Relative sea-level trend from tide gauge observation

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Introduction

The relative sea level (RSL) is the height of the sea surface measured at the pier of a harbor by means of a tide gauge (TG); the measurement is performed respect to a local reference frame, that usually is the pier itself or the sea bottom. The TG measures the combined effect of the absolute sea-level change and of the vertical land movement (VLM) at the site. While the overall sea level results from the different types of tides plus the long-term changes of the sea height, the ground deformation is the result of subsidence plus other phenomena such as tectonics, glacial isostatic adjustment, earthquakes, volcanism and so on.
Measuring the long-term component of the rate of RSL change is a complex task that plays a crucial role for the comprehension of the local transposition of the global sea-level rise linked to the climate change [IPPC AR5 report, Stocker et al., 2013]. The main reason of the complexity is the presence of different tides with amplitudes that prevail in the signal. This prevalence complicates the assessment of the long-term component by enlarging the error bar associated to the trend. Furthermore, the assessment of the long-term trend is complicated by the strong autocorrelation of TG time-series (i.e. RSL height at a generic sample of the time-series more likely equals the height at the next sample) that can be verified by statistical tests. Direct consequence of autocorrelation is that the least square (LSQ) method cannot be applied because one of the underlying rules is violated. For the above reasons, a more sophisticated approach is proposed with the goal of providing a robust assessments of the rate of RSL change over time and of its associated error. The methodology is then applied to the case of the Napoli Mondracchio (Southern Italy) TG time-series.

Methodology

The first stage of the proposed workflow aimed at analyzing one TG time-series, that could have gaps or different sampling rate over different epochs, consists in the application of the EMD (Empirical Mode Decomposition). This is an adaptive method by which any arbitrary data set can be deconvolved into a finite and often small number of oscillatory Intrinsic Mode Functions (IMFs), with increasing instantaneous period, plus a residual (RES) which can be a monotonic or a single-extremum function [Huang et al., 1998].
Since its introduction by Huang et al., [1998], EMD has found a large number of applications in different fields of physics and geophysics [Huang and Shen, 2005; Huang and Wu, 2008]. To mention some of the benefits of using EMD in sea–level analysis from TG observations, it does not require the removal of trend, IMFs are mutually orthogonal functions, each IMF can have variable period and amplitude. EMD can better reproduce non stationary and non linear phenomena characterizing the sea–level variability [Galassi and Spada, 2015]. EMD is here used to remove noise, tides and all those periodic signals and to obtain the aperiodic component of the time series (i.e. RES in the EMD method). It is noteworthy here that, RES time-series does not follow any a-priori assumption neither on the periodicity of the removed oscillatory signals

neither on the linearity of the residual itself. However, RES time-series is still strongly autocorrelated and the LSQ regression remains inappropriate. The second phase is devoted to determine the mean rate and its error. To mitigate the autocorrelation and keep the associated errors small, we downsample the time series averaging each set of six (for the case of monthly mean time-series) samples assigning the time stamp of the mean of the six times to the average value. This is a preferable option with respect to the standard running mean since it use each sample of the time-series only once. Then, a three points derivative (namely OUT(J)= 1/2 * (DATA(J+1) - DATA(J-1)) / (T(J+1)-T(J-1)) where OUT(J) is the derivative, T(J) is the time and DATA(J) is the sea-level height at sample J) is applied to the resulting time-series. Statistic test, not displayed, can confirm the removal of the autocorrelation. The final time-series describes the rate of the RSL change over time by representing its distribution, mean, variance, median and the other modes, if needed can be analyzed.

Application: Site 105 Napoli Mandracchio (Italy)

As an example, we applied the above methodology to the time series recorded at one of the TGs placed in the gulf of Naples (Italy), namely the TG labelled with id 105 at the PSMSL archive [PSMSL, 2015]. This is a RLR (Revised Local Reference) monthly mean time series that covers the time span 1896-1922.

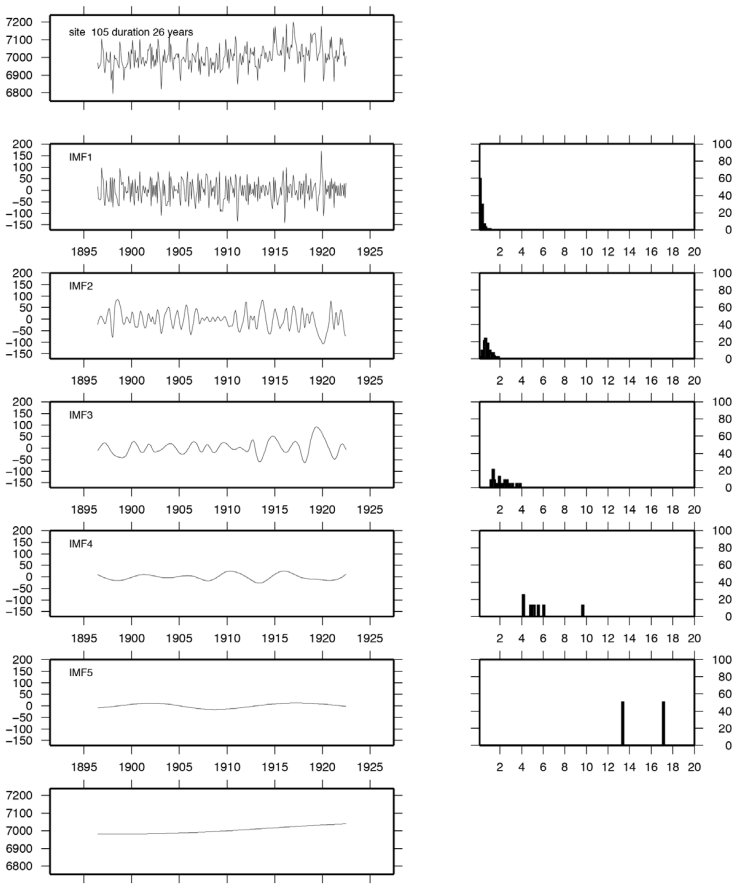

Figure 1 Left column (from top to down): the original TG 105 time-series, each of the IMF resulting from the EMD analysis and the monotonic residual RES. Right column: Each panel represents the frequency content, as percent, of the instant periods (in years) of the corresponding IMF.

The TG 105 RSL time series change, estimated by the difference between first and last sample is 38±2 mm that corresponds to an average rate of about 1.5±0.1 mm/yr. Conversely, the trend of the time series, as determined by means of standard least square (LSQ) regression results in

a rate of 2.5±0.5 mm/yr even though in this case, according to the above discussion, the strong time-series autocorrelation leads to an underestimation of the error-bar associated to the trend. Figure 1 shows the original time-series, the resulting IMFs time-series, the periodicity of each IMF and the residual. EMD analysis highlights that: i) harmonic components of the original signal do not have constant amplitude and period; ii) the long-term trend represented by the residual (RES) is monotonic but in this case does not show a constant trend. Figure 2 shows the result of downsampling and derivation as applied to RES and its distribution. Rate values do not follow a normal distribution around the mean. This might results from a not steady process of rise for RSL over the time span of about three decades. This observation is confirmed by the relevant discrepancy between the mean 2.1±1.2 mm/yr and the median 2.8±1.0 mm/yr.

Conclusions

This work describes a methodology for removing the high frequency content of a time series, for assessing the rate of RSL change in a robust manner and for providing realistic estimates of the associated error. The analysis of TG 105 time series helps to understand the limits of LSQ linear regression. In particular, this approach provides non realistic values for the error associated to the resulting trend. For the case described above, we remark that, the three methods (LSQ trend, mean and median of the distribution) give close central values 2.5, 2.2, 2.8 mm/yr respectively, but the last two values have a much larger associated error-bar that should be considered more realistic, given the above considerations. Finally, the discrepancy between mean and median and the not-gaussian distribution confirm that the rise over that epoch was not a steady process suggesting that either some acceleration occurred or the time span is too short to remove oscillations (tides) at longer periods.

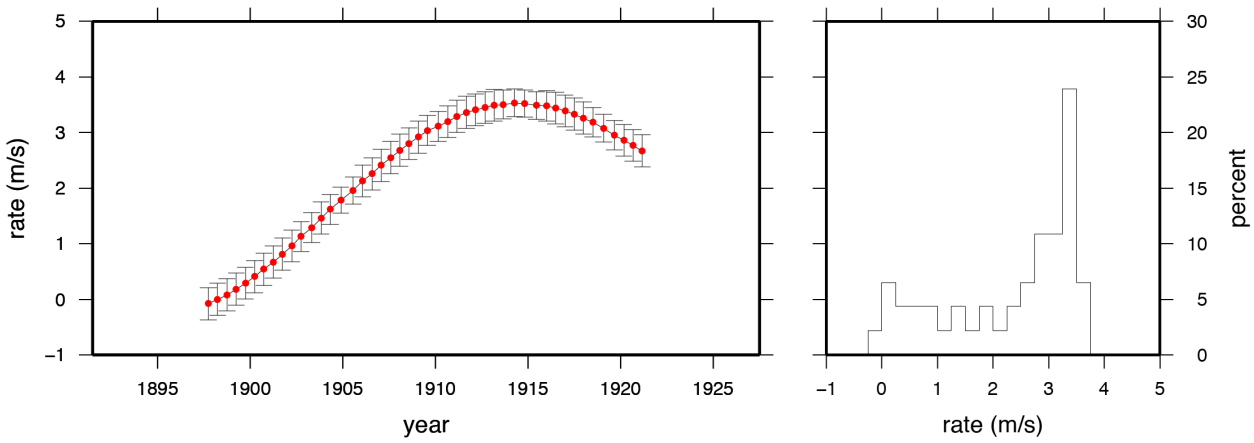

Figure 2 (left panel) The result of the downsampling and derivation of the EMD residual (open red circles). Error-bars result from averaging and discrete derivation process. These do not account for the uncertainty resulting from the EMD analysis. (right panel) Frequency distribution, in percent, of the rate. This considers only the central values (open red circles) plotted in left panel.

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EMD code was originally developed by Lionel Ludet in [2009]. Data for the TG at Napoli Mandracchio have been retrieved from the PSMSL site (www.psmsl.org). The authors thanks Laura Beranzoli for the fruitful review.

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