overall scope is to find representative values for the mouth of the estuaries of the Ems, the Jade, the Weser and the Elbe. The major North Sea ports of Germany are located in these estuary systems. The lengths of the time series varies are between 56 years and 166 years. Three tide gauges (Cuxhaven, Lt. Alte Weser and Norderney) provide sea level data of more than 100 years. For this study we calculated a "theoretical gauge", which based on weighted averages of the eight gauges. The resulting theoretical gauge is representative for the mouths of the estuaries in this region.

Figure 1 shows the processing path of raw high-and low-water data to a secular course of rMSL for this theoretical gauge. First, the measurements are quality controlled and corrected for local datum shifts ((1.); Hein, 2010). The data sets contain semidiurnal information about high-tide and low-tide. To calculate a mean sea level from the tidal information we use the so called k-value approach (2.), a nearer description of this method can be found at Lassen und Seifert (1991). Next, we use a fuzzy logic approach (3.) to extend the shorter time series of some gauges towards secular and even towards longer periods. Because no comprehensive studies exist about the functional physical relationships on time scales of years or decades in the region, fuzzy logic is a quite effective method for the backwards prediction of the time series. A fuzzy inference system simulates the behavior of the sea level system by means of "if-then" rules of correlations in the different gauge data. Fuzzy logic based on fuzzy sets and membership functions, which depict the tide gauge measurements to fuzzy sets and towards suitable logical operations on these quantities and their inference. Fuzzy logic is also excellent with an additional quality control: with a comparison between trained and measured time series we see rather good any discontinuities, outliers and systematic errors in a single time series. The uncertainty of the predicted time series by fuzzy logic must be seen in relation to the aleatoric uncertainty of the system. In general the uncertainty of the reconstructed time series is below 1 cm for yearly averages, which is less than 5 % of the natural variability. However, the fuzzy logic we use in this study results in not adequate extreme value prediction.

Moreover, we include land-subsidence into the data set (4.). Here we use an innovative method: The Land-subsidence (βt) is calculated by recognizing both, geodetic (IKÜS, 2008) and hydrologic data sets. We use a least squares fit between the sinking rates from long-term trends of the different tide gauge observations and the geodetic observations from the IKÜS-Report to reduce the epistemic uncertainty of βt. The uncertainty is defined as difference between geodetic and hydrologic observations, which leads to a a-priori uncertainty of: $\sigma\beta t_{pre}$ = ±0.6 mm a^{-1}). To reach a solution, we must reduce the degrees of freedom: We assume that the rise of the rMSL in the spatial limited coastal area is defined by a linear function, which implies that differences between the observed values of sea level rise at different gauges is a result of both, small scale subsidence and stochastic uncertainty. Secondly, we assume that the mayor uncertainty of the geodetic dataset is defined by the general bearing of the network, rather than by the point to point observation uncertainty of the geodetic methods. The bearing of geodetic networks is an addressed challenge for geodic observations of crustal movements (Baldi and Unguendoli, 1987). Including both assumptions, the procedure of a least squares fit allows us to reduce the uncertainty of land-subsidence to a sufficient accuracy (a-posteriori) of about $\sigma\beta t_{post} = \pm 0.2$ mm a^{-1}.

To get an overall regional value we calculate the rMSL, based on the definition by the IHO (1994) from the overall monthly mode of the tide gauge time series (5.). The different modes of the tide gauges are weighed by the power of the inverse distance toward the mouth of the estuaries. The result is a "most-likely" theoretical gauge, which is quite perfect to analyze non-linear changes of the rMSL. For the analysis, first, we use a frequency based Monte Carlo singular spectrum analysis of the second derivative (6.). This method is a further development of the Monte-Carlo autoregressive padding (MCAP; Wahl et al., 2010). If anyone uses a low-pass filter, there is the general problem of the boundary area of the time series, since the filter equation is difficult to solve in this region of the time series. Wahl et al. (2010) show a solution to bypass this problem, they describe the boundaries of the dataset with a stochastic process – by white noise. In contrast to their method, however, we use the second derivative for predicting the boundary values and calculate the white noise Monte Carlo simulation in the frequency space (Little, 2007). This takes into account that the variability of sea level rise describes rather Brownian or pink noise process, than a white noise process. As Wahl et al. (2010) we use a least squares fit to find values for ζ_t at the boundary and integrate the time series back into the sea level.

Finally, we use continuous wavelet transformations (CWT) as an additional analysis method (7.). Here, we do not want to describe the mathematics of CWT in detail, the CWT is adequately described elsewhere (e.g. Daubechies, I., 1992; Torrence and Compo, 1998). A wavelet transform requires the choice of a transformation function, a so called "mother wavelet", therefore we choose a Morlet-Wavelet. A Morlet Wavelet is a sine-function with a Gaussian envelop, i.e. Grosmann and Morlet (1984) describe this wavelet-form. For better numerical results of the analysis we remove the linear long-term before the CWT and we add the trend after the CWT again on the scale dependent visualization.

Results & Discussion

The rMSL for the last 166 years at the mouths of the estuaries in the southern German Bright is shown in Figure 2a. In this figure, all values before 1905 must be taken with care, simple because, although the extension of all gauges toward 166 years, before 1905 finally the time series based only to one tide gauge. From 1906 ongoing fuzzy logic allows the quality control of the rMSL. From the MSL of the theoretical gauge we estimate a secular sea level rise in the last century (1908 – 2008) of $\alpha_t t$ = 1.4 mm a^{-1} ± 0.2 mm a^{-1}. This is a reasonable value, as it is the same derived by Woodworth et al. (2009) for the coastline of the United Kingdom. However, it is less the global sea level rise, which is almost 20 % higher than in the North Sea. For the rMSL an additional land-subsidence increases the effect of the sea level rise (the green dashed line in Figure 2a visualizes the effect of the land-subsidence). We calculate a regional mean hydrologically calibrated value of almost βt = 1.0 mm a^{-1} ± 0.6 mm a^{-1}. The uncertainty of 0.6 mm a^{-1} is mainly driven by the spatial variability of the vertical motions (IKÜS, 2007), the epistemic uncertainty was reduced (see Methods). For common time scales of future planning the subsidence can be taken as constant, but must be proven for every spatial region.

There should be no discussion that the rMSL was rising significantly between the beginning of the last century until 1960, when a pronounced break in the rise let the sea level decrease until 1980. Later the rMSL rises again. A nearer view into the rise of the rMSL gives Figure

2b, which shows the first deviation of the rMSL. Although we use a 19 year smoothing, we can see that the rMSL underlies pronounced fluctuations – and we think that the variability is deterministic rather than stochastic nature. The orange line represents reconstructed fluctuations by a Fourier-series, which do not fit well at the beginning of the time series. A result of uncertain measurements or zero point detection during this time? - there is no chance to control this anymore. The mayor frequencies of the variability in Figure 2a are approximately 35 and 75 years. Wahl et al. (2011) reported an acceleration after 1970 and an intensification of the acceleration from the 90's of the last century. On a first view the rMSL at the mouths of the German estuaries seems to accelerate - the highest rates of sea level rise were measured during the last decade. However, if we take the orange line into account (deterministic fluctuations), the acceleration is the result of interference of long-term processes. We prove the acceleration by the use of the second derivation (figure 2c), where no long-term trend is visible.

Figure 3 shows a nearer inspection of the variability of the regional monthly mean sea level represented by a wavelet analysis in relation to the long-term linear trend. The long-term trend is small relative to the variability on most scales. Thereby, the greatest variability is to find on scales, which are representative for typical atmospheric timescales of months to several years. Sea level periods smaller than one year seem to be white noise process, related to quasi random storm events. However, ee estimate, that the monthly mean sea level is positively correlated with the NAO on time-scales of 4 to 7 years (≈ 40 - 80 months). The variability on scales of the Nodaltide (223 month) is indicated since 1930 and before 1900. Periods of 30 to 40 years (≈ 400 months) seem to increase with increasing rMSL. Theoretically, this is possible with a change of the self oscillation of basin (here: North Sea or North Atlantic), because self oscillation is related to the depth (sea level) of the basin. However, such effects are not yet reported for the North Sea or the North Atlantic. The results of the CWT confirm the variability of the sea level rise (figure 2b), again fluctuation on periods of 30 to 40 years and a period of approximately 70 to 75 years (≈ 900 months).

We compare the history of gMSL and rMSL to get an idea of the rise for future planning proposes. Therefore figure 4 compares the Church and White dataset for the gMSL with the results of out theoretical gauge. Figure 4a presents both gMSL and rMSL. The lower rise of the sea level in the southern North Sea cannot be neglected. Figure 4b images the probability density functions of the rise of the gMSL and the rMSL. Here one difference is obvious: the regional sea level rise in strongly influenced by long term oscillations. This results in a bi-modal probability distribution, while for the gMSL a clear mode is visible. We can estimate that for periods of strong regional sea level rise this rise overcomes the global sea level rise, but on the other hand during the other periods, the rMSL rise is much lower than the rise of the gMSL. Figure 4c is the probability density distribution of the acceleration of the MSL (second derivation). For the rMSL an acceleration in the last century can be excluded, however on the global scale an acceleration seems likely (see also Church and White, 2006). A deceleration during the last century, reported for the US tide gauges (Houston and Dean, 2011), can be estimated in the long-term mean (the modal of the acceleration is negative), but this is not significant. According to (Jevrejeva, 2008) gMSL start to rise 200 years ago - this could not be proved with our data series.

Conclusions

To investigate into future rise of the MSL on a regional scale it is more necessary to investigate into the functional changes, which are associated with significant oscillations. Often the future estimations of the rMSL based on assumptions using global estimates.

According to the updated data-set from Church and White (2006) the global sea level has the tendency to accelerate. In the region studied here, the tide gauges measurements show no long term trend in the second derivation. Moreover the sea level rise is only $\alpha_t t$ = 1.4 mm a^{-1} ± 0.2 mm a^{-1} and therefore 20 % less than the global rise. In addition about βt = 1 mm a^{-1} ± 0.6 mm a^{-1} land-subsidence is evident as a linear long-term trend, which has also an important small scale regional variability.

Hence, the tide gauges reveal, that the future sea level at the German North Sea estuaries will rise less than in the global mean. Including the land-subsidence at the southern North Sea the numbers given by the IPCC (2007) are more likely than recent semi-empiric calculations, which seem to overestimate recent rise in this region. Although the extreme values of sea level rise originated from the semi-empiric models are absolutely unlikely in the southern North Sea, we can not anticipate, that in future governing processes change and thus an extreme acceleration of the rMSL is not generally impossible. The regional inhomogeneous reaction of sea level rise due to melting (Mitrovica, 2001) is confirmed by our study.

In the introduction we ask how useful gMSL predictions are in practice. According to the historic rises and variability, both on global and regional scale, we conclude that the global predictions are just numbers and they should not be used carelessly for practical planning purposes. Moreover, the expected increase of the natural variability discovered in figure 3 must be recognized for future regional sea level estimations. A change in variability may be associated with the fact, that while the long-term average increases less than expected, over a period of decades, the rMSL exceeds the suggested values and falls back to lower values later on. In general, the lengths of quality controlled tide gauges time-series are too short to estimate a possible future acceleration. So we conclude that the tide gauges reveal, that in the next years and decades the monitoring of the sea level - including both quality management and continuous scientific analysis - is the most important adaptation challenge for planning proposes.

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Figures

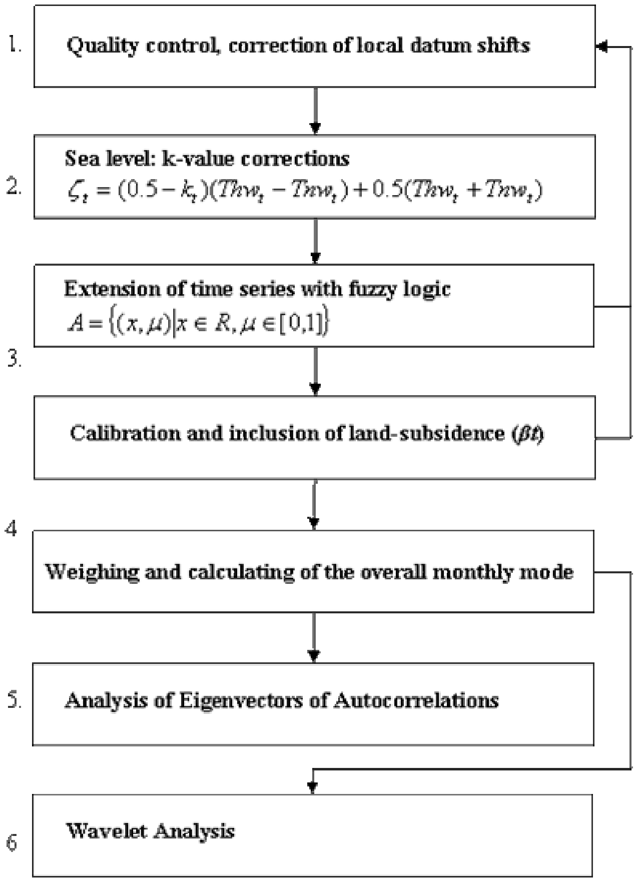

Figure 1: Processing path from raw high- and low-water data to a non-linear sea level rise.

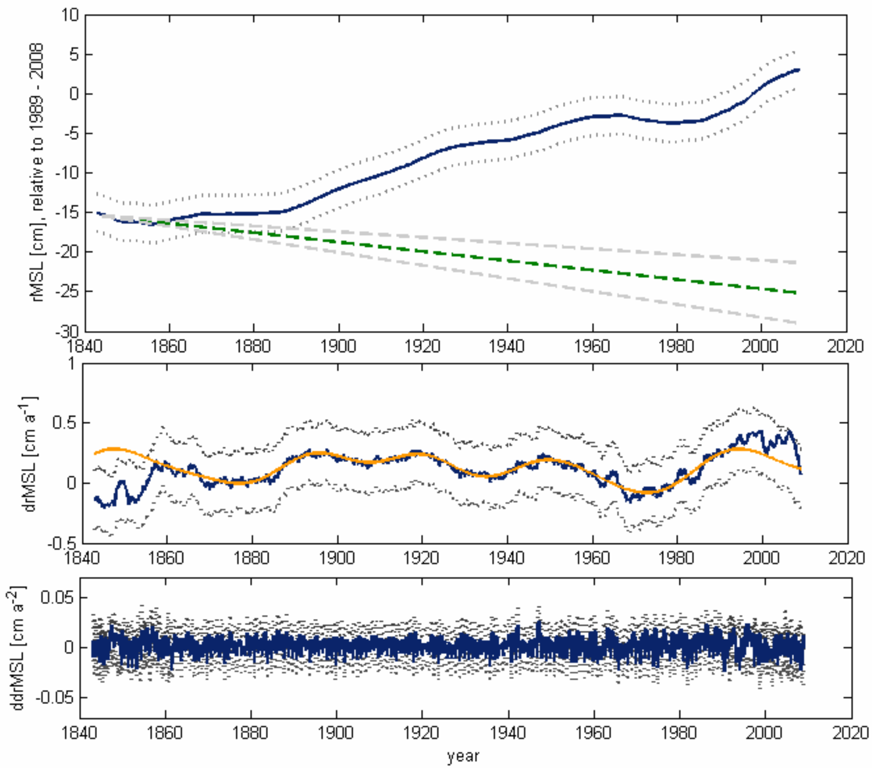

Figure 2: a) Regional sea level and land-subsidence, b) rise of the regional mean sea level and long-term fluctuations, c) acceleration of the regional mean sea level

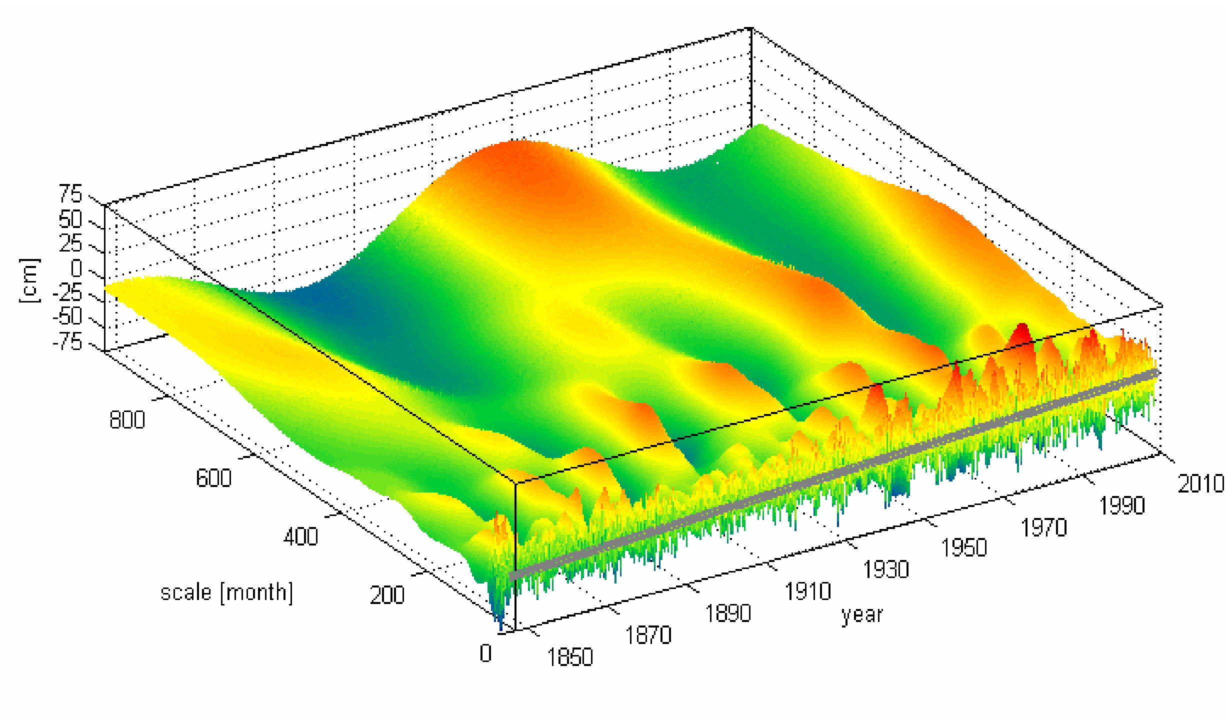

Figure 3: Wavelet spectrum of the regional monthly mean sea level. Grey line: linear long-term trend.

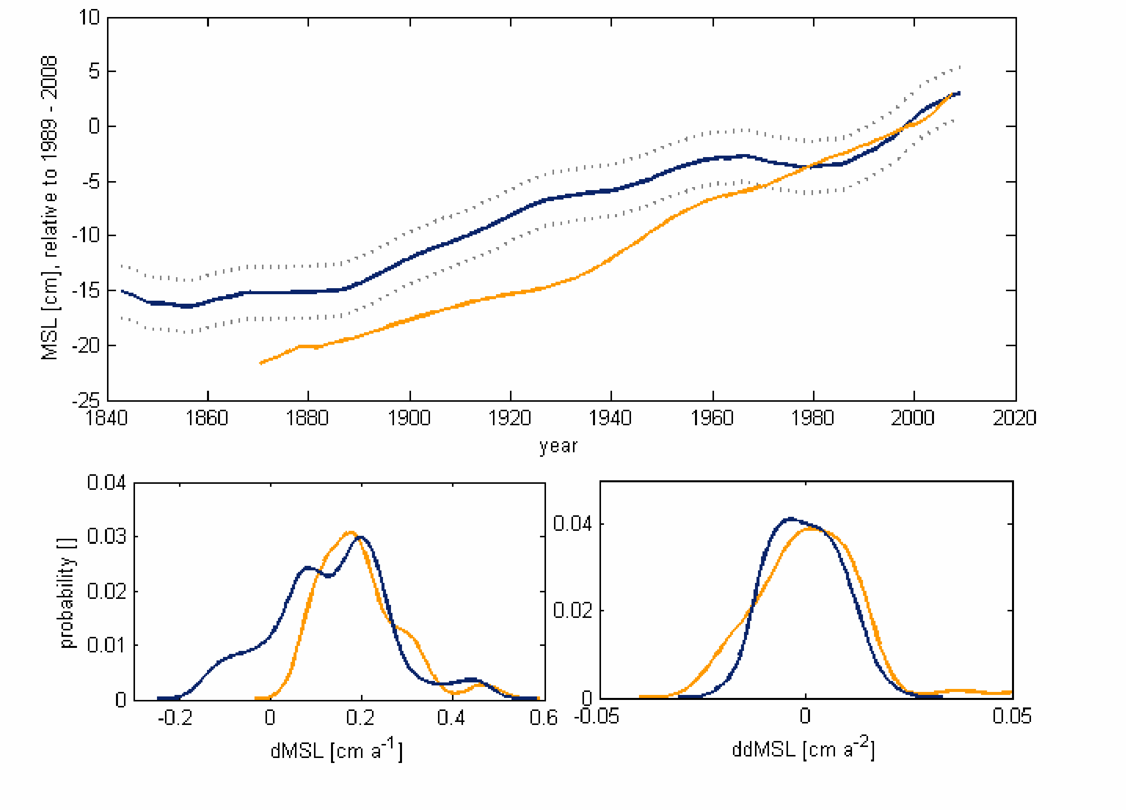

Figure 4: a) regional (blue line) vs. global (orange line) mean sea level, b) probability density functions of regional (blue line) vs. global (orange line) mean sea level rise, c) probability density functions of regional (blue line) vs. global (orange line) mean sea level acceleration.