Precise determination of relative mean sea level trends at tide gauges in Adriatic

M. Repanić, T. Bašić
Croatian geodetic institute, Savska c. 41/XVI, 10144 Zagreb, p.p.19, Croatia.

Abstract. Relative mean sea level trends for nine tide gauges in Adriatic have been determined with high precision using common mean sea level variability. Respective tide gauges are Venezia – Punta Della Salute and Trieste in Italy; Koper in Slovenia; Rovinj, Bakar, Split – Rt Marjana, Split – Harbour and Dubrovnik in Croatia and Bar in Montenegro.

Annual and inter-annual sea level changes, which are driven by climate variations, make it difficult to calculate precisely the sea level trends. Averaging over a year removes seasonal changes. However, systematic effects from changes of meteorological parameters and associated ocean circulation that last for longer than a year are maintained, as well as long-periodic tidal effects. One can assume that such inter-annual changes are very similar for close sites, especially in closed seas such as Adriatic. Accordingly, common inter-annual variation of sea level can be determined for all nine tide gauges in question from annual means, under assumption that residual variations for each site are close to random. Such approach makes it possible to separate before mentioned systematic effects from eustatic rise of global sea level and effects of regional and local vertical land movements. However, to separate two latter effects reliable vertical land movement from several decades of GPS measurements are needed.

Through common adjustment of nine tide gauge time series of annual means from PSMSL, common mean sea level variability as well as relative mean sea level trends and mean sea level for each tide gauge have been determined. For 50-year period relative trends have been determined with standard deviations from 0.1 to 0.3 mm/yr (later is for data-gauges with shorter records). Values of annual common mean sea level variability are determined with standard deviations of less than 4 mm.

Once when GPS record reach required length for precise determination of vertical land movement with respect to the ellipsoid, from such precise relative trends, reliable absolute mean sea level trends could be determined.

Keywords. Relative MSL trends, sea level variation, tide gauges.

1 Introduction

Today, a rise of mean sea level is frequently in focus of public attention. Unlike satellite altimetry that provides absolute sea level variations (measured relative to reference ellipsoid), tide gauges data provide sea level variations relative to specific point on Earth's crust and consequently include the effects of vertical land movements. In spite of absolute character, global coverage and high precision of altimetry data, tide gauges are still crucial in measuring sea level and determining its rise. While satellite altimetry data is available for several decades, some tide gauges records cover the time span of more than a century. Moreover, high-quality tide gauge network is used to remove satellite bias and drift form altimetry data (Pugh 2004). If collocated with continuous GPS stations, vertical land movements can be removed from tide gauge data and absolute sea level trends can be determined. However, reliable measurements of trends from GPS may take several decades (Pugh 2004).

This paper deals with precise determination of relative mean sea level (MSL) trends in closed sea from tide gauge records. Annual and inter-annual sea level changes, which are driven by climate variations, make it difficult to calculate precisely the sea level trends. Averaging over a year removes seasonal changes. However, systematic effects from changes of meteorological parameters (e.g. steric effect, air pressure effects) and associated ocean circulation that last for longer than a year are maintained, as well as long-periodic tidal effects (e.g. nodal tide with 18.6 year period, Chandler wobble).

Thus, in order to precisely determine a sea level trend, it is necessary to remove periodic and irregular variations from sea level records. One can assume that such inter-annual changes are very similar for sites in small closed seas and residual variations for each site are close to random. Accordingly, mathematical model that distinguish between inter-annual variations of sea level common for all sites in some small closed sea and linear trend effects specific for each site can be defined. Sea level trends determined in such a way are precise, but relative. Beside absolute rise of sea level, such sea level trends include effects of regional and local vertical land movements.

2 Data

For the purpose of this study annual MSL values from Permanent Service for Mean Sea Level (PSMSL) have been used. Nine tide gauges in Adriatic with significantly long records have been selected. These are Venezia – Punta Della Salute and Trieste in Italy; Koper in Slovenia; Rovinj, Bakar, Split – Rt Marjana, Split – Harbour and Dubrovnik in Croatia and Bar in Montenegro (Fig. 1). Respective annual MSL values are plotted in Fig. 2, while information on records is summarised in Table 1.

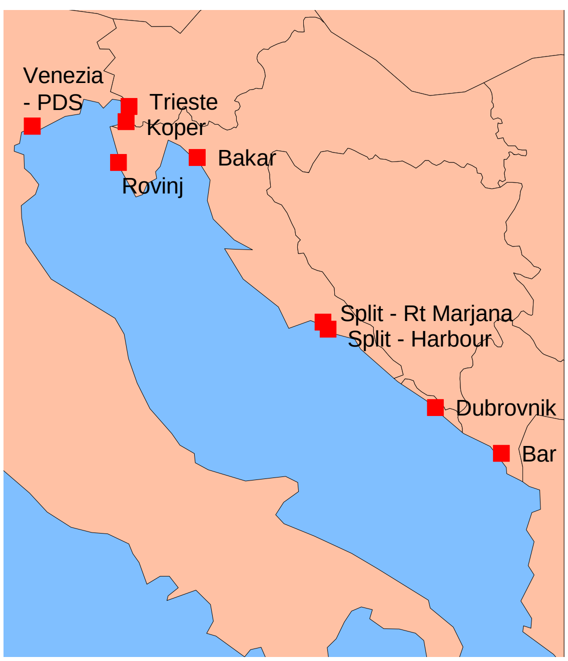

Fig. 1 Tide gauges involved in the study

Since distance between two farthest tide gauges in question is about 600 km and all sites are in the small closed sea, one can assume that inter-annual sea level changes, driven by climate variations and long-periodic tidal effects, are highly coherent. High correlation between annual MSL values is apparent form Fig. 2.

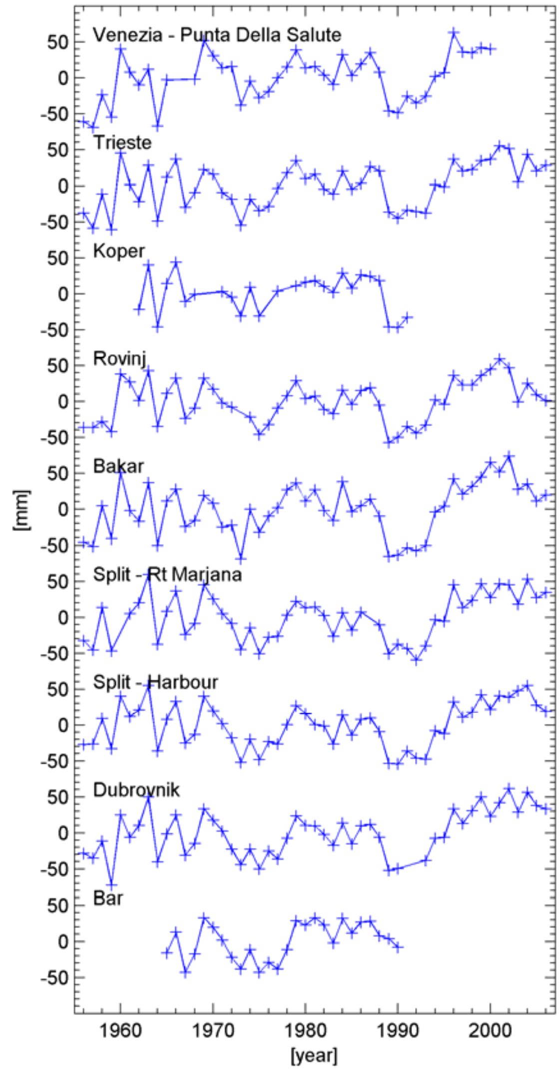

Fig. 2 Annual MSL at tide gauges

Table 1 Tide gauges data overview

Tide gauge	PSMSL code	Time span	No. of annual MSLs
Venezia – Punta Della Salute	270/054	1956-2000	43
Trieste	270/061	1956-2006	51
Koper	279/002	1962-1991	26
Rovinj	280/006	1956-2006	50
Bakar	280/011	1956-2006	51
Split – Rt Marjana	280/021	1956-2006	49
Split – Harbour	280/031	1956-2006	51
Dubrovnik	280/081	1956-2006	49
Bar	281/011	1965-1990	26

If calculated directly from each MSL record independently according to least squares (LSQ) principle, relative MSL trends can be obtained with standard deviations from 0.3 up to 0.6 mm/yr (Table 2).

Table 2 Relative MSL trends from each record

Tide gauge	MSL trend [mm/yr]	St. dev. [mm/yr]
Venezia – Punta Della Salute	0.93	0.37
Trieste	0.87	0.27
Koper	-0.22	0.58
Rovinj	0.49	0.27
Bakar	0.81	0.32
Split – Rt Marjana	0.63	0.30
Split – Harbour	0.44	0.29
Dubrovnik	0.96	0.28
Bar	1.26	0.63

3 Mathematical model

In order to determine values of common MSL variability for each year and relative MSL trends for each tide gauge, all the data have been adjusted simultaneously according to well known Gauss-Markov model and LSQ principle.

Trend line at each tide gauge has been modelled by two unknown parameters:

$$TL_{TG}^{t} = a_{TG} + b_{TG}(t - t_0)\,, \tag{1}$$

where TL_{TG}^{t} is a trend influence at tide gauge TG at time t (in years), t_0 reference time (set to middle year 1981), and a_{TG} and b_{TG} are unknown trend line parameters. Accordingly, measurement equitation for annual MSL at tide gauge TG for year t is:

$$\begin{aligned} MSL_{TG}^{t} + v_i &= TL_{TG}^{t} + V^{t} \\ &= a_{TG} + b_{TG}(t - t_0) + V^{t}\,, \end{aligned} \tag{2}$$

where v_i is respective measurement residual and V^t MSL variability for year t common to all tide gauges. Thus, for 9 tide gauges and time interval from year 1956 to 2006 there is 69 unknown parameters (2 trend line parameters for each tide gauge and common MSL variability value for 51 years).

Parameter a_{TG} corresponds to an offset of each tide gauge's RLR datum, as defined by PSMSL (URL1), from common MSL variability, while b_{TG} can be seen as a scale factor. Since there is no reference offset and scale defined, there is a datum defect in the model, that, if compared with free network adjustment (Feil 1990), accounts for translation and scale freedom of movement. Consequently, in the course of adjustment pseudo inversion has been applied.

All annual MSL values are presumed to be of equal accuracy. Described model is valid under assumption that residual MSL variations for each site are close to random.

4 Results

Applied mathematical model resulted in significant decrease in standard deviations of estimated relative MSL trend values (Table 3) as compared to independently estimated trends (Table 2). Specifically, standard deviations of estimated trends at all tide gauges amount 0.1 mm/yr, except for Koper and Bar, which have only 26 annual MSLs available (Table 1). Moreover, because referred to common MSL variability, relative trend values estimated in this way all corresponds to same time interval, although not all the tide gauge records cover entire time span.

Table 3 Relative MSL trends from common adjustment

Tide gauge	MSL trend [mm/yr]	St. dev. [mm/yr]
Venezia – Punta Della Salute	1.29	0.12
Trieste	0.87	0.09
Koper	1.04	0.23
Rovinj	0.52	0.09
Bakar	0.81	0.09
Split – Rt Marjana	0.53	0.10
Split – Harbour	0.44	0.09
Dubrovnik	0.85	0.10
Bar	2.67	0.27

Values of annual common mean sea level variability are determined with standard deviations of less than 4 mm (Fig. 3)

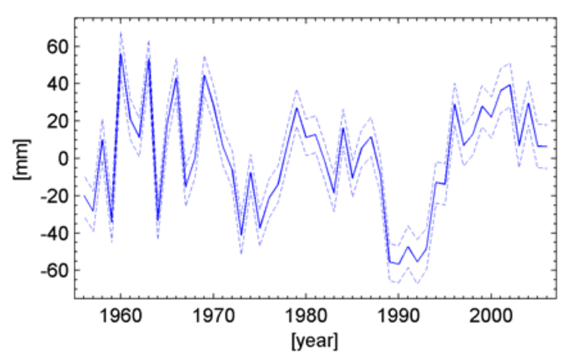

Fig. 3 Common MSL variability ± 3 standard deviations

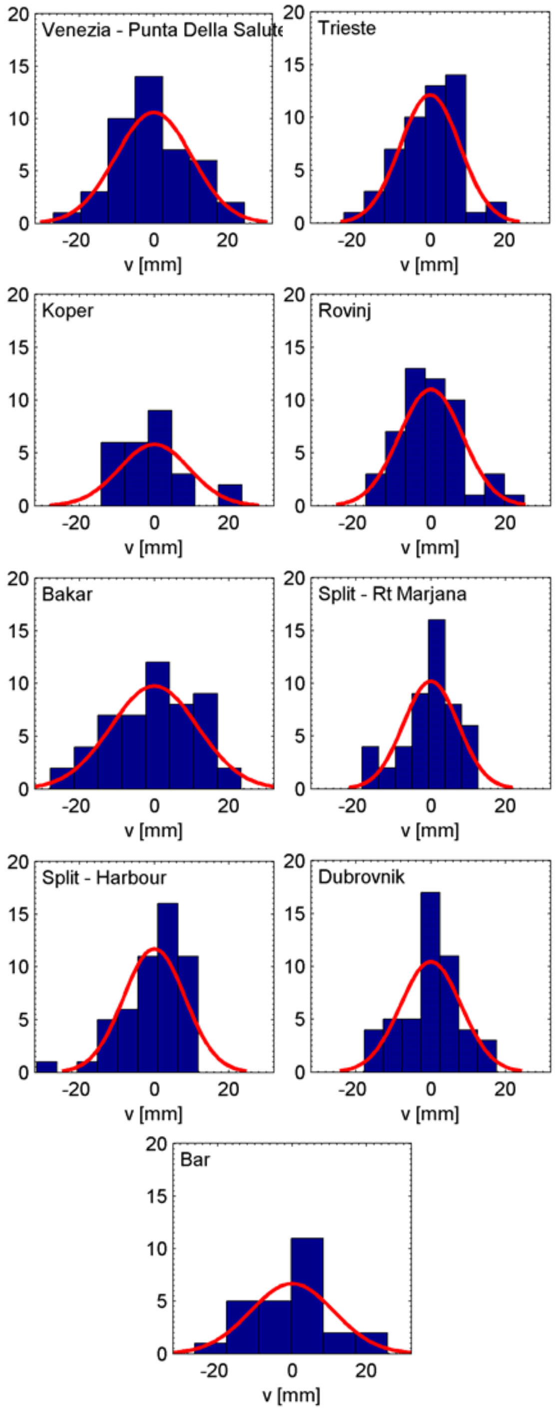

Fig. 4 Histograms of residuals for respective tide gauges with superimposed normal density curves

In order to validate the assumption on randomness of residual MSL variations, histograms of residuals with superimposed normal density curves for each tide gauge are plotted in Fig. 4. Since none of superimposed normal density curves is significantly bias with respect to zero, one can deduce the assumption is valid for data set in question.

5 Conclusion

Presented adjustment model enables estimation of relative MSL trends with up to three times smaller standard deviations as compared to independently estimated trends, without the aid of complicated models for sea level variability. Moreover, all estimated trends are related to common time interval, even though not all the tide gauge records cover entire time span.

Full significance of the model can be reached when estimated trends shall be associated with measurements of vertical land movements from collocated continuous GPS stations. From such measurements at one or more tide gauges, the scale factor for adjustment model (discussed in chapter 3) can be defined. Consequently, absolute MSL trends for all tide gauges can be estimated. However, in order to reliably determine vertical land movement and the scale factor, sufficient time interval of continuous GPS measurements is needed.

References

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