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Assessment of present sea level velocity and acceleration in Europe

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ABSTRACT

There is an open debate about the present sea level velocity and acceleration in Europe. Despite some uncertainty due the quality and length of the records, on average the European tide gauges show sea levels with very small velocity and negligible acceleration at the present time The average sea level rise for Europe is -0.432 mm/y with a 95% confidence interval of 0.391 mm/y (76 tide gauges of average record length 101.0 years, average completeness 91.9%). Without considering the stations in Sweden, Finland and Norway, the average sea level rise is 1.35 mm/y with a 95% confidence interval of 0.36 mm/y (46 stations of average record length 101.6 years and completeness of 91.34%). Because of this present lack of acceleration about the low velocities of the tide gauge results, the lower bound of future sea level rise scenarios should be lowered to the simple continuation of the trend measured so far.

INTRODUCTION

Sea levels around the world are certainly rising, however the debate if they are presently accelerating or not is still open. Reconstructions of the global mean sea level (GMSL) based on tide gauge and proxy sea level records show that the sea levels were rising with a lower rate in the past centuries and are rising much faster since recently, with the discussion focused on the precise timing the sea levels started to rise quickly and if the accelerating behaviour is still present or even increased right now.

Jevrejeva et al.[8] present a reconstruction of the GMSL since 1700 calculated from tide gauge records. The authors compute average sea level acceleration up to the present of about 0.01 mm/y^2. The acceleration appears to have started at the end of the 18th century. Their GMSL rose by 6 cm during the 19th century and 19 cm in the 20th century. The authors conclude that if the conditions that established the acceleration continue, then sea level will rise 34 cm over the 21st century. The authors recognised that superimposed on the long-term acceleration are quasi-periodic fluctuations with a period of about 60 years.

Gehrels and Woodworth[7] also discuss accelerations and inflexions in recent sea-level records as they are known from tide gauge datasets. They comment that such records are generally too short to shed light on the question when modern rapid rates of sea-level rise commenced, and propose to also consider proxy sea-level records. In their review the authors compare recent proxy and instrumental sea-level records from the North Atlantic, Australia and New Zealand with the long-term (linear) rate of relative sea-level change that prevailed in the centuries and millennia before the 19th century. For seven coastal sites the authors determine the start of recent rapid sea-level rise by identifying the time when sea-level rise first departed from the long-term background rate. The authors find that within a 40 year period, centred on 1925, sea-level rise in all sites started to exceed the late Holocene background rate consistently with local tide-gauge records and also with global and regional tide-gauge compilations. The authors conclude that proxy and instrumental sea-level datasets record a similar 20th century inflexion.

These reconstructions are certainly correct, but certainly also not accurate enough to assess not the actual value of the present acceleration, but also the simple presence or absence of any present acceleration. The question point is the presence or the absence of an acceleration of sea levels over the last few decades as predicted by the IPCC models as a result of the predicted global warming.

The first problem is the variable demography of the population considered in the statistics, with the number of tide gauge records serving the evaluation of the GMSL changing over the time, and their distribution to cover the world oceans. No tide gauge currently operated is recording since the 1700s. At the best, the tide gauges of PSML (2013) are recording with an approach close to today’s technology since the early 1800s. The tide gauges covering the 1800s are very scattered. All the Pacific Ocean has for example only very few tide gauges (less than 10) extending more than 100 years with continuous operation, and 1 single tide gauge recording since 150 years (San Francisco). The Pacific Ocean is the largest division of the World Ocean and covers about 46% of the Earth’s water surface and about one-third of its total surface area making it larger than all of the Earth’s land area combined. If about one half of the world oceans are not covered at all before the 1850s and are covered by 1 single tide gauge until the end of the 1800s, with a proper coverage still presently missed, therefore the margins of uncertainty in any GMSL reconstruction are huge because the missed information cannot be replaced with reconstructions without introducing large uncertainties. In the present and recent past there are a number of tide gauges recording in a geographical area much larger than the number of tide gauges recording in the past. Furthermore, the information that may be inferred from the tide gauge also depends on the quality and length of the record as discussed later.

The second problem is the naturally oscillating behaviour of the oceans exhibiting different periodicities, from hours to days to months to years to decades, with the quasi-60 years periodicity introducing significant requirements in terms of length and completeness of a tide gauge records to permit the evaluation of a rate of rise of sea levels prior to the evaluation of the acceleration. The quasi-60 year oscillation of the climate parameters is not a novelty[22], but this feature is often disregarded in the most part of the literature. Chambers, Merrifield and Nerem[5] clearly state the presence of a quasi-60 years oscillation in sea levels. According to the authors the averaging of tide gauges over regions shows that the phase and amplitude of the fluctuations are similar in the North Atlantic, western North Pacific, and Indian Oceans, while the signal is shifted by 10 years in the western South Pacific and the only sampled region with no apparent 60-year fluctuation is the Central/Eastern North Pacific. As shown by Parker, 2013a,b,c, the presence of a quasi-60 year multidecadal oscillation requires records of length exceeding the 60-70 years of continuous recording to permit the assessment of a long term velocity in the tide gauge time series. Without this minimum requirement satisfied, the apparent velocity may be order of magnitudes larger than the legitimate long term value, as clearly shown in the analysis of the long term tide gauges with different time windows by Parker, 2013a,b,c.

The third problem is the estimation of the acceleration from this velocity. The velocity obtained by linear fitting of more than 60-70 years of data is not constant but continues to oscillate even after more than 100 years, and rather than a present value of the acceleration computed as the time derivative of this velocity, it make sense to compute an average over the last few decades to assess the presence or the absence of a present acceleration. If this acceleration oscillates about zero from small positive to small negative values, and on average this parameter is very close to zero, small positive or small negative over the last 2 decades, then there is no possible claim of acceleration over the last 2 decades[18-20].

The fourth problem is estimating the error in the velocity and acceleration computed through the statistical analysis of time series. If y is the monthly average mean sea level (MSL) and x is the time, by linear y=a”’x +c fitting of the recorded monthly averaged mean sea levels x_i, y_i the statistical analysis provides standard error values, the regression sum of squares and the residual sum of squares all indicating how close to linear is the recorded time series. The statistical analysis does not tell us how accurate are the measurements collected in every location and more generally how reliable is the estimation of the rate of rise as the first order coefficient in view of missed values and record length, and finally how precise a limited compilation of scattered tide gauges of various length and quality may be representative of the world's oceans behaviour. The coefficient of determination of every individual linear fitting tells us absolutely nothing about the accuracy of the GMSL computation.

The major mistake presently made in analysing sea level records is being selective in filtering in and out the information. An example is the computation of the sea level rise by using only the data recorded over the last 17-18 years in only 16 stations of the 86 available for Australia and comparing these sea level velocities with other velocities obtained somewhere else with different time windows in previous times to assess the accelerating behaviour[1,2]. Because of the relevance of the multi decadal oscillations, without at least 60-70 years of data there is no opportunity to compute a proper velocity.

It has been shown in recent papers[18-20] that the long term tide gauges consistently show periodic oscillations about an almost perfectly linear trend since the beginning of the 1900s and it has been suggested that what has been claimed as present sea level acceleration and presently higher than before rates of rise of sea levels is only the result of the selective focusing on the latest valley to peak movement of the quasi-60 years multi decadal oscillation. The present manuscript addresses the rate of change and the acceleration of sea level in Europe from an analysis of long tide gauge records. The points raised in the paper are the importance of having long and high quality tide gauge records for sea level change estimation, and the influence that multi-decadal oscillations have on resulting trends, not exactly new points but very important ones in the context of sea level research.

THE MULTI-DECADAL OSCILLATING LONG TERM TIDE GAUGES

The problem of sea level trends is that quality and length of the record and method of analysis play an important role in providing reliable estimates[18-20]. The length of the record is a major issue. The quality of the record is also important. Discontinuous operation, changes in the instrumentation, adjustments always reduce the reliability of the record.The lack of significant global coverage until the very recent past and the need to consider records long enough to cover at least the most important multi decadal oscillations are the major factor producing uncertainties in the assessment of sea level rises and accelerations at present[18-20].

Since multi decadal oscillations are generally present in all the worldwide locations and are generally and specifically for Europe of longer time scale 60 – 70 years[5,18-20,22], it is necessary to consider time series with at least 100 years of continuously recorded data to determine the length and quality requirements of tide gauge results and define the procedure to compute the present velocity and acceleration of sea levels from these data.

Figure 1 presents the measured monthly sea levels[21], the linear trend with all the data considered, the periodogram of the oscillations about the linear trend, the sea level rises (SLR) computed at any time by considering 20, 30, 40, 50 and 60 year time windows and all the data, the present SLR computed with time windows from a decade to the full record length, and finally the acceleration for Maassluis, Netherlands and Bergen, Norway.

Bergen, Norway (Station ID: 58, Latitude: 60.4, Longitude: 5.3) has a time span of data: 1915 – 2011 and Completeness (%): 95. The dataset for Bergen has been revised. According to the Norwegian website the data set begins 01/01/1915. However PSMSL (2012) hold data for 1883-1889 this does not appear on the Norwegian website. The composite record considered here is obtained by filling the substantial gaps interpolating the data from the neighbouring years. No shift is operated in the data for 1883-1889. These issues affect the reliability of this record.

Maassluis, Netherlands (Station ID: 9, Latitude: 51.916667, Longitude: 4.25) has a time span of data: 1848 – 2011 and Completeness (%): 100. This is possibly one of the best quality tide gauges, with no issue affecting the reliability of the record. This result that represents the relative variation of sea level vs. the land (what is of interest for coastal planning) for the specific locations. This trend is very well reproduced in all the other long term tide gauges spanning more than a century available worldwide, from Seattle to San Francisco, from San Diego to Baltimore, from Honolulu to Sydney, from Galveston to Fernandina Beach, from Portland to Philadelphia[18-20]. The rate of rise of sea level may differ considerably in between locations because of subsidence, isostasy and other phenomena, but the regular natural oscillations about the linear trend which is much the same for the last 100 years immediately suggest that there is no present acceleration of sea level rise.

To compute a reasonable sea level velocity and assess the presence or absence of a positive acceleration, particular attention has to be paid to the multi decadal oscillation of about 60-70 years that may produce wrong estimations when not enough data are available. Fortunately, for Bergen and Maassluis enough data is available to properly compute the sea level velocity distributions in time and to show the oscillatory behaviour of the parameter especially when computed with short time windows.

The sea level rise computed with 20, 30, 40, 50 or even 60 years of data largely oscillates. The present values have been previously computed in time. For Bergen, the 30 years SLR has a positive peak in 2002 and a previous peak 63 years before in 1939.

For Maassluis, the 30 years SLR has a positive peak in 1989 and a previous peak 71 years before in 1917. The many spikes suggest the relevance of other oscillations having different periodicities shorter and longer. The sea level rise computed with all the years of data also oscillates. A reasonable value is obtained only after 60-70 years of recording in both Bergen and Maassluis. After this delay, this velocity is stable.

The acceleration may be computed as the first derivative with respect to time of the velocity. The 12 months moving average clearly show oscillating values very close to zero to conclude that there is no detectable component of acceleration for both Bergen and Maassluis. The average acceleration over the last 6 decades is $3 \cdot 10^{-5}$ mm/y^2 in Maassluis and $1 \cdot 10^{-4}$ mm/y^2 in Bergen. Considering the measurement accuracy and the accuracy of the computational procedure for the velocity and the acceleration, these numbers are well below the accuracy of the evaluation.

As recently proposed by PSMSL[21] the data collected before the 1900 are neglected in the analysis of the Maassluis and Bergen data repeated in Figure 2. The conclusions are similar to those that can be inferred in Figure 1. There is no sign of a significant positive acceleration over the last two decades, beibng the module of the acceleration well below any reasonable accuracy limit.

THE EUROPEAN AVERAGE 60+ TIDE GAUGE BEHAVIOUR

A proper analysis of the longer tide gauges of the world with quality issues properly addressed indicates the lack of positive acceleration, see Figures 1 and 2 and Boretti, 2012; Boretti and Watson, 2012; Parker, 2013a,b,c; Morner, 2010a,b,c; Morner, 2011a,b; Houston and Dean, 2011; Watson, 2011; Wöppelmann et al.., 2009; Henry et al., 2012; Hannah and Bell, 2012; Donner, 2012. The rate of rise of sea levels may then be computed along the coastline by using even shorter tide gauge records spaning however more than 60 years by the simple linear fitting of all the data. These sea level rises may change as soon as new data are made available but this is not a sign of positive or negative accelerations, just the presence of the oscillations. If the record length is shorter than 60 years, the changes may be larger.

A compilation of sea level rises for 76 European locations is shown in NOAA[17] and reproduced in TABLE 1. The table shows that the sea level is not even increasing on average in the proposed 76 different stations of Europe (the average SLR is -0.432 mm/y with a 95% confidence interval of 0.391 mm/y, average record length 101.0 years, average completeness 91.9%). The regular oscillation about the linear trend is already evident in the graphs of monthly averaged MSL vs. time proposed in NOAA (2013), but in case the analysis of Figures 1 and 2 may provide even further confidence on the lack of any present acceleration.

Without considering the stations in Sweden, Finland and Norway, the remaining 46 stations have an average record length of 101.6 years, completeness of 91.34%, SLR of 1.35 mm/y and 95% confidence interval of 0.36 mm/y.

The sea level rises where more than 60 years of data are available are the most reasonable parameters to be used to infer the lower bound of the 2020s to 2080s sea level rise needed in coastal planning. What is relevant for coastal management is the local rise of the sea levels vs. the land providing the absence of any

TABLE 1 : SLR of European tide gauges recording since more than 70 years.

Station Name	First Year	Last Year	Year Range	% Complete	MSL Trend	+/- 95% CI	Station Name	First Year	Last Year	Year Range	% Complete	MSL Trend	+/- 95% CI
Barentsburg, Norway	1948	2010	63	93	-2.25	0.42	Gedser, Denmark	1898	2011	114	99	1.05	0.18
Tiksi, Russia	1949	2009	61	100	1.56	0.72	Kobenhavn, Denmark	1889	2011	123	98	0.67	0.21
Vardo, Norway	1947	2011	65	65	-0.32	0.51	Hornbaek, Denmark	1898	2011	114	98	0.37	0.22
Andenes, Norway	1938	2011	74	61	-0.93	0.5	Korsor, Denmark	1897	2011	115	98	0.81	0.18
Narvik, Norway	1928	2011	84	88	-2.06	0.48	Slipshavn, Denmark	1896	2011	116	96	1.01	0.16
Heimsjo, Norway	1928	2011	84	96	-1.46	0.31	Fredericia, Denmark	1889	2011	123	99	1.09	0.11
Maloy, Norway	1943	2011	69	96	0.59	0.4	Aarhus, Denmark	1888	2011	124	96	0.63	0.11
Bergen, Norway	1883	2011	129	76	-0.52	0.2	Frederikshavn, Denmark	1894	2011	118	96	0.14	0.15
Stavanger, Norway	1919	2011	93	91	0.42	0.22	Hirtshals, Denmark	1892	2011	120	96	-0.17	0.21
Tregde, Norway	1927	2011	85	96	0.26	0.2	Esbjerg, Denmark	1889	2011	123	98	1.23	0.26
Oslo, Norway	1885	2011	127	77	-3.17	0.3	Cuxhaven 2, Germany	1843	2008	166	100	2.53	0.16
Smogen, Sweden	1911	2011	101	100	-1.85	0.26	Zeebrugge, Belgium	1942	2010	69	72	2.35	0.39
Goteborg - Ringon, Klippan & Torshamnen, Sweden	1887	2011	125	99	-1.19	0.36	Oostende, Belgium	1937	2010	74	93	1.78	0.25
Klagshamn, Sweden	1929	2011	83	99	0.64	0.4	Nieuwpoort, Belgium	1943	2010	68	67	2.53	0.44
Kungholmsfort, Sweden	1887	2011	125	100	0.02	0.25	Aberdeen I & II, UK	1862	2011	150	95	0.72	0.09
Landsort Norra & Landsort, Sweden	1887	2011	125	100	-2.84	0.3	North Shields, UK	1895	2011	117	93	1.91	0.14
Stockholm, Sweden	1889	2011	123	100	-3.81	0.32	Newlyn, UK	1915	2011	97	99	1.76	0.17
Ratan, Sweden	1892	2011	120	100	-7.75	0.39	Dublin, Ireland	1938	2001	64	99	0.07	0.42
Furuogrund, Sweden	1916	2011	96	100	-8.1	0.57	Dunkerque, France	1942	2011	70	60	1.71	0.4
Kemi, Finland	1920	2010	91	96	-6.99	0.63	Brest, France	1807	2011	205	89	1.05	0.08
Oulu/Uleaborg, Finland	1889	2010	122	95	-6.38	0.41	La Coruna I, Spain	1943	2010	68	98	1.53	0.43
Raahe/Brahestad, Finland	1922	2010	89	92	-6.85	0.66	Cascais, Portugal	1882	1993	112	93	1.27	0.15
Pietarsaari/Jakobstad, Finland	1914	2010	97	98	-7.29	0.57	Lagos, Portugal	1908	1999	92	78	1.5	0.24
Vaasa/Vasa, Finland	1883	2010	128	92	-7.33	0.34	Algeciras, Spain	1943	2002	60	81	0.43	0.3
Kaskinen/Kasko, Finland	1926	2010	85	97	-6.5	0.68	Malaga, Spain	1944	2010	67	82	0.65	0.5
Mantyluoto, Finland	1910	2010	101	98	-5.91	0.5	Marseille, France	1885	2011	127	97	1.25	0.14
Turku/Abo, Finland	1922	2010	89	98	-3.67	0.61	Genova, Italy	1884	1997	114	78	1.2	0.14
Foglo/Degerby, Finland	1923	2010	88	94	-3.75	0.59	Trieste, Italy	1905	2011	107	94	1.27	0.2
Hanko/Hango, Finland	1887	2010	124	88	-2.67	0.37	Bakar, Croatia	1930	2009	80	86	0.97	0.36
Helsinki, Finland	1879	2010	132	100	-2.33	0.34	Bourgas, Bulgaria	1929	1996	68	86	1.91	0.9
Hamina, Finland	1928	2010	83	98	-1.03	0.79	Varna, Bulgaria	1929	1996	68	95	1.22	0.85
Daugavgriva, Latvia	1872	1938	67	93	0.16	0.99	Constantza, Romania	1933	1997	65	95	1.37	0.97
Liepaja, Latvia	1865	1936	72	88	0.88	0.72	Sevastopol, Ukraine	1910	1994	85	97	1.26	0.78
Kaliningrad, Russia	1926	1986	61	86	1.84	0.89	Tuapse, Russia	1917	2010	94	99	2.44	0.58
Klaipeda, Lithuania	1898	2011	114	92	1.48	0.4	Poti, Georgia	1874	2009	136	94	6.59	0.29
Swinoujscie, Poland	1811	1999	189	96	0.8	0.12	Ceuta, Spain	1944	2009	66	96	0.52	0.29
Warnemunde 2, Germany	1855	2010	156	100	1.25	0.12	Ponta Delgada, Portugal	1978	2007	30	69	2.58	1.01
Wismar 2, Germany	1848	2010	163	100	1.41	0.1	Santa Cruz de Tenerife I & Tenerife, Spain	1927	2009	83	88	1.62	0.31

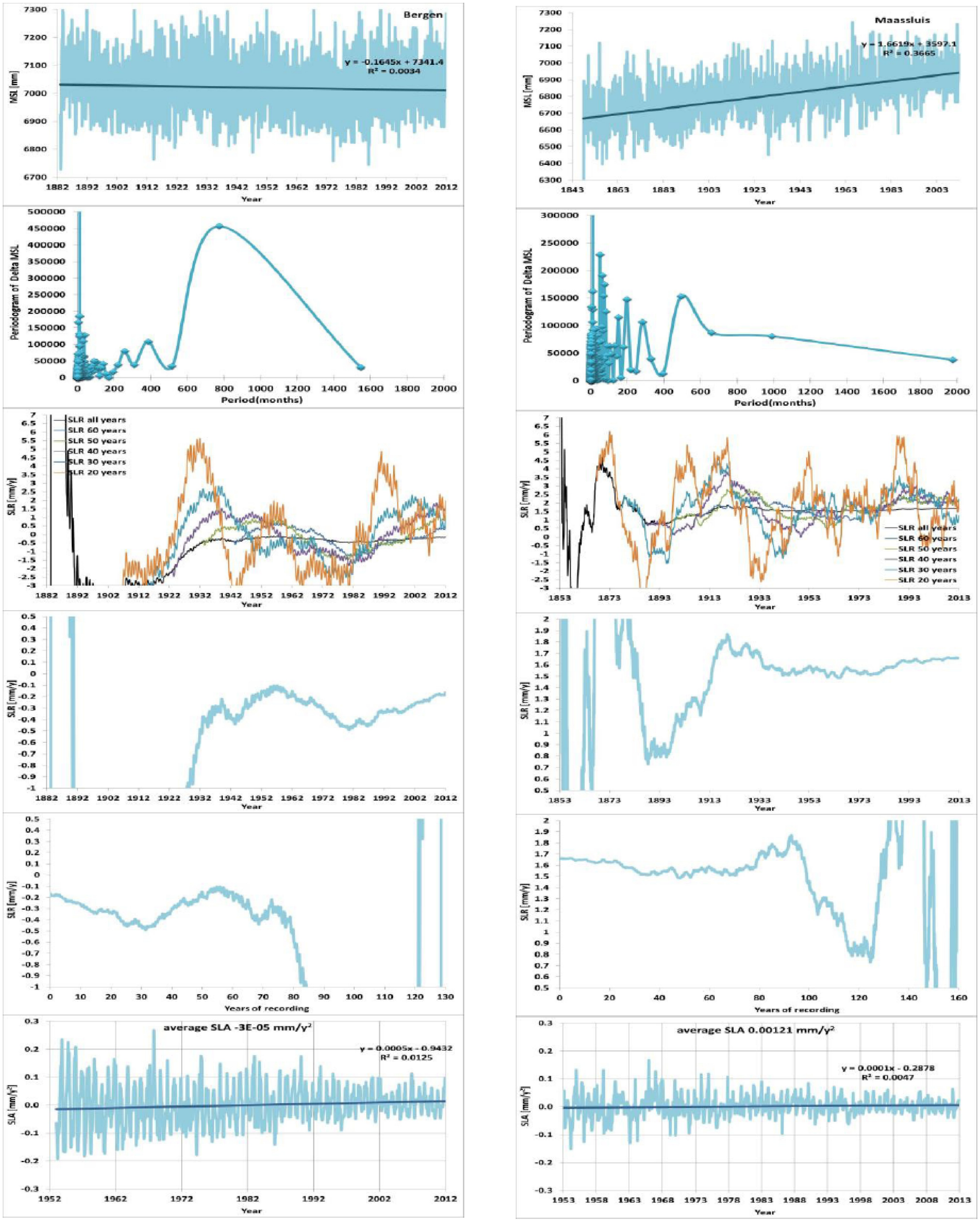

Figure 1 : Measured MSL (data from PSMSL, 2013), linear trend with all the data considered, periodogram of the oscillations about the linear trend, SLR computed at any time by considering 20, 30, 40, 50 and 60 year time windows and all the data, present SLR computed with time windows from a decade to the full record length, and finally the acceleration for Maassluis, Netherlands and Bergen, Norway

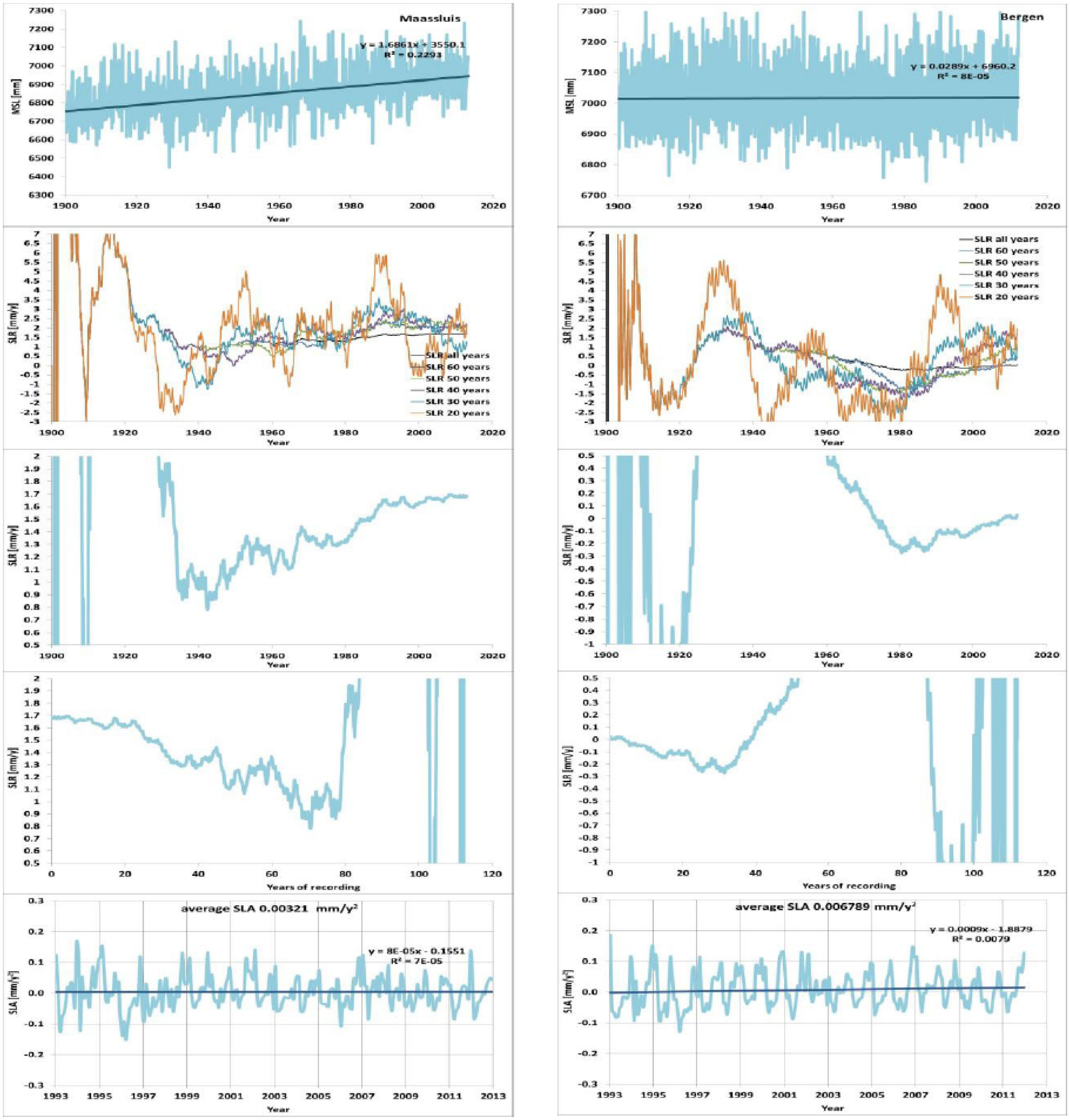

Figure 2 : Measured MSL (data from PSMSL, 2013), linear trend with all the data considered, periodogram of the oscillations about the linear trend, SLR computed at any time by considering 20, 30, 40, 50 and 60 year time windows and all the data, present SLR computed with time windows from a decade to the full record length, and finally the acceleration for Maassluis, Netherlands and Bergen, Norway. Only the data since 1900 are considered.

accelerating trend locally and globally. The sea level rises computed with less than 60 years of data should be used only with extreme caution. Similarly, a comment on the quality of data should be added to every station because possible biasing also reduces the reliability of the estimation.

The decrease of sea level of Norway, Finland and Sweden is due to the post-glacial rebound or glacial isostatic adjustment. This is the rise of land masses that were depressed by the huge weight of ice sheets during the last glacial period through a process known as isostasy and it affects Scotland, the Scandinavian Peninsula, Finland, Karelia, the Kola Peninsula, northern Denmark, Siberia, Canada, the Great Lakes of Canada and the United States, the coastal region of Maine, parts of Patagonia and Antarctica.

CONCLUSIONS

The sea levels are oscillating with important multi decadal periodicities, and more than 60 years of data of good quality are needed to assess the longer term sea level rise. Without enough length, or if the quality of the data is compromised, there is no opportunity to properly evaluate the present velocity and acceleration.

It has been shown that the long and medium term tide gauges of good quality have oscillating sea levels without any significant positive acceleration component. Because there is no sign of a positive acceleration locally or globally, it is therefore reasonable to assume that locally the sea level will continue rising with the current slope in the next few years.

The average sea level rise for Europe is -0.432 mm/y with a 95% confidence interval of 0.391 mm/y (76 tide gauges of average record length 101.0 years, average completeness 91.9%).

Without considering the stations in Sweden, Finland and Norway, the remaining 46 stations have an average record length of 101.6 years, completeness of 91.34%, SLR of 1.35 mm/y and 95% confidence interval of 0.36 mm/y.

The update of Table 1 may provide an indication of the presence or absence of any acceleration in the future. If all the SLR increases of a significant quantity, then there is acceleration. If some SLR increase and some others decrease, and on average the change is negligible small positive or small negative, then there is no acceleration.

Because of this present lack of acceleration about the low velocities of the tide gauge results, the lower bound of future sea level rise scenarios should be lowered to the simple continuation of the trend measured so far.

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