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Sea level variability and trends in the Adriatic Sea in 1993–2008 from tide gauges and satellite altimetry

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ABSTRACT

The scope of this paper is to give a consistent view of the low frequency sea level variability in the Adriatic Sea from both satellite altimetry and tide gauge records. We analyze 16 years of sea level observations from multi-satellite altimetry and tide gauge records in the time interval 1993–2008. First, the impact of the corrections applied to the altimetry-derived sea level variations and the consistency of the altimetric and the tide gauge sea level observations are evaluated. Both observations are then used to characterize sea level trends, interannual variability and land vertical motion in the Adriatic region.

Eight tide gauges along the coast show very coherent interannual sea level variations, with an increase in sea level before 2001 and decrease afterwards. The average of the eight de-seasoned time-series agrees with the basin average of the altimeter data, with correlation coefficient 0.84 and root mean square difference 12 mm. The linear change is higher for altimetry than for tide gauges and strongly depends on the length of the time-interval, being 3.2 ± 0.3 mm/yr and 1.9 ± 0.3 mm/yr in the interval 1993–2008. The steric contribution to sea level change correlates well with the sea level suggesting that the low frequency variability is likely related to oceanic and climatic processes and mainly due to temperature and salinity variations. The decadal sea level variability is correlated in Adriatic and Eastern Mediterranean, anti-correlated in Adriatic and Ionian Sea.

At a given location, the trend of the differences of sea level observations by tide gauges and co-located satellite altimetry gives the vertical land motion, if we assume that the sea level signals are truly common. We find trends statistically significant at the 90% confidence level at two locations, that indicate land uplift along the eastern coast in Rovinj (3.0 ± 1.2 mm/yr) and land subsidence in Marina di Ravenna (−1.5 ± 1.1 mm/yr), while at other locations, e.g. in Trieste (1.3 ± 1.1 mm/yr) the significance is lower. The results agree in general in sign with GPS derived rates, but not in magnitude, like in Marina di Ravenna, where the strong subsidence measured by GPS is related to the local anthropogenic subsidence. The differences are partly explained by the spatial distance between the tide gauge and the co-located altimeter locations.

1. Introduction

Sea level rise is an important environmental parameter and indicator of climate change (Bindoff et al., 2007). Its impact is particularly important in selected coastal zones. The Northern Adriatic Sea is one of those vulnerable areas presenting a great sensitivity to climate change and a low adaptability. The Adriatic Sea is an elongated semi-closed basin communicating with the Mediterranean Sea through the narrow and shallow Otranto Strait. The eastern Po plain, from Ravenna to the Venice region, is part of a subsiding sedimentary basin. Over the last millennia, changes in the ground elevation with respect to the Adriatic Sea level have caused modifications in the features of the region. Nowadays, the relative sea level rise (RSLR), resulting from the combination of land vertical motion due to natural and anthropogenic causes and of the eustatic sea level rise, represents a threat for the region (Carbognin et al., 2009; Lionello et al., 2005).

Various authors (Orlić and Pasarić, 2000; Wöppelmann et al., 2006; Zerbini et al., 2007; Antonioli et al., 2009) have reported on land subsidence in the Northern Adriatic, with a weak or even positive (uplift) rate in Trieste, small negative rate in Venice and larger negative rate in Marina di Ravenna, partly related to human effects. Some post-glacial isostatic response models predict subsidence of 0.3–0.5 mm/yr (Lambeck and Johnston, 1995; Stocchi and Spada, 2009), whereas others predict uplift of 0.2–0.3 mm/yr (Tushingham and Peltier, 1989). For the last decades an integrated monitoring system based on earth observation techniques has confirmed a land subsidence along the coasts of the lagoon (Tosi et al., 2009).

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It is generally agreed that at least 50-year-long tide gauge records are needed to separate secular, decadal and interannual variations (Douglas, 2001) because interannual and low frequency signals affect the recovery of secular trends in short records. Tide gauge records give for the 20th century a global mean positive RSLR rate of ~1.7 mm/yr (e.g., Church et al., 2008; Holgate, 2007; Domingues et al., 2008), that is higher than the corresponding regional mean RSLR rate over the Adriatic.

In the Adriatic Sea, the long-term RSLR trend derived from tide gauge records over the last century varies between 0.5 ± 0.2 and 1.2 ± 0.1 mm/yr (Marcos and Tsimplis, 2008; Raicich, 2007), except for the higher trend in Venice (2.5 ± 0.1 mm/yr). The latter is due to anthropogenic subsidence ascribed to water extraction, which ceased in 1970 (Pirazzoli, 1991; Tiezzi and Marchettini, 1997; Woodworth, 2003). For the period 1960–2000 small rates between −0.4 ± 0.4 mm/yr and +0.3 ± 0.4 mm/yr have been found, higher rates correspond to the last decade of the twentieth century. Sea level trend exhibits large interdecadal variability with good coherence between the tide gauge records (Marcos and Tsimplis, 2008; Klein and Lichter, 2008; Pirazzoli and Tomasin, 2008). The tide gauges in the Adriatic are particularly important for sea level change studies, as the records of Trieste and Venice are two of the longest in the world.

Since early 1993, sea level variations are also accurately measured by satellite altimetry. The total measurement accuracy for the altimetry based sea surface height is about 80 mm (95% error) for a single measurement based on one-second along-track, the 95% error associated with a 10-day mean sea level estimate is approximately 8 mm (Bindoff et al., 2007; Chelton et al., 2001). Current results indicate that the residual error in the mean sea level variations is about 0.8 mm/yr, differences up to 0.5 mm/yr in altimetry-based rates of sea level rise are found between investigations and mainly result from data processing differences and values used for the orbit and the geophysical corrections (Beckley et al., 2007; Ablain et al., 2009). In terms of global mean, the 16 year-long altimeter data set between 1993 and 2008 shows a positive rate of ~3.1 ± 0.4 mm/yr (Prandi et al., 2009; Fenoglio-Marc and Tel, 2010), that is comparable to the RSLR trend derived over the same time interval from a set of tide gauge records. It has been shown that over intervals shorter than 10 years the interannual variability affects more the rate of global mean sea level from tide gauges than the rate of global mean sea level from altimetry.

Owing to its global coverage, altimetry reveals considerable regional variability in the rates of sea level change and is therefore particularly suited to determine global mean sea level change and low frequency processes of annual and interannual variability. One of its main problems is still the aliasing of short-period signals that cannot be resolved due to the coarse temporal sampling of the satellites.

Another difference between the tide gauge and altimetric measurements is their different reference frame. While satellite altimetry measures sea level in a geocentric reference frame, the tide gauge observes the sea level with respect to a reference point on land which can move vertically relative to the geocenter due to geodynamic effects, as tectonics, volcanism, post-glacial isostatic adjustment or due to anthropogenic causes. At present, vertical land motions at tide gauges can be measured to a high accuracy by means of space techniques such as Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) (Blewitt et al., 2010). Several studies have estimated vertical land motion from the difference between satellite altimetry and tide gauge sea level height measurements at selected locations (Braitenberg et al., 2010; Cazenave et al., 1999; Dong et al., 2002; Mitchum, 2000; Nerem and Mitchum, 2002; Fenoglio-Marc et al., 2004; Kuo et al., 2004; Ray et al., 2010). A positive difference corresponds to land uplift and a negative difference to land subsidence, therefore, in case of land subsidence the tide gauge measures an higher sea level rise than satellite altimetry. Care is needed to match up the two types of sea level measurements, and the method is not applicable everywhere, since the tide gauges are not always located near to the satellite groundtracks and the altimetry measurements have lower accuracy near coast than on open sea.

Various authors have analysed the sea level change in the Mediterranean Sea derived from altimetry data and have reported for the Adriatic Sea on a positive sea level rate between 1993 and 2002 and a negative rate after 2002 (Cazenave et al., 2001; Fenoglio-Marc 2001, 2002; Vigo et al., 2005). In this study, we estimate the low frequency sea level variability from multi-satellite altimetry and eight tide gauges in the Adriatic Sea over a 16-year long time interval. The analysis aims at clarifying the following issues, namely the description of (1) the long-term difference between eustatic sea level rise observed by altimetry and sea level rise relative to land observed by tide gauge records and of (2) the main spatial and temporal characteristics of sea level change over the Adriatic basin. The first issue opens the discussion on the interpretation of differential trends as land motion at the coast. The multi-satellite missions enhance temporal and spatial resolutions with respect to a single satellite analysis. The coherency in the variability of the tide gauge and co-located satellite altimetry indicates how representative the altimetry data are for the coastal sea level variability. The comparison of sea level trends observed by tide gauges and altimetry allows in principle to derive vertical crustal movements. We discuss here whether for a basin like the Adriatic this method is usable, taking into account the location of the tide gauges relative to the position of the satellite tracks and the presently available time interval.

Data and method of analysis are presented in Section 2. In Section 3 we describe the results. The differences observed and the possible geophysical interpretations are further discussed in Section 4.

2. Data and method of analysis

2.1. Altimetry data

We use altimetric sea level height data from the satellites Topex/Poseidon, Jason-1, Jason-2 and Envisat. The 16-year long altimetric time series allows an analysis of interannual variability and trend of sea level at regional scales relative to a geodetic reference frame.

In the Adriatic Sea the spacing between the ground-tracks is of about 230 km for the 10-day repeat cycle (Topex/Poseidon and Jason) and 60 km for the 35-day repeat cycle satellites (ERS-2, Envisat) (Fig. 1). Using Topex/Poseidon and Jason missions alone, the coverage is poor and ground-track is 161 is the nearest track to most of the tide gauge stations. By including Envisat data the coverage is improved, we do not include data of the ERS-1 and ERS-2 missions because of their lower accuracy.

First, the impact of the corrections applied to the altimetry-derived sea level variations and the consistency of altimetric and tide gauge sea level observations are evaluated and a suitable procedure is identified. Special attention has been paid to the consistency of the corrections applied to altimeter and tide gauge data.

We perform two types of comparisons, that we call "monthly" and "daily" comparison methods. In the first multi-mission gridded altimeter data are compared to monthly tide gauge records, in the second along-track altimeter data are compared to tide gauge records, corrected for the ocean tide effect, at the point of nearest approach (diamond in Fig. 1). Both comparison methods require the same corrections to be applied to the altimeter data

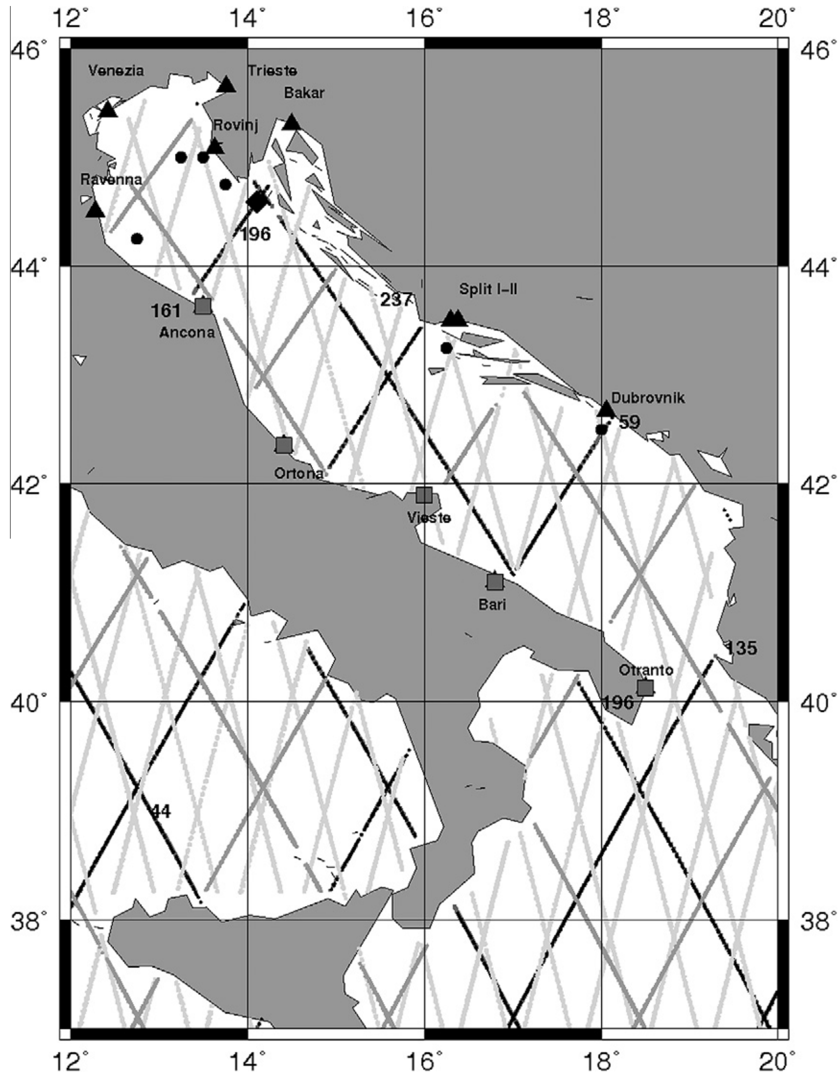

Fig. 1. Location of the eight tide gauge (triangle) and co-located altimeter time-series used in monthly (dots) and daily (diamond) comparisons. Ground-tracks are from Envisat (light grey), Topex/Poseidon phase b (grey), Jason-1 and Topex/Poseidon phase a (black with track number). Additional tide gauge stations available over a shorter interval are shown (squares).

to compute sea level height anomalies above a reference surface. We use the Radar Altimeter Database System (RADS) database, that provides an harmonized, validated and cross-calibrated set of altimeter data (Naeije et al., 2008). To merge data from different satellites we apply the reference frame biases that reflect the differences in the orbits as well as some other geographical differences in the altimeter dependent models. For the small area we are considering, these modelled biases amount to an almost constant value (Trisirisatayawong et al., 2011). Detailed inspection and special care is needed because we are analysing data close to the coast.

The impact of the altimeter corrections on sea level variations has been evaluated through comparing the standard deviation of sea level anomalies for different choices of a given correction, we select the choice giving the smallest standard deviation. Table 1 presents a summary of the chosen models and corrections to infer sea level anomalies from the altimeter record, that coincide in most of the cases with the default corrections of the RADS database. The pole tide correction is not applied for consistency with the tide gauge records. We apply environmental (wet and dry tropospheric, ionospheric, sea state bias) and geophysical corrections (solid earth, ocean and load tides). To retain more data near coast we choose the wet tropospheric correction derived from the European Centre for Medium-range Weather Forecasts (ECMWF) model and ignore most of the conservative flags, thus allowing inclusion of data closer to land. The response to atmospheric pressure forcing is here accounted for by applying the Dynamic Atmospheric Corrections (DAC), which consists at low frequencies of the Inverse Barometer (IB) response and at high frequencies of the barotropic model MOG2D-G (Carrère and Lyard, 2003). This correction is particularly suitable for the Adriatic Sea, as here the response is far from an inverse barometer (Pascual et al., 2008). The DAC Corrections are produced by CLS Space Oceanography Division using the Mog2D model from Legos and distributed by Aviso, with support from Cnes (http://www.aviso.oceanobs.com/) with temporal resolution of 6 h and spatial resolution of 0.25°. The correction for the one second altimeter data is included in the RADS database.

In the monthly comparison method the multi-mission altimeter data sets have been merged in monthly grids by a Gaussian weighted average method with grid spacing of 0.2°, half-weight of 1° and search radius of 150 km. The nearest grid point to the tide gauge station location has been selected for the comparison (dots in Fig. 1). In the daily comparison method the nearest altimeter point along-track has been considered (diamond in Fig. 1). The differences between the results obtained in the two approaches are investigated in Section 3.

Table 1
Corrections and models for altimeter analysis, changes to RADS default corrections are indicated by (*).

Correction/model	Edit criteria (m)		Description
	Min	Max	
Orbit			EIGEN GL04C
Dry troposphere	−2.4	−2.1	ECMWF
Wet troposphere (*)	−0.6	0.0	ECMWF
Ionosphere	−0.4	0.04	All sats: altimeter dual frequency, smoothed
Dynamic atmosphere	−1.0	1.0	MOG2D model
Ocean tide	−5.0	5.0	GOT4.7 model
Load tide	−0.5	0.5	GOT4.7 model
Solid earth tide	−1.0	1.0	Elastic response to tidal potential (Cartwright)
Sea state bias	−1.0	1.0	TOPEX/JASON/ENVISAT: CLS non parametric
Reference	−1.0	1.0	DNSC08 mean sea surface (Andersen and Knudsen, 2009)
Data engineering flag (*)			Only altimeter land flag based on 2′ × 2′ mask
Applied reference frame biases (cm)			From global analysis of differences with Topex reference frame: ENVISAT = 5.2, Jason-1 = −4.8, Jason-2 = 15.9

2.2. Tide gauge data

The tide gauge data have been made available from the Permanent Service for Mean Sea Level (PSMSL, – http://www.pol.ac.uk/psmsl/, Woodworth and Player, 2003) and from the Istituto Superiore per la Protezione e Ricerca Ambientale (APAT-ISPRA, http://www.idromare.com). The first provides monthly data, the second hourly data. Additional time-series have been made available by local institutions for Trieste (Department of Geosciences of the University of Trieste), Venezia and Marina di Ravenna (Zerbini, Raicich private communication). Fig. 1 shows the location of thirteen tide gauge stations. For consistency with the satellite altimetry data processing described in the previous sub-session, we have applied the DAC correction to the tide gauge data to account for the effect of pressure and wind on the sea level. The DAC correction has been derived from the gridded data distributed by AVISO described in the previous section using the nearest grid point to the tide gauge station. In Trieste the DAC and the inverse barometer correction estimated from hourly pressure data are in good agreement at low frequencies, correlation and root mean square (RMS) differences are 0.7 and 2 cm respectively for monthly averaged time-series.

For daily comparison of sea level records from altimetry and tide gauges the hourly tide gauge data have been reduced to daily sampling and the daily values corresponding to the altimeter observations have been selected to build the time-series. The daily sampling is obtained by a two-step filtering operation. First, the dominant diurnal and semi-diurnal tidal components are removed from the quality controlled hourly values. Secondly, a 119-point convolution filter (Bloomfield, 1976) centred on noon is applied to remove the remaining high-frequency energy and to prevent aliasing.

The seasonal variation is a large amplitude signal, which essentially depends on yearly temperature variations. To achieve more reliable trends this signal has been estimated from the sea level records. We have applied different procedures depending on data sampling. Using daily data the linear trend and the annual and semi-annual signals have been evaluated separately for the altimeter and tide gauge time-series through a least-squares procedure fitting the function:

$$m(t) = a_0 + a_t t + a_{\cos 1}\cos\omega_1 t + a_{\sin 1}\sin\omega_1 t + a_{\cos 2}\cos\omega_2 t + a_{\sin 2}\sin\omega_2 t \quad (1)$$

where a_0, a_t, $a_{\cos1}$, $a_{\sin1}$, $a_{\cos2}$, $a_{\sin2}$, are the parameters to be determined, and ω_1 and ω_2 are the yearly and half-yearly angular frequency, respectively. The linear trend is given by the parameter a_t and its uncertainty is equal to the standard error of the coefficient estimate; we assume that the residuals have zero mean and Gaussian distribution (Parker, 1994). We compute the linear trend $a_{t\_al\text{-}tg}$ of the sea level difference between altimeter and tide gauges as difference of the linear trends:

$$a_{t\_al\text{-}tg} = a_{t\_al} - a_{t\_tg} \quad (2)$$

where a_{t_al} is the altimetric trend and a_{t_tg} is the tide gauge trend. When analysing the monthly time-series, the seasonal component is first evaluated by computing the mean variability for each month in the interval of analysis and then removed from the monthly values to obtain de-seasoned monthly values. To obtain the linear trend of the difference between altimeter and tide gauge records we consider two alternative methods. In one method, the trends are first estimated from the de-seasoned sea level time-series and then their difference is computed, in the other method the trend of the de-seasoned difference "altimeter minus tide-gauge" is computed. Linear regression is used to estimate the linear trend and its standard error σ. We further assess the trend significance by applying the t-test to the ratio between the estimated trend and its standard error σ. As shown in Santer et al. (2000) and Maul and Martin (1993) classical tests of trend significance may underestimate the standard errors if the detrended time series are not statistically independent. Accounting for the temporal autocorrelation of the detrended time series, we compute an effective sample size n^1 based on the lag-1 autocorrelation coefficient r^1 (see also Eq. (6) in Santer et al., 2000):

$$n_1 = n\frac{1 - r_1}{1 + r_1} \quad (3)$$

where n is the number of monthly time samples. By using the effective sample size n_1 one obtains a bigger standard error for the trend:

$$\sigma^1 = \sigma F_1 = \sigma\sqrt{\frac{1 + r^1}{1 - r^1}} \quad (4)$$

where F_l is the inflation factor. This procedure does not alter the value of the trends, but leads to an increase of the estimated error by about 40% for de-seasoned time-series (Fenoglio-Marc et al., 2004).

The steric sea level variability has been estimated from temperature and salinity values of the Ishii climatology (Ishii and Kimoto, 2009) and of the Mediterranean Forecasting System ocean circulation (MFSTEP) (Tonani et al., 2008). The steric sea level is computed from Eq. (5), as the vertical integration of the specific volume $1/\rho$ between the two surfaces of constant pressure p_1 and p_2:

$$h(p_1, p_2) = \frac{1}{g}\int_{p_1}^{p_2}\frac{1}{\rho}dp_1 \quad (5)$$

where ρ is the density and g the gravity acceleration. The specific volume is computed from the gridded temperature and salinity in situ data using the formulas of state for sea water (Gill, 1982). We integrate between each two levels using the mean of the specific volume anomaly of the two levels. Integration is made down to the lowest available depth. We derive grids of steric sea level with one degree spacing and monthly temporal sampling.

We perform a Principal Component Analysis (PCA) of both altimetry and tide gauge data to quantify the spatio-temporal sea level variations in the Adriatic Sea as well as reveal regional differences between the Adriatic and the rest of the Mediterranean Sea. This is an efficient way of analysing the dominant patterns of variability, which expands the signal in terms of the basin functions that concentrate most of the variance into a small number of components, called Empirical Orthogonal Functions (EOF) (Preisendorfer, 1988). We apply a significance test based on a Monte Carlo technique to find the number k of components corresponding to a signal above the noise level. Independent sequences of Gaussian variables are generated and the eigenvalues of the correlation matrix are computed, the procedure is repeated 100 times. The normalized eigenvalue statistics (percentage of variance explained) corresponding to real and random data are compared. The rule N (Overland and Preisendorfer, 1982) is applied, that consists in considering significant the principal components having eigenvalues greater than the value 95 in the sequence. The input data are normalized to standardized anomalies by dividing each point time-series by its standard deviation and the output spatial vectors are normalized to the maximum value for each mode.

3. Results

We have first analysed the quality of the hourly data to identify outliers and spurious change in the reference level of the data before computing monthly and daily values. A $3-\sigma$ test is used to detect the outliers. All hourly data of the APAT-ISPRA dataset present a jump in the time-series in summer 1998 due to the change of the tide gauge instrument (APAT personal communication), therefore the five stations of Ancona, Ortona, Vieste, Bari, Otranto (squares in Fig. 1) cannot be used over the complete interval without estimation of the vertical displacement of the reference point. This datum shift, estimated in Fenoglio-Marc et al. (2004) using the Topex-Poseidon data, is almost zero in Ancona and about 800 mm in Otranto and Bari. Fig. 2 shows the de-seasoned monthly time-series at the thirteen stations, the last five (i–m) have the datum shift in summer 1998.

We have defined selection criteria to be applied to monthly records, based on the length of the time-series, on the length of the gaps and on the correlation with nearby stations. The criteria are as following: the data should be available over 90% of the selected time-interval, gaps should be shorter than 2 years and correlation with nearby stations in a radius of 200 km should be higher than 0.7. The tide gauge stations with monthly data fulfilling the above selection criteria in 1993–2008 are eight (triangle in Fig. 1, stations a–h in Fig. 2) and include seven stations with monthly data from the PSMSL database (Rovinj, Bakar, Split Harbour, Split Marjana, Dubrovnik, Trieste, Venezia) as well as stations with hourly data from local institutions (Trieste, Venezia, Marina di Ravenna). The correlation between the de-seasoned sea level time-series of the eight stations (a–h) is higher than 0.9 over 1993–2008.

We investigate the differences between the monthly and daily comparison methods in Trieste. The monthly and daily time-series are shown in Fig. 3. The grid and the along-track altimeter points are in this example located respectively at 75 km and 110 km from the tide gauge station and are 30 km apart. Correlation and RMS differences are 0.65 and 65 mm for monthly comparison, 0.57 and 112 mm for daily comparison. The differences arise from the different time sampling: monthly averages of daily time-series used in daily comparison (Fig. 3c) give results (0.69 and 77 mm) similar to the monthly comparison (Fig. 3a). The correlation of monthly and monthly averages of daily time-series is 0.8 for tide gauge data and 0.6 for altimeter data. Here the lower correlation found for altimetry arise from the different way of building the monthly and daily altimeter time-series. The correlation is still significant and allows us to conclude that sea level time-series extracted from gridded and along-track altimeter data are comparable. The two methods give also comparable results for the trend, as shown below.

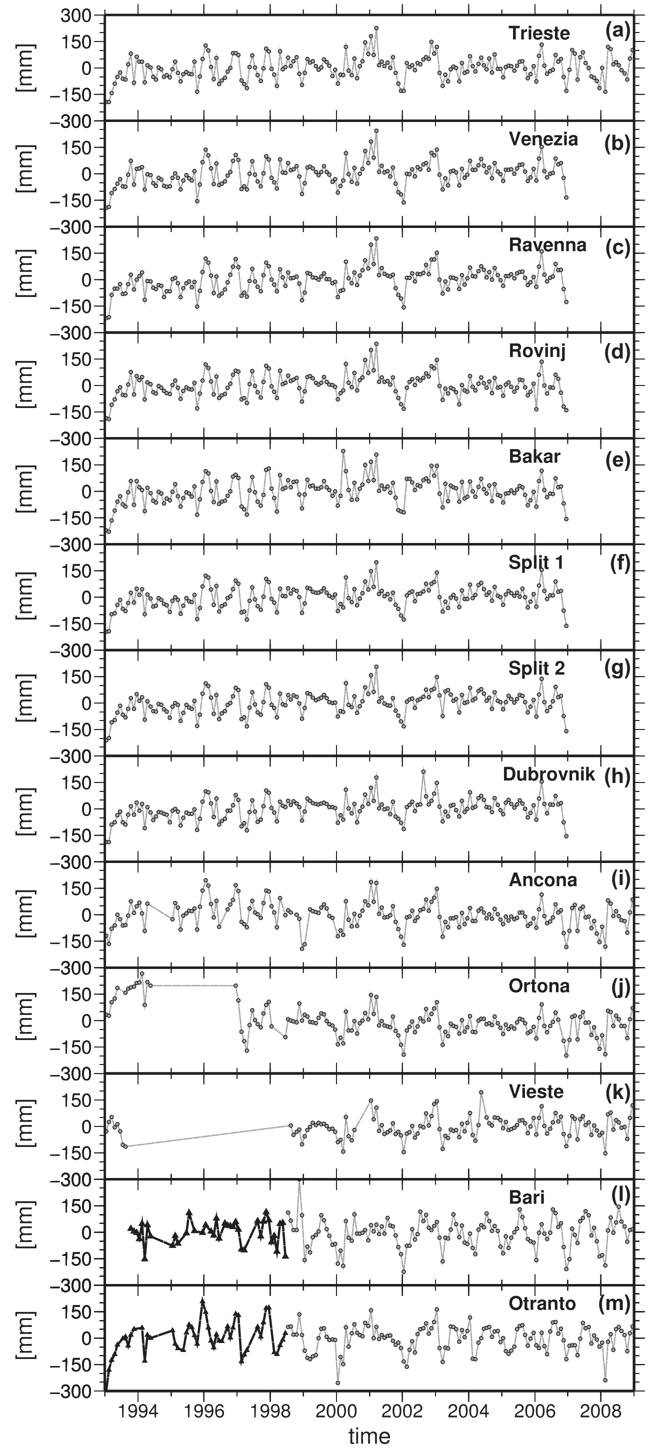

Fig. 2. Sea level time-series at tide gauge stations in the Adriatic Sea. The seasonal component and the mean has been removed. The first eight stations from the top (a–h) have been selected for the analysis. The other stations (i–m) present a vertical jump in summer 1998 and are not further analysed. In Bari and Otranto the data have been divided in two time-series before (black) and after the discontinuity, for representation purpose.

3.1. Long-term difference between altimetry and tide gauge sea level

At a given location P, the geocentric vertical land motion $\dot{u}$ is the difference between the rates of the geocentric sea level change $\dot{g}$ and of the sea level change relative to the Earth crust $\dot{s}$

$$\dot{u}(P) = \dot{g}(P) - \dot{s}(P) \tag{6}$$

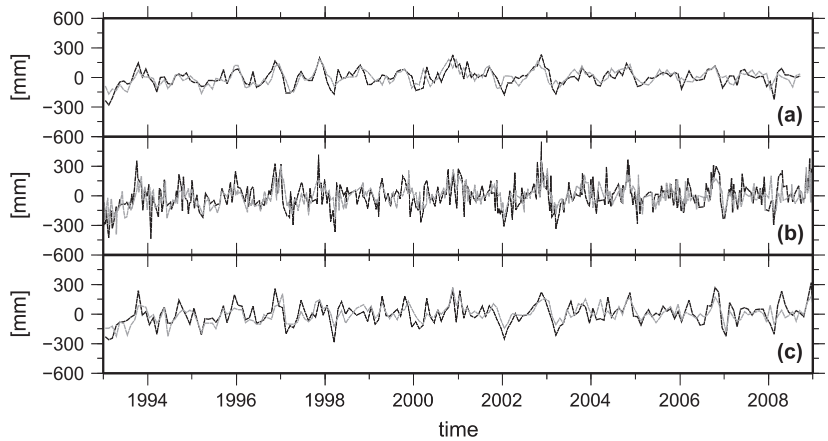

Fig. 3. Time-series of altimetry (grey) and tide gauge (black) data in Trieste: monthly (a), daily (b) and monthly averages of daily (c). The mean of the time-series has been removed.

In our application the sea level change derived from tide gauge and the altimeter is not measured at the same location *P*. The distance between the two locations depends on the type of comparison defined in Section 2 (monthly or daily comparison), and is at least several kilometres.

We apply the monthly comparison method to the eight selected locations. The altimeter and tide gauge monthly time-series, corrected for DAC and with the seasonal signal still included, have correlation of about 0.67 and standard deviation of the differences between 50 and 80 mm. The distance between the tide gauge and the co-located altimeter point is between 13 km in Rovinj and 79 km in Venezia. At each tide gauge we first compute the monthly differences "altimeter minus tide gauges" time-series by subtracting the tide gauge de-seasoned time-series from the altimeter de-seasoned time-series, then we estimate the trend of the resulting time-series (second procedure described in Section 2 for monthly comparison). Table 2 shows the results. The sea level trends estimated independently from altimetry and tide gauge are positive. The trends of the difference of the time-series are smaller than 1.5 mm/yr at most locations and have errors of similar magnitude. They are small compared to other regional studies (Ray et al., 2010; Fenoglio-Marc et al., 2004; Kuo et al., 2004). The t-test applied to the ratio of those trends to their errors leads to values above 1.3 (threshold of statistical significance for the 90% significance level) only at the stations of Rovinj (3.0 ± 1.2 mm/yr) and Marina di Ravenna (−1.5 ± 1.1 mm/yr). Trends are statistically significant at the 75% level of confidence (threshold is 0.68) in Trieste, Bakar and Split. Interpreting these trends as vertical motion, we finally found uplift in the eastern Adriatic (Rovinj, Trieste, Bakar), subsidence in Marina di Ravenna and not significant vertical motion (below the 75% confidence level) at the other stations. In Trieste the trend is 1.3 ± 1.2 from monthly comparison and 1.0 ± 1.8 mm/yr from daily comparison, it is below the 75% confidence level in this second case.

We have compared the estimated vertical motions to GPS trends at a few stations. A strong land subsidence of −10.2 ± 0.15 mm/yr has been derived in Marina di Ravenna by continuous GPS measurements over 9 years from 1996 to 2005 (Wöppelmann et al., 2006) and a smaller negative trend has been found more recently over 1997.5–2005.5 (Zerbini, personal communication). Measurements from GPS are also available over intervals shorter than 5 years at Trieste (2000.5–2005.5) and Venezia (2005.5–2007.5) (Zerbini, personal communication). Fig. 4 shows, for the time-interval of the GPS observations, the de-seasoned monthly sea level measured from altimetry and tide gauge data at the three stations. The errors of the trends are here bigger than in Table 2 due to the shorter time intervals. The trends are −1.6 ± 1.9 mm/yr in Marina di Ravenna, 2.4−/−4.0 mm/yr in Trieste and −2.7 ± 4.1 in Venezia and agree in sign with the GPS rates. Only the trend in Marina di Ravenna is statistically significant at 75% confidence level and is significantly smaller than the GPS derived rate.

3.2. Temporal and spatial characteristics of sea level change

The mean seasonal sea level cycle parameters computed for the monthly records of the eight tide gauges are given in Table 2. The annual sea level amplitude varies between 45 and 62 mm in agreement with Marcos and Tsimplis (2007). The annual cycle peaks between late September in the north and late October at the southern stations. On average, the mean seasonal cycle accounts for 60% of the total variance of monthly sea level records. The annual amplitude of sea level from altimetry ranges between 70 mm in the north and 40 mm in the south of the Adriatic Sea; the annual cycle

Table 2
Comparison of tide gauges (tg) and co-located altimetry (al) monthly sea level records in 1993–2008. Given are: distance between altimeter and tide gauge (column 2), standard deviation of the differences (column 3), correlation (column 4), trend of altimetric and tide gauge records (columns 5–6), trend of the differences (column 7), annual amplitude and phase of sea level at the tide gauge (columns 8–9).

Station	al-tg dist (km)	al-tg std (mm)	al-tg corr	alt trend (mm/yr)	tg trend (mm/yr)	al-tg trend (mm/yr)	tg Amp (mm)	tg phase (day)
Trieste	75	86	0.67	5.9 ± 1.3	4.1 ± 1.6	1.3 ± 1.2	59.8 ± 2.2	266 ± 2
Venezia	79	76	0.66	5.9 ± 1.4	5.6 ± 1.6	−0.2 ± 1.3	60.4 ± 2.2	272 ± 2
Ravenna	46	84	0.68	5.6 ± 1.4	6.5 ± 1.5	−1.5 ± 1.1	62.2 ± 2.2	278 ± 2
Rovinj	13	77	0.65	5.9 ± 1.3	2.6 ± 1.5	3.0 ± 1.2	58.2 ± 2.2	276 ± 2
Bakar	87	81	0.67	5.9 ± 1.3	4.2 ± 1.6	1.2 ± 1.1	49.0 ± 2.2	285 ± 2
Split Harbour	29	48	0.68	5.0 ± 1.0	5.2 ± 1.4	−0.2 ± 1.1	48.2 ± 2.2	295 ± 3
Split Marjana	31	52	0.67	5.0 ± 1.0	5.9 ± 1.4	−0.9 ± 1.1	45.3 ± 2.2	296 ± 3
Dubrobnik	20	53	0.66	5.8 ± 1.0	5.4 ± 1.3	−0.1 ± 1.1	50.2 ± 2.2	292 ± 3

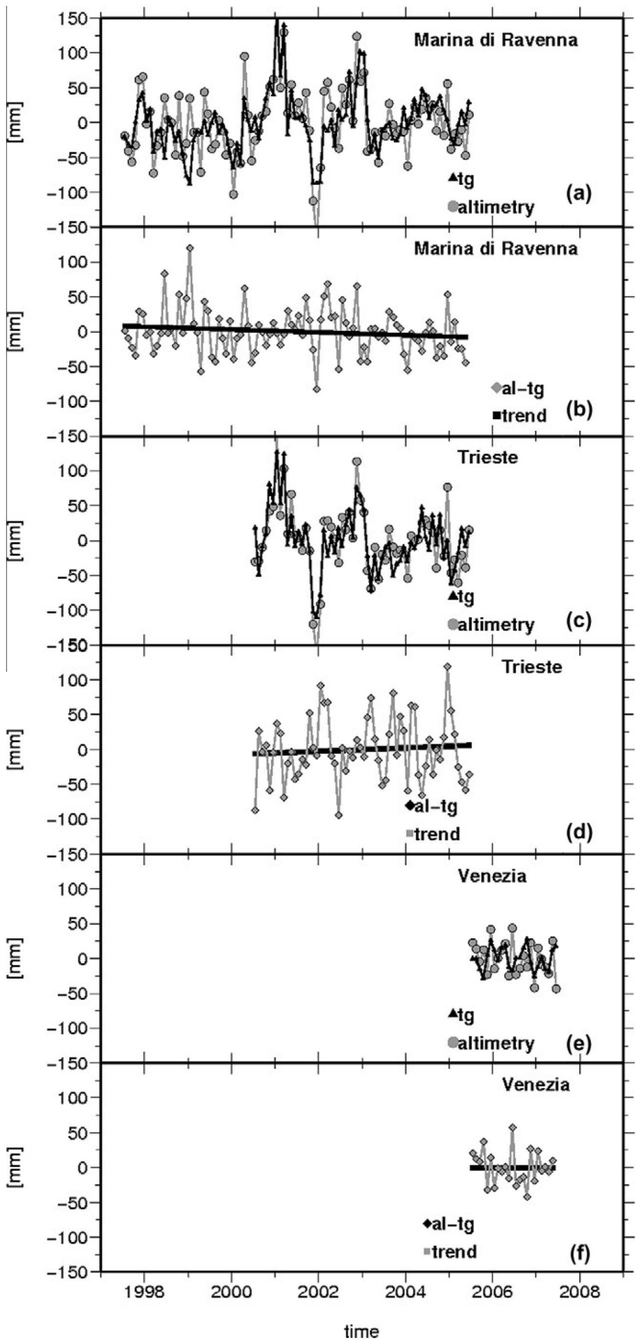

Fig. 4. Altimeter and tide gauge time-series with seasonal signal removed (a, c and e), their difference with trend (b, d and f) at Ravenna, Trieste and Venezia during the time-interval of GPS measurements.

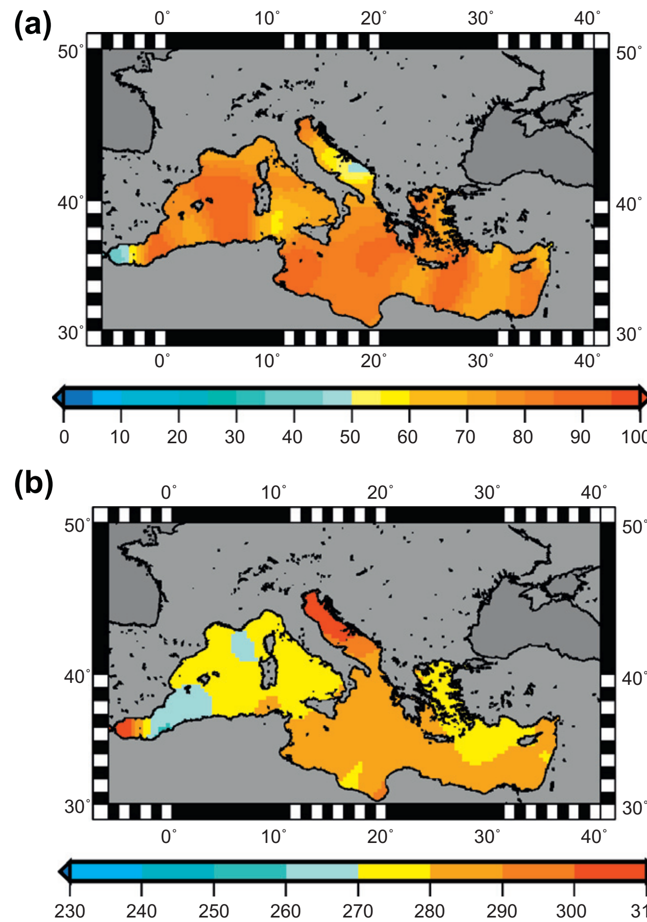

Fig. 5. Annual amplitude (mm) (left) and annual phase (right) of sea level from Jason-1 altimetry.

peaks in Autumn, later than in the rest of the Mediterranean Sea (Fig. 5).

The average over the Adriatic Sea of the altimetry-based sea level has been low-pass filtered by computing a running average over 12 months (Fig. 6). Its trend over 1993–2008 indicates a rise of sea level of 3.2 ± 0.3 mm/yr. The rate is not uniform and two distinct periods, before and after year 2001, are identified. The trend is positive (9 ± 0.5 mm/yr) between 1993 and 2000 and negative (−2.5 ± 0.5 mm/yr) between 2001 and 2008. A composite tide gauge record has been computed by averaging the monthly eight tide gauge records. In 1993–2006 all eight stations have contributed to compute the composite tide gauge record, while in 2006–2008 only the station of Trieste could be used (see also Fig. 1). Finally the composite tide gauge record was low-pass filtered like the altimetric basin average. Correlation and RMS differences of the two filtered time-series are 0.84 and 12 mm, confirming the high coherence of coastal and offshore sea level variability in the Adriatic at interannual time scales. In 1993–2008 the linear rate of the low-pass filtered composite tide gauge record (1.9 ± 0.3 mm/yr) is lower than the linear rate of the corresponding altimeter basin average. As for the altimetric basin average, the trend is positive before 2001 (7.6 ± 0.5 mm/yr) and negative afterwards (−3.7 ± 0.8 mm/yr). Our results agree with the common mode of the tide gauge sea level found by Buble et al. (2010) after 1993, although their trends of absolute and relative sea level are different as they refer to a longer time interval.

The high correlation between costal and offshore sea level variability is typical for the Adriatic Sea and partly due to the high number of tide gauges available. Other sub-basins of the Mediterranean Sea show a lower agreement between offshore and in situ interannual variability. In the Ionian Sea only the two tide gauges of Valletta (Malta) and Katakolon (Greece) have been available (Fig. 7). The tide gauge records are in this case less representative for the sea level of the sub-basin, being correlation and RMS differences of the low-pass filtered basin averages 0.4 and 31 mm respectively. The amplitude of the interannual signal (160 mm) in Ionian and in Adriatic Sea are comparable, their trends have opposite sign, with negative sign between 1996 and 2000 and positive sign after year 2001 in the Ionian Sea. In the Mediterranean Sea we have used 16 tide gauge stations, which are available over most part of the interval 1993–2006. Nine of them (Malaga,

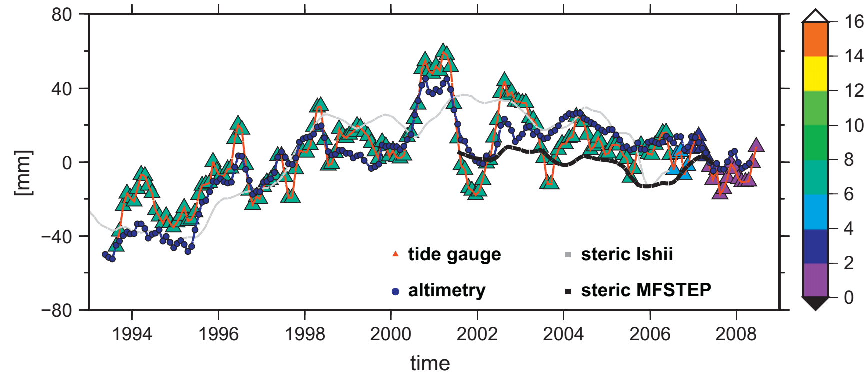

Fig. 6. Basin average of sea level in Adriatic Sea from altimetry (circle) and from tide gauges (triangle). A maximum of eight tide gauge stations (triangles in Fig. 1) have been used and the colour bars indicates the number of tide gauge stations used at each time step. Basin average of the steric component of sea level from the Ishii database (grey) and from the MFSTEP model (black) are also drawn. A moving average has been applied to the monthly de-seasoned data.

Barcelona, Marseille, Toulon, La Valletta, Khalkis, Khios, Leros, Hadera and Ceuta) have been considered in addition to those used for the Adriatic (eight) and the Ionian Seas (two) (Fig. 8). The tide-gauge- and the altimetry-based basin averages have good correlation and small RMS differences (0.85 and 9 mm). The amplitude of the interannual signal (80 mm) is smaller than in the two previous analysed sub-basins. The time-series show a steep increase between 1994 and 1996 and a lower interannual variability after 1996 (Fig. 7).

In the Adriatic Sea the sea level is highly correlated to the steric component of sea level computed from the temperature and salinity of the Ishii database (Ishii and Kimoto, 2009). The low-pass filtered basin averages have correlation and RMS differences of 0.86 and 15 mm. The linear trend of the steric sea level basin average is positive before 2001 (8.1 ± 0.4 mm/yr) and negative after 2001 (−5.1 ± 0.5 mm/yr). The MFSTEP model, available after year 2000, gives a smaller negative trend in the interval 2001–2008 (−2.2 ± 0.3 mm/yr) (Fig. 6).

The rates of the geocentric sea level have been evaluated at each grid point of the altimeter grids. Over the interval 1993–2008 the trends are statistically significant at the 90% level of significance in most of the basin, with negative rates only in the Ionian Sea. The linear rates have opposite signs in the central and eastern Mediterranean Sea over the intervals 1993–2006 and 2002–2008,

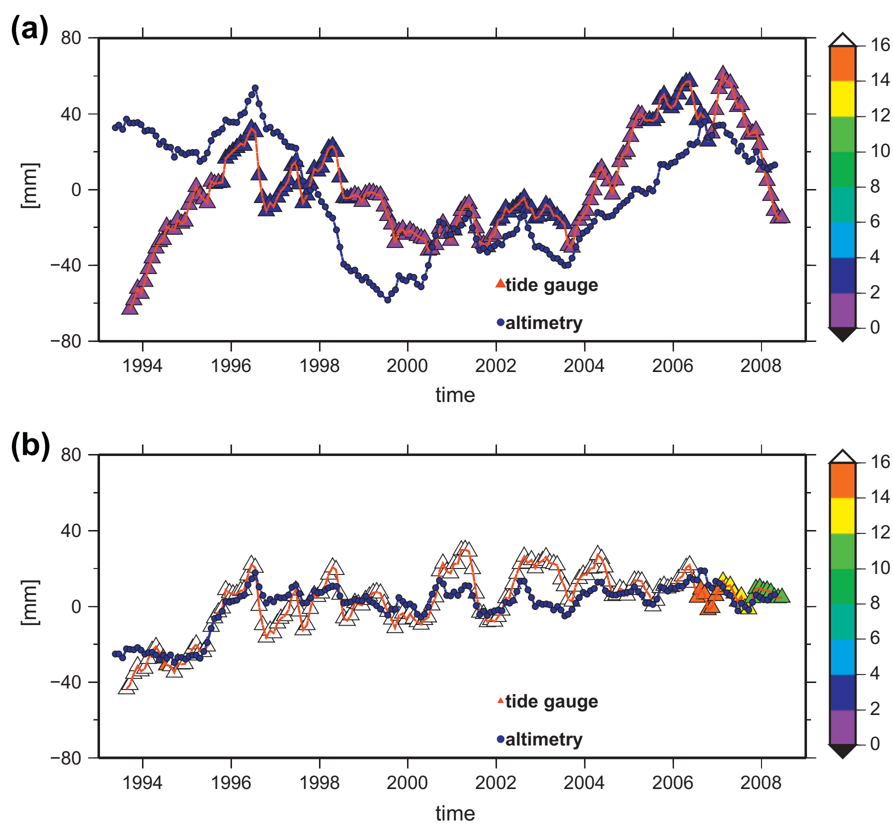

Fig. 7. Basin average in Ionian Sea (left) and in Mediterranean Sea (right) of sea level from altimetry (circle) and tide gauges (triangle). Maximum number of tide gauge stations used is two and nineteen respectively, colour bars indicates the number at each time step. A moving average has been applied to monthly de-seasoned data.

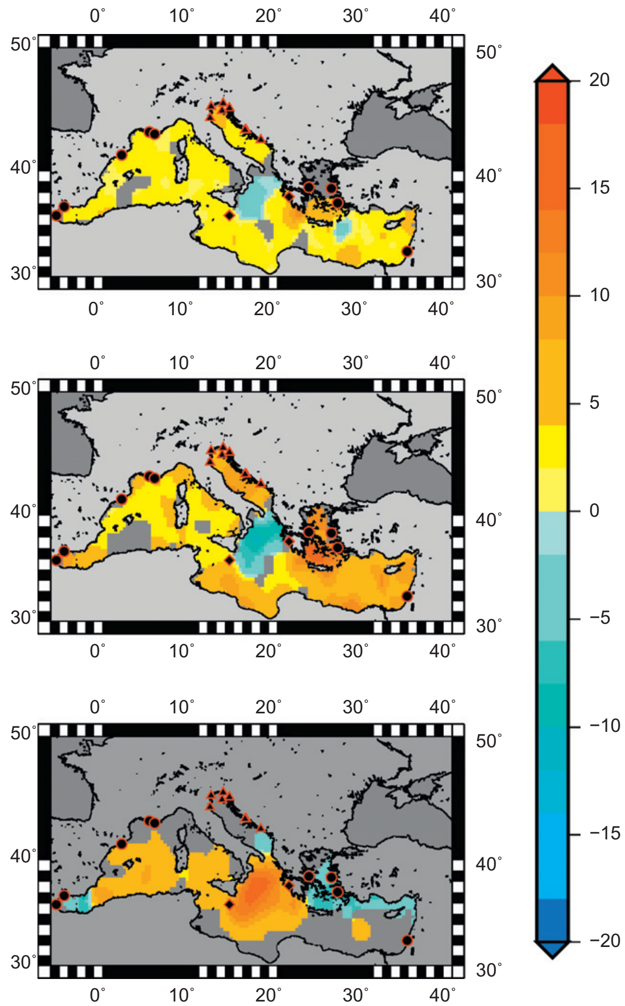

Fig. 8. Sea level trends (mm/yr) in Mediterranean Sea from multi-satellite altimetry in 1993–2008 (top), from Topex/Poseidon in 1993–2006 (centre) and from Jason-1 in 2002–2008 (bottom). Only trends significant at least at the 90% significance level are represented. The tide gauge stations used to compute the basin averages in the Adriatic Sea (triangle), in the Ionian Sea (diamond) and in the Mediterranean Sea (all) are indicated.

corresponding to the Topex/Poseidon and Jason-1 missions (Fig. 8). The first interval is characterized by positive rates in Adriatic and Eastern Mediterranean and by negative rates in the Ionian Sea, the rates being of opposite sign in the second time-interval. The significance of the trends is lower over the sub-intervals, due to the shorter time span.

The PCA decomposition of the altimeter grids covering the complete Mediterranean Sea shows regional differences between the Adriatic Sea and the rest of the Mediterranean Sea. The first four modes are statistically significant and explain together about 80% of the variance of sea level. The spatial and temporal components are shown in Fig. 9. The first mode accounts for 70.3% of the variability and primarily represents the annual cycle. The second mode (5.3% of the variance) corresponds to the sea level rise in 1993–2001 in the Adriatic and the Eastern Mediterranean, and to the simultaneous sea level drop in the Ionian Sea. The third mode (2.8%) represents the variability in the Ionian Sea, the forth mode (2.0%) the sea level rise in the Eastern Mediterranean Sea after year 2000 and the simultaneous decrease in the Adriatic Sea.

The first four modes of the PCA of sea level in the Adriatic Sea represent together about 98% of the variance, the first mode corresponds to an homogenous signal (84.8% of the variance) that includes both annual and interannual components. The other modes represent local signals of higher temporal variability: the second mode (6.6% of the variance) corresponds to the variability localized in the central part of the sub-basin, the third mode (5.5%) shows a seesaw between the northern and southern Adriatic Sea. Fig. 10 shows the four dominant modes, all satisfy the N rule. The PCA decomposition of the eight tide gauge monthly records shows similar dominant patterns, with the first mode corresponding to the common signal that explain 81% of the total variance.

4. Discussion and conclusions

With a combined analysis of altimetry and tide gauge data in the interval 1993–2008 we have investigated the absolute sea level rise and crustal motion in the Adriatic Sea. We have used the different characteristics of the two data types, namely their different reference and the different time and spatial sampling, to derive relevant information. Merging multi-mission altimeter data we have increased the length and the spatial and temporal resolution of the altimeter data and obtained co-located altimeter data much closer to the tide gauge stations. Applying the different definition of the sea level measured by altimeter and tide gauges, we have attempted to estimate the vertical crustal (land) motion at the tide gauge station.

The trends of the sea level differences between the altimeter and the tide gauges time-series at near locations are small compared to their uncertainties and therefore not all are statistically significant. A statistically significant land movement (90% confidence level) is detected in 1993–2008 only at Rovinj (3.0 ± 1.2 mm/yr) and Marina di Ravenna (−1.5 ± 1.1 mm/yr). A 75% confidence level is found in Trieste (1.5 ± 1.1 mm/yr) and Bakar (1.2 ± 1.1 mm/yr). Continuous GPS-measurements in Marina di Ravenna give a higher land subsidence rate than the rate obtained from the altimetry and tide gauge differences. The difference can arise from very local characteristics of anthropogenic origin, from the spatial distance between the locations corresponding to the altimetry and tide gauge measurements and from residual errors in the corrections applied.

The values we found for the crustal rates are in agreement with estimations made by geologic methods. Antonioli et al. (2009) compare relative sea-level change during the late Holocene, derived from geologic and archeological markers, with sea-level curves predicted from two post-glacial rebound-models (Lambeck et al., 2004; Stocchi and Spada 2009). In the North-Eastern Adriatic most of the measurements points indicate subsidence using both isostatic models as reference, the average of all points being −0.51 and −0.29 mm/yr respectively from the two models. However, in a few cores drilled in the Gulf of Trieste the tectonic subsidence reaches lower values, or even weak uplift, like in our results. This area of relative stability or weak uplift could result from the active growth of an NW–SE trending structural high recently detected across the Gulf of Trieste using high resolution seismic profiling (Busetti et al., 2007). Finally, Furlani et al. (2010) obtain tectonic rates between −1.99 mm/yr and 1.01 mm/yr near Trieste, using a multidisciplinary approach, that consists in comparing predicted curves with published data and new ^{14}C dating and geomorphological/archaeological/sedimentological observations. It is however not obvious that our estimation and the estimation made by geologic methods should be equal, as the time constants used in the averaging process are very different: 16 years for the instrumental records and 1–100 kys for the geologic estimates. In a seismic zone the short term rates can be very different from the long term rates, because the instantaneous rates depend on the phase of the seismic cycle (e.g. Meade and Hager, 2004). Moreover, the geologic site usually does not coincide with the tide gauge, so local

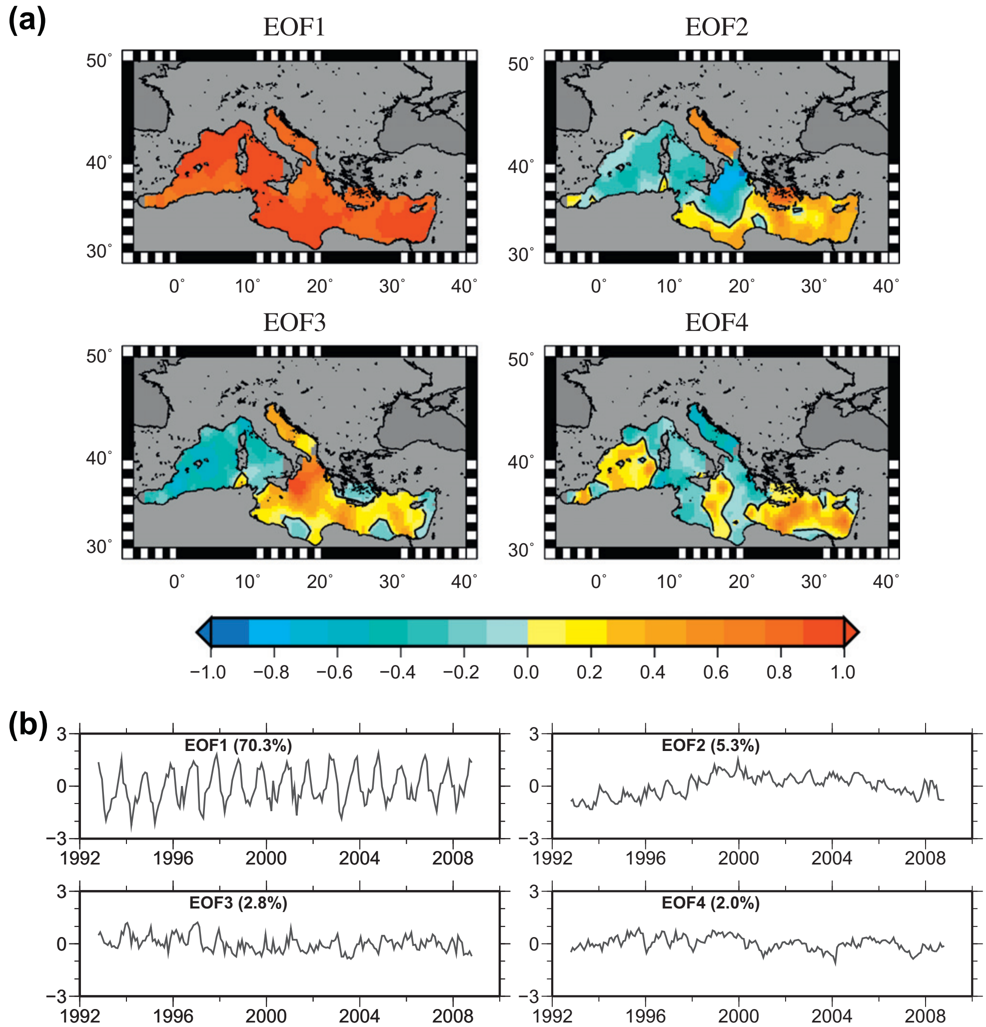

Fig. 9. Dominant spatial patterns (top) and temporal coefficients (bottom) of sea level variability in Mediterranean Sea from altimetric standardized monthly grids. The cumulative percentage of variance is given for each EOF component.

effects can provoke differences in vertical movement rates, especially in the presence of faults and changes in the compactness of the coastal rocks or sediment cover.

We have shown that both the absolute (altimetry-derived) and the relative (tide-gauge derived) sea level changes are spatially homogeneous in the region and indicate a sea level rise over 1993–2008. When averaged over the Adriatic they have both a positive trend, which is higher for the absolute (3.2 ± 0.3 mm/yr) than for the relative (1.9 ± 0.3 mm/yr) estimation. The rates are positive before 2001 and negative after 2001 and are contaminated by the inter-annual variability. At basin scale in the Adriatic Sea the linear-term of sea level change is strongly correlated to the linear-term in the steric component of sea level, suggesting that sea level changes in the Adriatic are governed by sea temperature and salinity changes. The variability in the Adriatic is coherent and strongly correlated to the eastern Mediterranean and anti-correlated with the Ionian Sea. Our results agree with Buble et al. (2010), that found over the common interval 1993–2008 similar dominant modes of sea level variability from tide gauges. These authors have considered a longer time-interval and therefore their trends of absolute and relative sea level are not comparable with ours. The crustal rates are of the same order of magnitude.

We recognize that the spatial and temporal differences between altimetry and tide gauge measurements cannot be ignored. With multi-mission altimetry data the coverage is greatly improved, however the distance between the locations of the altimeter and tide gauge observations is still several kilometres, because of the geometry of the ground-tracks and of land–water interference caused by the radiometer and radar footprints. The differential sea level rates are correctly interpreted as crustal movement if the rates are measured at the same location or if they are spatially homogeneous. If the wavelengths of the sea level rates are of a few tens of km, then this supposition is granted, because the distance between the stations and the satellite location is of this magnitude. Also the application of specific models or empirical corrections, as ocean tide and atmospheric pressure effects can effect the results. The altimeter error budget in coastal regions remains therefore an important topic of research and discussion. In general, the comparison of altimeter and coastal tide gauge measurements needs to be thoroughly examined, in view of the growing importance of satellite altimeter measurements as a means of monitoring sea level rise and of the recent improvement of shallow-water satellite altimetry (Vignudelli et al., 2011).

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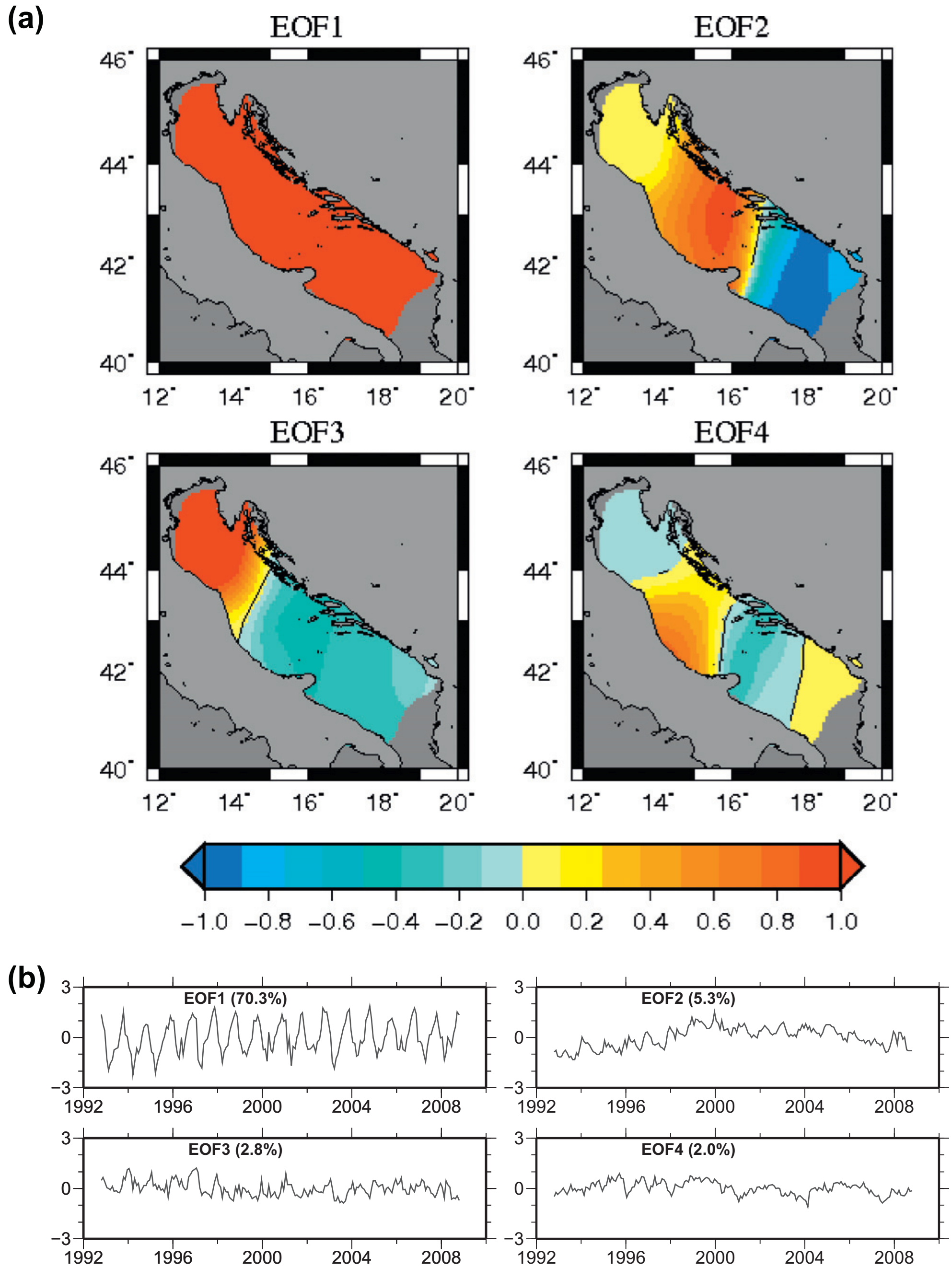

Fig. 10. Dominant spatial patterns (top) and temporal coefficients (bottom) of sea level variability in the Adriatic Sea from altimetric standardized monthly grids. The cumulative percentage of variance is given for each EOF component.

of Marina di Ravenna, Venezia and Trieste, the GPS rates and for discussion. Comments by two anonymous reviewers helped to improve the manuscript. This research was supported by the Deutsche Forschungsgemeinschaft (DFG BE-1277, FE-354) and has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri – Dipartimento della Protezione Civile (DPC). Scientific papers funded by DPC do not represent its official opinion and policies.

References

Ablain, M., Cazenave, A., Valladeau, G., Guinehut, S., 2009. A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008. Ocean Sci. 5, 193–201.

Andersen, O.B., Knudsen, P., 2009. DNSC08 mean sea surface and mean dynamic topography models. J. Geophys. Res. 114, C11001. doi:10.1029/2008JC005179.

Antonioli, F., Ferranti, L., Fontana, A., Amorosi, A.M., Bondesan, A., Braitenberg, C., Dutton, A., Fontolan, F.G., Furlani, S., Lambeck, K., Mastronuzzi, G., Monaco, C., Spada, G., Stocchi, P. 2009. Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines. Quatern. Int. doi: 101016/j.quaint.2008.11.008.

Beckley, B.D., Lemoine, F.G., Luthcke, S.B., Ray, R.D., Zelensky, N.P., 2007. A reassessment of global rise and regional mean sea level trends from Topex and Jason-1 altimetry based on revised reference frame and orbits. Geophys. Res. Lett. 34, L14608. doi:10.1029/2007GL030002.

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L., Unnikrishnan, A., 2007. Observations: oceanic climate and sea level. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergouvernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, New York, USA, pp. 385–428.

Blewitt, G., Altamimi, Z., Davis, J.L., Gross, R.S., Kuo, C., Lemoine, F., Moore, A.W., Neilan, R., Plag, H., Rothacher, M., Shum, C., Sideris, M., Schöne, T., Tregoning, P., Zerbini, S., 2010. Geodetic observations and global reference frame contributions to understanding sea level rise and variability. In: Church, J., Woodworth, P.L., Aarup, T., Wilson, S. (Eds.), Understanding Sea Level Rise and Variability. Wiley-Blackwell, London, pp. 256–284.
Bloomfield, P., 1976. Fourier Analysis of Time Series: An Introduction. John Wiley and Sons, New York, pp. 129–137.
Buble, G., Bennett, R.A., Hreinsdottir, S., 2010. Tide gauge and GPS measurements of crustal motion and sea level rise along the eastern margin of Adria. J. Geophys. Res. 115, B02404, doi: 10.1029/208JB006155.
Braitenberg, C., Mariani, P., Tunini, L., Grillo, B., Nagy, I., 2010. Vertical crustal movements from differential tide gauge observations and satellite altimetry in southern Italy. J. Geodynam. doi: 10.1016/j.jog.2010.09.003.
Busetti, M., Gordini, E., Baradello, L., Cova, A., Caburlotto, A., Deponte, M., Nieto, D., Tomini, I., 2007. The morphological and seismic stratigraphic characterization of the Grado and Marano lagoon (northern Adriatic). In: Convegno Nazionale "GeoItalia 2007", Rimini 12–14 sett. 2007, vol. 2, pp. 48–50.
Carbognin, L., Teatini, P., Tomasin, A., Luigi, T., 2009. Global change and relative sea level rise at Venice: what impact in term of flooding. Climate Dynamics Springer Berlin/Heidelberg Earth and Environmental Science 1039-104735610.1007/s00382-009-0617-5.
Carrère, L., Lyard, F., 2003. Modelling the barotropic response to the global ocean to atmospheric wind and pressure forcing with observations. Gephys. Res. Lett. 30, 8–1.
Cazenave, A., Dominh, K., Ponchaut, F., Soudarin, L., Cretaux, J.F., Le Provost, C., 1999. Sea level changes from TOPEX-Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS. Geophys. Res. Lett. 26 (14), 2077–2080.
Cazenave, A., Cabanes, C., Dominh, K., Mangiarotti, S., 2001. Recent sea level change in the Mediterranean Sea revealed by TOPEX-Poseidon satellite altimetry. Geophys. Res. Lett. 28 (8), 1607–1610.
Church, J., White, N.J., Arrup, T., Wilson, W.S., Woodworth, P.L., Domingues, C.M., Hunter, J.R., Lambeck, K., 2008. Understanding global sea levels: past, present and future. Sustain. Sci. 3, 9–22, doi: 10.1007/s11625-008-0042-4.
Chelton, D.B., Ries, J.C., Haines, B.J., Fu, L.L., Callahan, P., 2001. Satellite altimetry. In: Fu, L.L., Cazanave, A. (Eds.), Satellite Altimetry and Earth Sciences. Academic Press, NY, pp. 57–64.
Domingues, C.M., Church, J., White, N.J., Gleckler, P.J., Wijffels, S.E., Barker, P.M., Dunn, J.R., 2008. Improved estimates of upper-ocean warming and multi-decadal sea level rise. Nat. Lett. 453, 1090–1093, doi: 10.1038.nature07080.
Dong, X., Woodworth, P., Moore, P., Bingley, R., 2002. Absolute calibration of the Topex/Poseidon altimeters using UK Tide gauges, GPS and Precise local Geoid-differences. Mar. Geod. 25, 189–204.
Douglas, B.C., 2001. Sea level change in the era of the recording tide gauge. In: Sea Level Rise, History and Consequences, International Geophysics Series, vol. 75, Academic Press.
Fenoglio-Marc, L., 2001. Analysis and representation of regional sea level variability from altimetry and atmospheric data. Geophys. J. Int. 145 (1), 1–18.
Fenoglio-Marc, L., 2002. Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauges. Phys. Chem. Earth 27, 1419–1431.
Fenoglio-Marc, L., Groten, E., Dietz, C., 2004. Vertical land motion in the Mediterranean Sea from altimetry and tide gauge stations. Mar. Geodesy 27 (3–4), 683–701.
Fenoglio-Marc, L., Tel, E., 2010. Coastal and global sea level change. J. Geodynam. doi: 10.1016/j.jog.2009.13.003.
Furlani, S., Biolchi, S., Cucchi, F., Antonioli, F., Busetti, M., Melis, R., 2010. Tectonic effects on late Holocene sea level changes in the Gulf of Trieste (NE Adriatic Sea, Italy), Quatern. Int. doi: 10.1016/j.quaint.2010.06.012.
Gill, A.E., 1982. Atmosphere–Ocean Dynamics. International Geophysics Series, Academic Press, pp. 662.
Holgate, S.J., 2007. On the decadal rates of sea level change during the twentieth century. Geophys. Res. Lett. 34, L01602. doi:10.1029/2006GL028492.
Ishii, M., Kimoto, M., 2009. Re-evaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. J. Oceanogr. 65, 287–299.
Klein, M., Lichter, M., 2008. Statistical analysis of recent Mediterranean Sea level data, Geomorphology, doi: 10.1016/j.geomorph.2007.06.024.
Kuo, C.Y., Shum, C.K., Braun, A., Mitrovica, J.X., 2004. Vertical crustal motion determined by satellite altimetry and tide gauge data in Fennoscandia. Geophys. Res. Lett. 31 (1), L01608 10.1029/2003GL019106.
Lambeck, Johnston, 1995. Land subsidence and sea-level change: contribution from the melting of the last great ice sheets and isostatic adjustment of the Earth. In: Barends, F.B.J., Brouwer, F.J.J., Schroder, F.H. (Eds.), Land Subsidence. Taylor and Francis, London, pp. 3–18.
Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004. Sea level change along the Italian coast for the past 10,000 yrs. Quaternary. Sci. Rev. 23, 1567–1598.
Lionello, P., Mufato, R., Tomasin, A., 2005. Sensitivity of free and forced oscillations of the Adriatic Sea to sea level rise. Climate Res. 29, 23–39.
Marcos, M., Tsimplis, M.N., 2007. Variations of the seasonal sea level cycle in southern Europe. J. Geophys. Res. 112, C12011. doi:10.1029/2006JC004049.
Marcos, M., Tsimplis, M.N., 2008. Coastal sea level trends in Southern Europe. Geophys. J. Int. 175, 70–82, doi: 10.1111/j.1365-246X.2008.03892.x.
Maul, G.A., Martin, D.M., 1993. Sea level rise at key west, Florida, 1846–1992: America's longest Instrument record? Geophys. Res. Lett. 20, 1955–1958.
Meade, B.J., Hager, B.H., 2004. Viscoelastic deformation for a clustered earthquake cycle. Geophys. Res. Lett. 31, L10610, doi: 10.1029/2004GL019643.
Mitchum, G.T., 2000. An improved calibration of satellite altimetric heights using tide gauge sea levels with adjustment for land motion. Mar. Geodesy 23 (3), 145–166.
Naeije, M., Scharroo, R., Doornbos, E., Schrama, E., 2008. Global Altimetry Sea-level Service: Glass, NUSP-2 report GO 52320 DEO, NIVR/DEOS, Netherlands.
Nerem, R.S., Mitchum, G.T., 2002. Estimates of vertical crustal motion derived from differences of Topex/Toseidon and sea level measurement. Geophys. Res. Lett. 29, 1934.
Orlić, M., Pasarić, M., 2000. Sea-level changes and crustal movements recorded along the east Adriatic coast. Nuovo Cimento Della Societa Italiana Di Fisica C – Geophys. Space Phys. 23, 351–364.
Overland, J.R., Preisendorfer, R.W., 1982. A significant test for principal components applied to cyclone climatology. Mon. Weather Rev. 110 (1), 1–4.
Parker, R.L., 1994. Geophysical Inverse Theory. Princeton University Press, Princeton, USA, 386pp.
Pascual, A., Marcos, M., Gomis, Damia, 2008. Comparing the sea level response to pressure and wind forcing of two barotropic models: validation with tide gauge and altimetry data. J. Geophys. Res. doi: 10.1029/2007JC004459.
Pirazzoli, P.A., 1991. Possible defenses against a sea-level rise in the Venice area, Italy. J. Coastal Res. 7, 231–248.
Pirazzoli, P., Tomasin, A., 2008. Sea-level and Surges in the Adriatic Sea: Recent Trends and Possible Near-future Scenarios. Atti dell'Istituto Veneto di Scienze, Lettere ed Arti, Tomo CLXVI.
Prandi, P., Cazenave, A., Becker, M., 2009. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007. Geophys. Res. Lett. doi: 10.1029/2008GL036564.
Preisendorfer, R.W., 1988. Principal Component Analysis in Meteorology and Oceanography, Developments in Atmospheric Science, N. 17, Elsevier, Amsterdam.
Raicich, F., 2007. A Study of the early Trieste sea level data. J. Coastal Res. 23 (4), 1067–1073.
Ray, R.D., Beckley, B.D., Lemoine, F.G., 2010. Vertical crustal motion derived from satellite altimetry and tide gauges and comparison with DORIS measurements. Adv. Space Res. 45, 1510–1522.
Santer, B.D., Wigley, T.M.L., Boyle, J.S., Gaffen, D.J., Hnilo, J.J., Nychka, D., Parker, D.E., Taylor, K.E., 2000. Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. J. Geophys. Res. 105 (D6), 7337–7356, doi: 10.1029/1999JD901105.
Stocchi, P., Spada, G., 2009. Influence of glacial isostatic adjustment upon current sea level variation in the Mediterranean Sea. Tectonophysics 474, 55–68.
Tiezzi, E., Marchettini, N., 1997. Venezia e il problema delle acque alte. II rischio di danno al patrimonio urbano a causa della crescita relativa del livello del mare. Quaderni Trimestrali Consorzio Venezia Nuova 5 (2), 23–45.
Tonani, M., Pinardi, N., Dobricic, S., Pujol, I., Fratianni, C., 2008. A high-resolution free-surface model of the Mediterranean Sea. Ocean Sci. 4, 1–14.
Tosi, Teatini, P., Carbognin, L., Brancolini, G., 2009. Using high resolution data to reveal depth-dependent mechanisms that drive land subsidence: The Venice coast, Italy (2009) Tectonophysics. TOPO-EUROPE: The Geoscience of coupled Deep Earth-surface processes 474 (1–2), p. 271–284. doi: 10.1016/j.tecto.2009.02.026.
Trisirisatayawong, I., Naeije, M., Simons, W., Fenoglio-Marc, L., 2011. Sea level change in the gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry. Gloabal Planet. Change in press, doi:10.1016/j.gloplacha.2010.12.010.
Tushingham, A.M., Peltier, W.R., 1989. ICE-3G: a new global model of late Preistocene deglaciation based upon geophysical predictions of post glacial relative sea level change. J. Geophys. Res. 96, 4497–4523.
Vignudelli, S., Kostianov, A., Cipollini, P., Benveniste, J. (Eds.) 2011. Coastal Altimetry, Springer Verlag. doi: 10.1007/978-3-642-12796-0.
Vigo, I., Garcia, D., Chao, B.F., 2005. Change of sea level trend in the Mediterranean and Black Seas. J. Mar. Res. 63, 185–1100.
Wöppelmann, G., Zerbini, S., Marcos, M., 2006. Tide gauges and Geodesy: a secular synergy illustrated by three present-day case, C.R. Geosci. doi: 10.1016/j.crte.2006.07.006.
Woodworth, C., 2003. Some comments on the long sea level records from the northern Mediterranean. J. Coastal Res. 19, 212–217.
Woodworth, P., Player, R., 2003. The permanent service for mean sea level: an update to the 21st century. J. Coastal Res. 19 (2), 287–295.
Zerbini, S., Richter, B., Rocca, F., van Dam, T., Matonti, F., 2007. A combination of space and terrestrial geodetic techniques to monitor land subsidence. Case study, the South Eastern Po Plain, Italy. J. Geophys. Res. 112, B05401. doi:10.1029/2006JB004338.