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Vertical crustal motions from differential tide gauge observations and satellite altimetry in southern Italy

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ABSTRACT

Our goal is to determine vertical crustal movement rates from tide gauge and satellite altimetry measurements. Tide gauges measure sea level, but as they are fixed to the crust, they sense both sea surface height variations and vertical crustal movements. The differential sea level rates of sufficiently nearby stations are a good means to determine differential crustal movement rates, when sea level height variations can be assumed to be homogeneous. Satellite altimetric measurements determine sea surface height variations directly and can be used to separate the crustal signal from the sea surface height variations in tide gauge measurements. The correction of the tide gauge sea level rates for the sea surface height contribution requires collocation of the satellite pass and the tide gauge station. We show that even if this is not the case, the satellite altimetric observations enable correction of differential tide gauge rates for the effects of sea surface rate inhomogeneities.

We apply the methodology to an area of broad scientific interest, due to its high seismic risk and its location as standpoint for a proposed major bridge connecting Sicily to the Italian mainland.

We find that the Southern Calabria and the eastern Sicily tide gauges have a deficit in sea level increase of 1–2 mm/yr with respect to the north western Sicilian tide gauge. The satellite altimetric observations show that this differential movement must be caused by a tectonic component, because the sea surface rates are higher offshore eastern Sicily compared to offshore western Sicily. The satellite altimetric rates show that the sea surface rates are inhomogeneous in the Mediterranean and have larger amplitudes as we move away from the coast than immediately offshore. Our technique can be applied to any part of the world where tide gauge observations are available, because satellite altimetric observations are global.

1. Introduction

The sea level measured by tide gauges is the sum of crustal movement rate and the sea surface height variation. In this paper we define sea surface height as the geocentric height as measured by satellite altimeters (e.g., Chelton et al., 2001). We use the term sea level to define the quantity measured by tide gauges, which must be tied to a geodetic height reference system in order to be an absolute quantity. Since sea level changes in space and time, a single tide-gauge station is insufficient to characterize vertical crustal movement, as independent information is necessary to separate crustal movement from the sea surface height change. The differential rate of two close tide-gauge stations is representative of differential crustal rates, where the differences in sea surface height rates are either negligible or known. The differential rate between a tide gauge and the sea surface height observed by satellite altimeter is equal to the geocentric crustal movement rate (Cazenave et al., 1999; Fenoglio-Marc et al., 2004; Kuo et al., 2004; Mangiarotti, 2007). Ideally the satellite track must fly over the tide gauge station (or at least close to it). The success of the method has been demonstrated by Kuo et al. (2004, 2008), where the vertical rates have been verified by GPS observations.

Along the Italian coast (7570 km length of coastline (Antonioli and Silenzi, 2007)) the number of tide gauges amounts to 26, and therefore is a valuable source of information for estimating vertical crustal movement rates. The sea level increase rates of the Mediterranean have been mapped (Klein and Lichter, 2008; Church et al., 2004; Marcos and Tsimplis, 2008; Pirazzoli, 1996; Douglas et al., 2001) using tide gauge data from the Permanent Service for mean Sea Level (PSMSL; http://www.pol.ac.uk/PSMSL (Woodworth, 1991; Woodworth and Player, 2003)). They vary between −16 mm/yr and 18 mm/yr (Piraeus and Khios, respectively, time interval 1990–2003; Klein and Lichter, 2008). The observed scatter of the rates is due to the combined effect of crustal movement, locally varying sea surface height, and biases introduced by the time intervals used for determining the rates. The specific time interval used for the calculation affects the rates because there is intrinsic variability in time of the sea surface vari-

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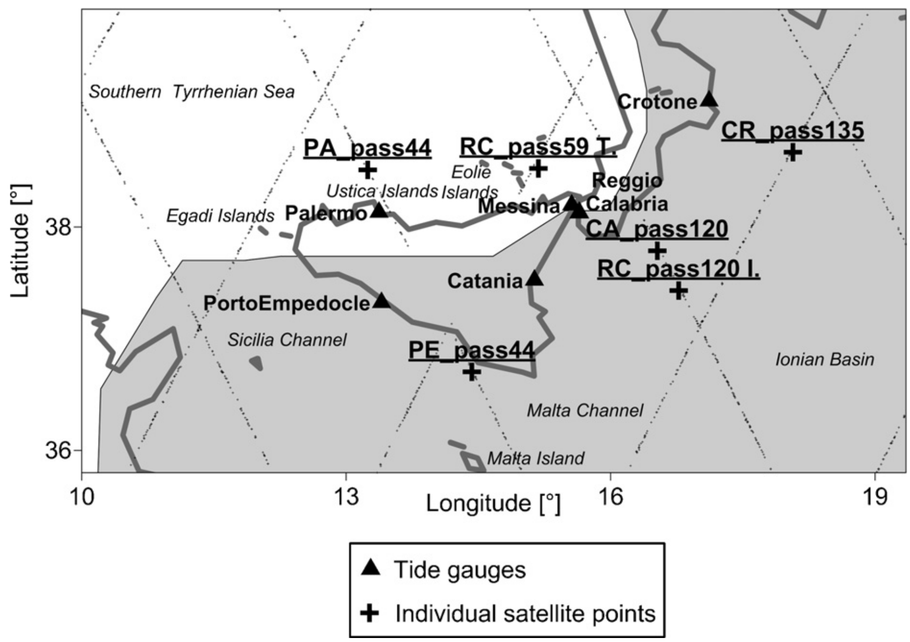

Fig. 1. Geographical index map. Italian tide gauges (black triangles), Topex/Poseidon and Jason 1 satellites passes (dotted lines), individual satellites points (black crosses). Grey/white shaded area: distinguishes the Tyrrhenian and Adriatic regions used for interpolation.

ation (e.g., Marcos and Tsimplis, 2007). Mangiarotti (2007) has analysed tide gauges and satellite altimetry for the Mediterranean with the aim of finding coastal sea level trends, neglecting the contribution of vertical crustal movement. Fenoglio-Marc (2002, 2003) and Fenoglio-Marc et al. (2004) obtained the first interesting results on crustal rates for the Mediterranean using tide gauges and satellite altimetry.

In our work we investigate the case in which the altimetric and tide gauge observations are relatively distant from each other, as is the case for many stations along the Italian coastline. In fact the longest altimetric time series stem from the Topex/Poseidon satellites and the subsequent Jason 1 and 2 missions which cross the Italian peninsula with only four tracks. The spatial coverage is greatly improved with the ENVISAT satellite, which presently has only a seven-year data-series, too short to be used for determining sea level trends robustly. Specifically we consider Sicily and Calabria which are of general interest, given the high seismic potential of the area (Doglioni et al., 1999; Ferranti et al., 2007) and the plan to connect Sicily to Calabria by bridge. The Holocene and Late Pleistocene rates are locally known from geomorphologic studies (Antonioli et al., 2006, 2009; Ferranti et al., 2006, 2007) and demonstrate one of the highest uplift rates in the entire Italian peninsula, with vertical Holocene rates in eastern Sicily (St. Alessio and Taormina) of 2.4 mm/yr and in southwestern Calabria (Scilla) of 2.1 mm/yr. These rates are average rates over a period of up to 10 kyr, and it is crucial to compare these with the present instrumental rates in view of the engineering applications and the seismic risk. The map in Fig. 1 shows the tide gauges and the satellite passes available for one segment of the Mediterranean Sea.

Several continuous GPS stations are presently maintained in Calabria-Sicily, and in the future it will be possible to obtain GPS-determined vertical movement rates (RING-network, http://ring.gm.ingv.it/). In 2010 the Sicilian-Calabria network has several stations with at least 4 years of data, which allows us to calculate the vertical rates, although special attention has to be given to methodology and to the choice of reference stations. The vertical rates are under study (personal communication Dr. Federica Riguzzi, Data Analysis for Geodesy, INGV), and have not yet been published, except for station Reggio Calabria (TGRC). To be compared with the tide gauges, the GPS stations must be collocated. The sites of the GPS stations were chosen disregarding the position of the tide gauges and are quite far from them. In Reggio Calabria the GPS station (TGRC) has 6.5 years of data (2000.5–2007), is mounted on the roof of a building and has some fluctuations in the linear trend. Serpelloni et al. (2006) report an uplift of 0.97 mm/yr with respect to the stable Sardinia block on a very limited data set of 3.4 years, the calculated GPS velocity being -0.23 ± 1.3 mm/yr (positive upwards). As will be shown later, we calculate the differential sea level rates between tide gauges. An instrumental validation of the results would require the differential rates between GPS stations, with at least one GPS common to the tide gauges. Due to the present distribution of GPS station and the time windows of available data, the differential GPS vertical movement rates are unavailable (personal communication Dr. Federica Riguzzi). Therefore the rates we derive from the tide gauges are complementary to the vertical rates that will be obtained by GPS in the next few years.

For the sake of simplicity, we choose one particular tide gauge station as a reference station with respect to which the differential rates are calculated. It is advisable to choose a station that has been classified geologically as the most stable. It should be noted that the results are also valid in the case that the reference station is moving. We choose the Palermo tide gauge as the reference station relying on the information from geological investigations. The average vertical movement rate since the last interglacial period (MIS 5.5: 132–116 kyr) can be determined from observation of the height and age of geological markers that document the past sea level. For Sicily Ferranti et al. (2006) report variations of the level of the MIS 5.5 markers between 2 m and 175 m. The authors compare these levels to the expected worldwide global height for a stable coast of 6 ± 3 m following Lambeck et al. (2004). They find a level very close to the expected level for the north-western Sicily coast near Palermo (7–10 m), levels up to 100 m for the north-eastern Sicily coast, and very high levels for the eastern Sicilian coast (140–170 m). High levels of the markers of MIS 5.5 highstand are also found for the Calabria coast (85–175 m) (Ferranti et al., 2006; Antonioli et al., 2009). The geological observations give us an average movement over the last 116–132 kyr years, and there-

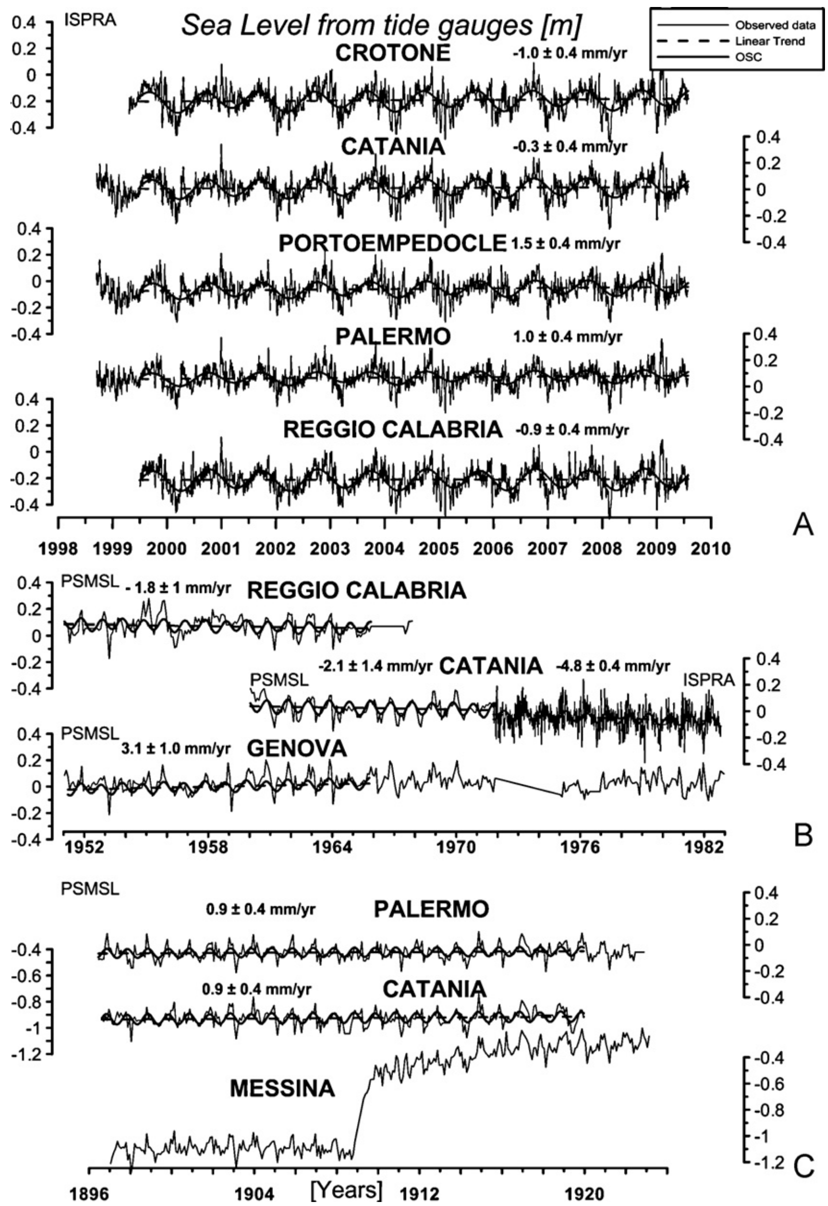

Fig. 2. Tide gauge data in three time intervals for the Sicily-Calabria study area: observed data (black), the best-fitting oscillation summed to the linear trend (black) and the linear trend (dashed line). (A) Recent (1999.5–2009.1) data with daily sampling (ISPRA). (B) Time interval between 1951 and 1983: monthly (PSMSL) and daily data (ISPRA). The station Genova is a reference station when Palermo is unavailable. (C) Historical data set (1896–1924). The Messina record includes the coseismic and postseismic sea level record of the 1906 earthquake.

fore not necessarily the present movement. Nonetheless, we may safely assume that among all tide gauge stations available in Sicily and Calabria, that located on the western Sicilian coast is relatively stable and has moved with rates that are one to two orders of magnitude smaller than the ones on eastern Sicily or Calabria. Presently this is the most rational choice we can make, as alternative instrumental measurements are unavailable.

2. The tide gauge data set

We refer to two oceanographic databases, the ISPRA (2009) (Istituto Superiore per la Protezione e la Ricerca Ambientale, http://www.apat.gov.it/site/it-IT) and the PSMSL (Permanent Service for Mean Sea Level, http://www.pol.ac.uk/psmsl/) data base. The PSMSL and ISPRA stations coincide, but cover different time periods. The ISPRA data are available with hourly sampling interval, while the PSMSL data only provide monthly sampling interval. Because of the higher sampling rate, we use only the ISPRA data for the recent interval and the comparison to the satellite. In Fig. 2 we present the available tide gauge data. Fig. 2A refers to the recent data (1998–2009) from the ISPRA data base. The hourly data have been reduced to daily sampling by averaging the values over an interval of 24 h. In order to determine a mean linear trend we fit the observations using a least square approximation with a sequence $m(t)$ composed of a linear function and an annual and semi-annual oscillation. An alternative two-step procedure could de-season the data and then fit the best linear trend. The function $m(t)$ is defined as follows, where a_0, a_{t}, $a_{\cos 1}$, $a_{\sin 1}$, $a_{\cos 2}$, $a_{\sin 2}$, are the parameters to be determined, and ω_1 and ω_2 are the yearly and half-yearly angular frequencies, respectively (for the yearly and half-yearly frequencies see, e.g. Maul and Martin, 1993).

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

We must define 6 unknown parameters by a multivariate least squares adjustment, using about 3600 constraining equations for the tide gauges (nearly 10 years of daily data samples) and about 360 equations (nearly 10 years with 10-day sampling for the altimeter. The average linear trend is given by parameter a_t and its uncertainty is equal to the standard error of the coefficient estimate. We assume zero mean and Gaussian distribution of the residual for the standard error estimate (e.g. Parker, 1994). Care should be taken when comparing the estimated errors from different authors, as some papers (e.g., Maul and Martin, 1993; Fenoglio-Marc et al., 2004) scale the errors using a formula that defines significant degrees of freedom by the auto-correlation analysis of the sequences. This procedure does not alter the trend results, but yields an increase of the estimated errors of nearly 50%. We prefer to keep the standard errors without inflation, as they are comparable to the majority of uncertainties published. The parameters obtained from the regression analysis are found in Table 1. All relevant quantities are listed: start and end year of the sequence, the number of equations for the regression analysis (N), the root mean square of the residual (Δt), and the regression parameters with the respective errors. The first seven rows of the table refer to ISPRA data, the following rows to PSMSL data. Differences of sea level rates must always be evaluated using identical time intervals. The linear sea level rate lies between -4.8 ± 0.4 mm/yr (Catania, 1971.8–1982.8) and 3.1 ± 1.0 mm/yr (Genova, 1951.2–1968). The amplitude of the annual signal (equal to $\sqrt{a_{\cos 1}{}^2 + a_{\sin 1}{}^2}$) is systematically greater than the half-year amplitude (equal to $\sqrt{a_{\cos 2}{}^2 + a_{\sin 2}{}^2}$) by a factor of about 7. The rms of the residual Δt is about 70 mm for the ISPRA data, and slightly lower (about 50 mm) for the PSMSL data. The reduction of Δt is ascribable to the reduced high frequency content in the PSMSL data. We find that all stations except Porto Empedocle have a systematic rate deficit with respect to Palermo over the interval 1999.5–2009.1. In Fig. 2A the black heavy line shows the best fitting annual and semi-annual oscillation and the dashed line the best fitting linear trend. The numbers indicate the annual linear trend with the respective error. The time interval between 1951 and 1983 is shown in Fig. 2B, and the data are monthly for the PSMSL data base. This interval shows the Genova data, as we will use it as a stable reference station when the Palermo data are missing. Genova is the reference tide gauge station of the Italian levelling system and has been shown to be stable (Salvioni, 1957; Serpelloni et al., 2006). The historic data (1896–1924) are shown in Fig. 2C, and are of interest as they cover the 1908 Messina-Reggio Calabria earthquake and span 10 years before and after the great earthquake of magnitude $M = 7.0$ (e.g., Bottari et al., 1986; Pino et al., 2000; Valensise and Pantosti, 1992; Michelini et al., 2006). The step in the Messina data demonstrates a co-seismic subsidence of 43 cm, which is recorded between start and end of the 5 months-long interruption of the data, and a subsequent post-seismic subsidence of 32 cm which continues until the end of the data series in 1922. The lack of subsequent data does not allow estimating the full duration of the post-seismic movement, or determining whether in 1922 it came to an end. The total subsidence composed of the co-seismic and post-seismic movement amounts to at least 77 cm.

The parameters obtained from the regression analysis are found in the second half of Table 1. For the older data (1950–1972) stations Catania and Reggio Calabria have a rate deficit with respect to Genova. This is interesting, as it would confirm that these two stations have a rate deficit with respect to a stable station. Due to the great distance of Genova from the Sicilian island, we do not pursue the calculation of the differential rates with this station any further, as the results are less reliable than the ones obtained with Palermo reference station and we do not have the control from the satellite altimetry.

Table 1
Sea level trends obtained from tide gauges for different time intervals. All relevant parameters of the regression are shown: start and ending year, number of equations (N), rms prediction error (Δt), linear trend (a_t), yearly ($a_{\cos 1}$, $a_{\sin 1}$) and half yearly ($a_{\cos 2}$, $a_{\sin 2}$) amplitude coefficients and respective errors.

Station	Year 1	Year 2	N	Δt (mm)	a_t (mm/yr)	Δa_t (mm/yr)	$a_{\cos}$ (mm) yearly	$\Delta a_{\cos}$ (mm) yearly	$a_{\sin}$ (mm) yearly	$\Delta a_{\sin}$ (mm) yearly	$a_{\cos}$ (mm) half-yearly	$\Delta a_{\cos}$ (mm) half-yearly	$a_{\sin}$ (mm) half-yearly	$\Delta a_{\sin}$ (mm) half-yearly
Single station regression analysis. Tide gauges. ISPRA data base														
Catania	1999.5	2009.1	3489	70.7	−0.3	0.4	−68.9	1.7	−9.4	1.7	−6.1	1.7	−6.7	1.7
Crotone	1999.5	2009.1	3489	74.5	−1	0.5	−70.7	1.8	−24.1	1.8	−6.5	1.8	−15.4	1.8
Genova	1999.5	2009.1	3489	76.2	0.1	0.5	−51.3	1.8	−17.6	1.8	0.3	1.8	−19.1	1.8
Palermo	1999.5	2009.1	3489	63.1	1	0.4	−48.3	1.5	−2.3	1.5	−4.2	1.5	−9.4	1.5
Porto Empedocle	1999.5	2009.1	3489	66.3	1.5	0.4	−56.9	1.6	1.5	1.6	−6.2	1.6	−7.3	1.6
Reggio Calabria	1999.5	2009.1	3489	72.1	−0.9	0.4	−67	1.7	2.4	1.7	−6.9	1.7	−9.6	1.7
Catania	1971.8	1982.8	4018	70.9	−4.8	0.4	33.6	1.6	−14.7	1.6	−4.1	1.6	−3.2	1.6
Single station regression analysis. Historic tide gauges. PSMSL data base														
Catania (Metric data)	1896.5	1920	281	50.2	0.9	0.4	−32.7	4.2	21.5	4.3	1.4	4.3	−2.9	4.2
Palermo	1896.5	1920	281	48.6	0.9	0.4	−30.5	4.1	20.5	4.1	2	4.1	−3.4	4.1
Catania	1960.2	1972	142	54.7	−2.1	1.4	−44	6.5	22.7	6.5	3.6	6.5	2.6	6.6
Genova	1960.2	1972	142	54.7	−0.6	1.4	−35.1	6.5	24.3	6.5	2.2	6.5	0.1	6.6
Reggio Calabria	1951.2	1965.8	176	66.4	−1.8	1.2	−35.5	7.1	30.4	7.1	−12	7.0	−1.8	7.2
Genova	1951.2	1965.8	176	55.8	3.1	1.0	−34.8	5.9	16.9	6.0	2.4	5.9	8.6	6.0

Table 2
Corrections applied to the altimetric signal (DEOS, 2009).

	TOPEX-A	JASON-1 (A)
Orbit	Pseudo EIGEN-GL04C orbital attitude	CNES-EIGEN-GL04C orbital attitude
Dry tropospheric correction	ECMWF dry tropospheric correction	ECMWF dry tropospheric correction
Wet tropospheric correction	ECMWF model wet tropospheric correction	ECMWF model wet tropospheric correction
Ionospheric correction	Smoothed dual-frequency ionosphere correction	Smoothed dual-frequency ionosphere correction
Inverse barometric correction	None	None
Solid earth tide	Solid earth tide	Solid earth tide
Ocean tide	GOT4.7 ocean tide	GOT4.7 ocean tide
Load tide	GOT4.7 load tide	GOT4.7 load tide
Pole tide	Pole tide	Pole tide
Sea state bias	CLS sea state bias	CLS sea state bias
Reference surface	EGM2008 geoid height	EGM2008 geoid height
Reference frame offset	Reference frame offset	Reference frame offset

3. Methodology in retrieving differential sea level rates

Taking the difference between the time series of two tide gauges $g_1(t)$ and $g_2(t)$ we obtain:

$$g_1(t) - g_2(t) = e_1(t) - e_2(t) - (c_1(t) - c_2(t)) \tag{2}$$

with $e_1(t)$ and $e_2(t)$ the sea surface height variation, and $c_1(t)$ and $c_2(t)$ the crustal vertical movement. The difference between the time series of a tide gauge station $g_1(t)$ and the collocated altimetric observation $s_1(t)$ is

$$g_1(t) - s_1(t) = e_1(t) - c_1(t) - e_1(t) = -c_1(t) \tag{3}$$

When the geocentric sea surface height variation in two tide gauge stations is the same, the difference between the tide gauge observations is equal to the differences in crustal uplift:

$$g_1(t) - g_2(t) \approx -(c_1(t) - c_2(t)) \tag{4}$$

We model the mean crustal and sea surface height variations to be linear. The problem therefore consists in determining the differential linear trends in sea level variations. We therefore propose the following relation with linear coefficients $b_i, i = 0, \ldots, 2, b_{dt}$ that are determined through fitting a multivariate regression model:

$$g_2(t) = b_0 + b_1 g_1(t) + b_2 {g_1}^q(t) + b_{dt} t + n(t) \tag{5}$$

where ${g_1}^q(t)$ is the quadrature of $g_1(t)$, and $n(t)$ represents the noise. The parameter b_{dt} represents the differential sea level variation of station 2 with respect to station 1. Introducing the quadrature of the series in the linear equation allows for a possible phase shift between the two time series.

An alternative way to obtain differential sea level change, is to take the difference between the sea level rises calculated separately at two stations. In this case we would also model the linear sea level trend in tide gauge and satellite altimetric data as explained above using Eq. (1).

4. Altimetric satellite observations

The altimetric satellites record sea surface height with respect to an ellipsoidal reference system. There have been three dedicated high quality missions. They are the Topex/Poseidon satellite, launched in 1992, and the Jason 1 and ENVISAT satellites, both launched in 2002 (e.g., Chelton et al., 2001). The Jason 1 satellite being the follower mission of Topex/Poseidon, it samples the same tracks, and guarantees continuity of the observations. ENVISAT has a higher spatial resolution, but, as mentioned before, a shorter time series. Precision of the single observation is estimated to be about 4 cm (Chelton et al., 2001), with a repeat time for each track of 10 days for Topex/Poseidon or Jason 1 and 35 days for ENVISAT. The altimetric satellite observations have been corrected for the delays caused by atmospheric refraction, the sea state bias and the tides as summarised in Table 2. The choices are standard and follow the investigations of Fenoglio-Marc et al. (2004). We do not correct the altimetric data for the inverse barometric effect, because this correction is not applied to the tide gauge data. As the pressure variations have almost no long term trend (e.g., Braitenberg et al., 2006), an artefact in the calculated linear trends can be excluded.

The satellite tracks available for the southern Tyrrhenian, Adriatic and Ionian seas are shown in Fig. 1. The satellite tracks are identified by a specific number, the pass, which in our case (study window Lat. 36–40°, Long. 10–19°) takes the values 9, 44, 59, 85, 120, 135, 146, 161, 196, 211, 222, and 237.

We rely on the sea surface heights stored in the DEOS (2009) database, which publishes the values along track. The data are sea level anomalies, defined as the difference between the geocentric sea surface height and the best available geoid model (EGM2008). The data are available at 1 Hz, which corresponds to a 7 km distance of each sample along track, each track being repeated after 10 days. We construct time series with 10 days sampling interval at discrete locations with the criterion of covering the Mediterranean homogeneously. We could use all data along track, but in the averaging process the result would be largely biased towards the variations along the tracks. This is avoided by choosing discrete points that homogeneously cover the area of interest. The points are at all track crossovers and the midpoints between crossovers, which yields points spaced 130 km apart along the tracks. As we use one satellite at a time no bias should be expected at crossovers. In coastal areas we increase the number of points to about 5 points between crossovers. The satellite observations that fall into a spatial window of 7 km distance from the discrete location and fall in the 10 days interval are averaged to produce one data point. We also select positions as near to the tide gauges as possible, compatible with the data availability in coastal areas. In Fig. 3 the data series for the stations closest to the tide gauges of Southern Italy are shown. In order to find the valid satellite point closest to the tide gauge, we calculate the histogram of observations during the entire 1992–2009 time interval along track. We find that at a distance of about 45 km from the coast the number of points is reduced drastically, leading to a time series with many interruptions. Inspection of Fig. 3 reveals a common sub-annual variability in the series, with some differences in the multi-annual sea level trend. The next step fits the time-series in a least squares sense with a model composed of a linear trend and the yearly and half-yearly oscillation (see Eq. (1)). The least squares fit is made on 10-year sliding windows, each shifted by one year, producing the linear geocentric sea level change rate in each location. The 10-year interval is justified by the length of the tide gauge time series. The rates are interpolated on a regular grid with 0.3° grid-spacing applying the nearest neighbour interpolation algorithm (GMT software package, Wessel and Smith, 1998). The algorithm determines the nearest points to each node in each quadrant and within a maximum search-radius from the node. For the nodes that have a full set of nearest neighbours, a weighted average value is computed. The weighting function used

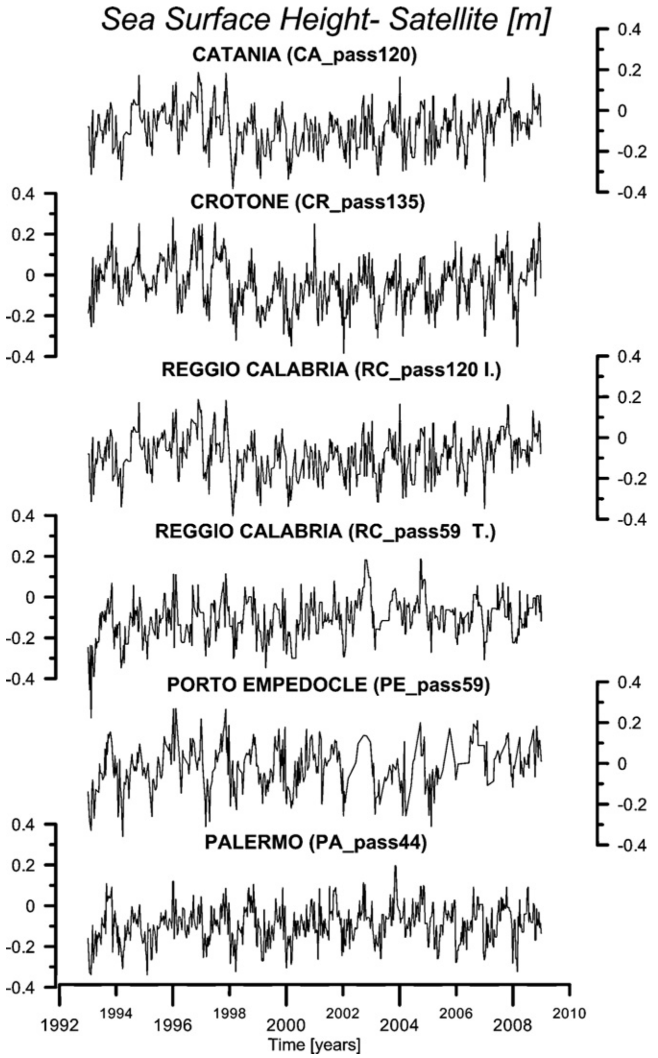

Fig. 3. Sea level variations recorded by altimetric satellites Topex/Poseidon and Jason 1 for 6 representative locations surrounding Calabria and Sicily. See Fig. 1 for locations.

is $w(r) = 1/(1 + d^2)$, where $d = 3r/search\_radius$ and r is distance from the node. The interpolation along the coast of the Italian peninsula presents a problem, as weighting should not be made across the land areas, as this would imply averaging of points pertaining to different oceanic basins. We therefore accomplish the interpolation in two distinct areas, the Adriatic and Ionian basins (grey area in Fig. 1) and the southern Mediterranean Sea (white area in Fig. 1), and merge the resulting grids in a second step.

4.1. Time evolution of sea level trends

In the following the results for the eight time windows (1992–2002, to 1999–2009) are discussed (see Fig. 4). The most recent interval is chosen to be equal to the tide-gauge data availability, so it is actually the interval 1999.5–2009.1. For the first interval (1992–2002, Fig. 4A) we find that the negative sea level anomaly in the Ionian Sea has its largest extension and most pronounced negative value, with respect to the following years. Values close to zero are found near Malta and along the coastline of Porto Empedocle. The northern sector of the Sicilian coast has positive values, with greater values close to the Eolian Islands and Messina, smaller values near Palermo (2.7 mm/yr) and again greater values towards the Egadi Islands.

A very similar pattern is also found for the successive time windows: for the 1993–2003 to 1996–2006 intervals (Fig. 4B–D), the negative Ionian basin rate decreases, as also the rates along the Sicily-Malta channel and the south Tyrrhenian Sea. For the time-interval (1995–2005, Fig. 4D) the Ionian area continues to reduce the negative anomaly, the Sicily-Malta channel shows slightly negative values, and the Egadi and Eolian Islands, and the southern Tyrrhenian area have low positive values. Starting with the series 1997–2007, we find slightly positive values for the Ionian basin, with even more positive values along the gulf of Taranto and eastwards towards Greece. The Sicily-Malta channel has reduced positive values. The Egadi and Eolian Islands have stable positive value, and Palermo a lower positive values. The most recent interval coincides with that covered by the tide gauges (Fig. 4H).

Summarising, we note that in the Ionian sea we have a negative anomaly, which decreases in time between 1992 and 2006, and may affect the Sicily-Malta channel, which generally has small positive values. The Egadi and Eolian Islands have stable medium to large positive trend values.

Finally we calculate the average linear sea surface increase for the entire interval of 17 years (1992–2009, Fig. 4J) and show the map of the errors (1992–2009, Fig. 4K). In the Ionian basin we find a negative geocentric sea level rate (−6 mm/yr), in agreement with previous work (e.g., Fenoglio-Marc, 2003; Fenoglio-Marc et al., 2004) which decreases towards the eastern Sicilian coastline turning into positive values southwards (1–3 mm/yr), and eastwards towards the Greek coastline (4–5 mm/yr). In the Sicily-Malta Channel we find weakly positive values (1.5–3 mm/yr). The values also increase towards the western coast of Sicily (Egadi Islands: 3.3 mm/yr). For the south Tyrrhenian Sea (northern Sicily coast) we find positive values, increasing from west (Palermo: 2 mm/yr) to east (Messina Strait and Eolian Islands: 5 mm/yr). The map of the errors in Fig. 4K shows the significance of the analysis, as the uncertainties are mostly uniformly distributed and much smaller than the observed rates.

In Fig. 5 the time evolution of the linear trends for the selected altimetric locations nearest to the Sicilia-Calabria coastline are graphed (location of points shown in Fig. 5B). Each data point in Fig. 5A represents the trend of the altimeter data series on the point of the track closest to the tide gauge in consecutive 10 years time intervals. As a reference the trends for the full 17 years time interval (1992–2009) are also shown. The change of the negative Ionian anomaly to a positive anomaly is clearly seen. The linear trends and the relevant parameters from the regression analysis for the satellite points nearest to the tide gauges are shown in Table 3. The time interval is that for which we have the tide gauge data. With respect to the tide gauges, the rms of the residual is almost the same (between 70 and 80 mm). The table is analogous to Table 1. The number of data points used for the regression varies, because there are missing data in the time series. Generally, the trends have greater amplitude (between 1.9 ± 1.4 and 11.9 ± 1.5 mm/yr; 1999.5–2009.1) compared to those of the tide gauge stations (between -1.0 ± 0.5 and 1.5 ± 0.4 mm/yr; 1999.5–2009.1), which presumably is due to the distance of the altimeter points from the coast. It shows that at the coast the sea level rates are confined to smaller values compared to the open sea. This could be due to the smaller effects of temperature and salinity, wind or current systems and to the particular ocean bottom topography and coast line geometry.

5. Statistical analysis of tide gauge data

We dedicate a first analysis to the statistical evaluation of the tide gauge data. The correlation coefficient between two series is a quantitative measure of their similarity. In Table 4 we report the

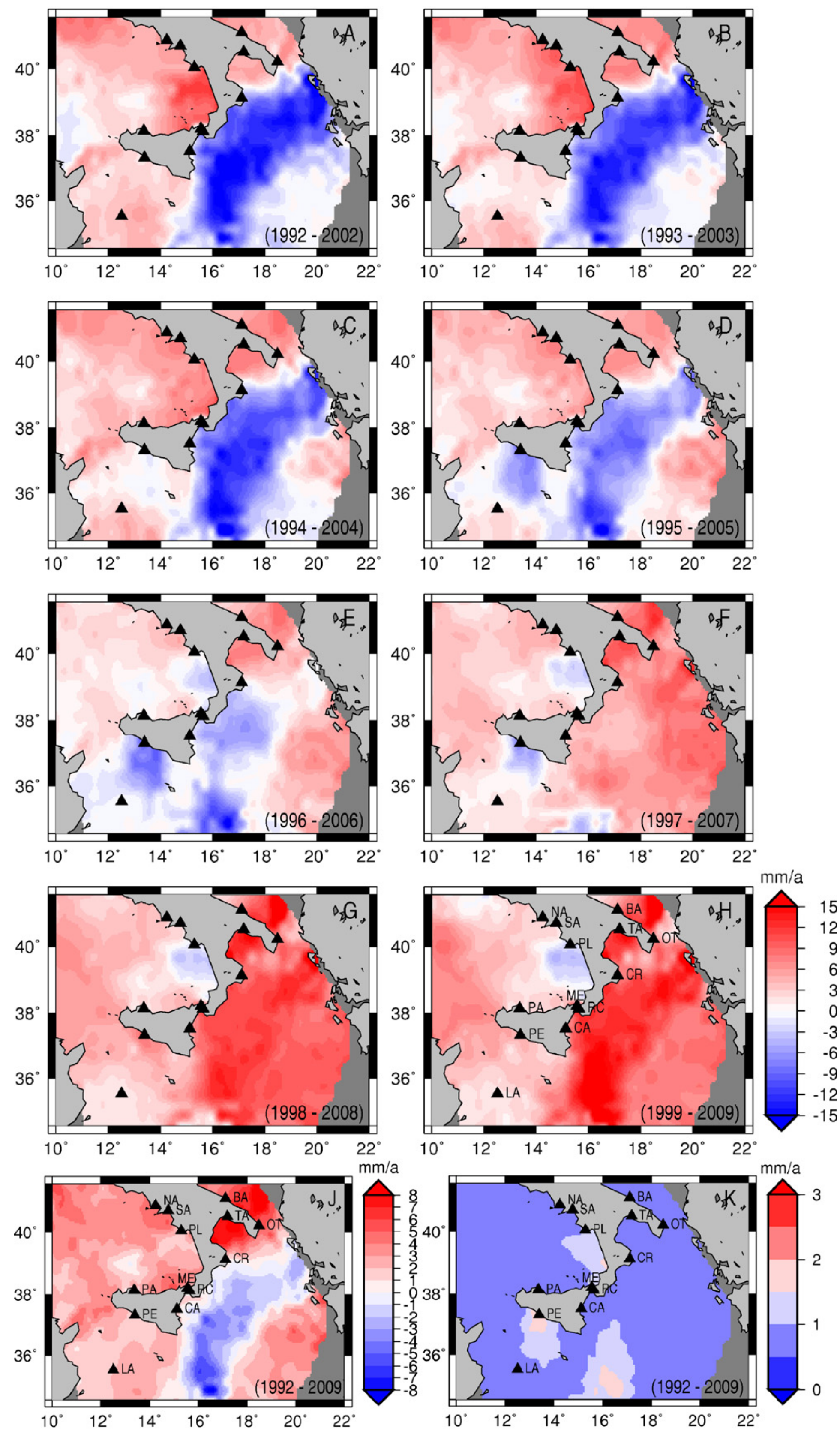

Fig. 4. Map of average sea surface height change from altimetric satellite for different time intervals. Triangles: location of tide gauge stations: NA: Napoli; SA: Salerno, PL: Palinuro, ME: Messina, PA: Palermo, PE: Porto Empedocle, LA: Lampedusa, CA: Catania, RC: Reggio Calabria, CR: Crotone, TA: Taranto, OT: Otranto, BA: Bari, VIE: Vieste. (A–H) Eight consecutive 10-year time intervals starting with the year 1992. (J) Average sea surface height change from altimetric satellite for time interval 1992–2008 and (K) map of the rate error for the same time interval 1992–2008.

Table 3
Sea level trends obtained from satellite altimeter points nearest to the tide gauges for different time intervals. All relevant parameters of the regression are shown: start and ending year, number of equations (N), rms prediction error (Δt), linear trend (a_t), yearly ($a_{\cos 1}$, $a_{\sin 1}$) and half yearly ($a_{\cos 2}$, $a_{\sin 2}$) amplitude coefficients and respective errors.

Single station regression analysis. Satellite points nearest to tide gauges														
Station	Year 1	Year 2	N	Δt (mm)	a_t (mm/yr)	Δa_t (mm/yr)	$a_{\cos 1}$ (mm) yearly	$\Delta a_{\cos 1}$ (mm) yearly	$a_{\sin 1}$ (mm) yearly	$\Delta a_{\sin 1}$ (mm) yearly	$a_{\cos 2}$ (mm) half-yearly	$\Delta a_{\cos 2}$ (mm) half-yearly	$a_{\sin 2}$ (mm) half-yearly	$\Delta a_{\sin 2}$ (mm) half-yearly
Catania-Pass 120	1999.5	2009.1	315	79.7	12	1.7	−60.3	6.3	−2.3	6.5	−16	6.4	8.1	6.4
Crotone-Pass 135	1999.5	2009.1	413	80.2	11.2	1.5	−71.1	5.6	−11.8	5.6	6.8	5.7	−13.6	5.6
Palermo-Pass 44	1999.5	2009.1	375	74.2	1.9	1.4	−62.9	5.5	−18.2	5.4	1.8	5.4	1.1	5.5
Porto Empedocle-Pass 44	1999.5	2009.1	425	70.3	1.4	1.3	−46.4	4.8	−1	4.9	2.7	4.9	−4.4	4.9
Reggio Calabria-Pass 120 I.	1999.5	2009.1	364	77.4	11.9	1.5	−58.7	5.8	−6.8	5.7	−3.7	5.8	−16.5	5.8
Reggio Calabria-Pass 59 T.	1999.5	2009.1	338	75.5	3.2	1.5	−60	5.9	−16.6	5.8	−0.9	5.9	−31.6	5.8

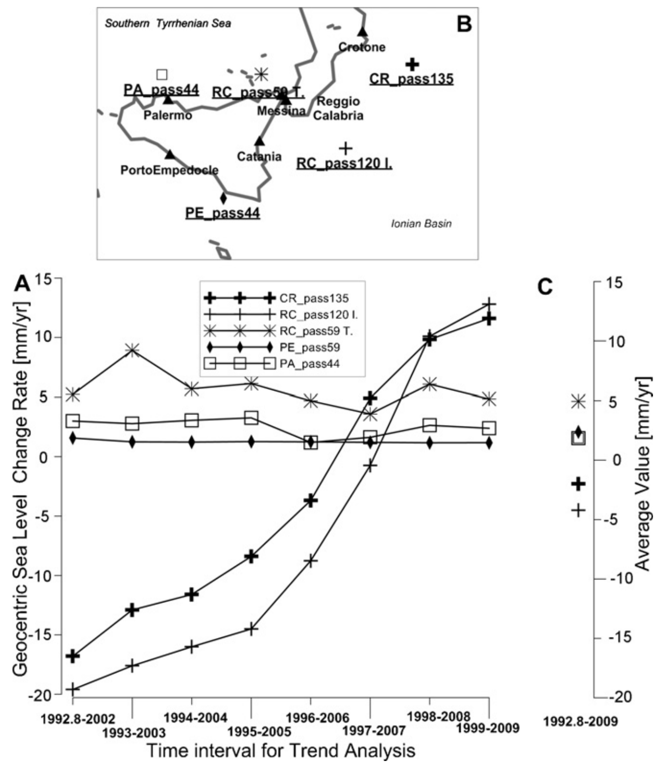

Fig. 5. Rates of sea surface height change obtained from satellite altimetric observations at selected points surrounding Sicily-Calabria. Rates are calculated on 10-year time intervals. (A) Rates for different 10-year time intervals. (B) Location of points. (C) Average rate for the interval 1992–2009.

mutual correlation coefficient between the tide gauges. The time interval for the calculation is 1999.5–2009.1, sampling is daily, and all data refer to the ISPRA database. The high values (0.82–0.97) of the correlation coefficients demonstrate an excellent similarity of the records, which is a guarantee for the good functioning and stability of the tide gauge stations. The lower left corner of the table gives the distances between stations, which range between 81 km (Catania-Reggio Calabria) and 381 km (Porto Empedocle-Crotone). Generally, smaller distances give rise to higher correlation coefficients. The correlation coefficients between altimeter data and tide gauges are slightly lower (about 0.7), as will be shown in more detail in the next paragraph.

6. Differential sea level trends

Following the procedure explained in Section 3, we calculate differential sea level trends between tide-gauges and between tide-gauges and altimetric observations. Differential trends are always calculated on identical intervals, to avoid bias caused by changes of the sea level trends (e.g. see Fig. 5).

We first consider the modern tide gauges from the ISPRA database (Fig. 2A) and calculate the differential sea level change with respect to the geologically stable station at Palermo (Ferranti et al., 2006). The differential trend is calculated from the differential linear change according to Eq. (5), and also from the difference between the linear trends at two stations. In Table 5 all relevant parameters of the differential regression are given: start and ending year, number of equations (N), correlation coefficient (ρ), rms of the residual (Δt), parameters b_{dt} (here named $b_{t\text{-Pal}}$ or $b_{t\text{-Gen}}$) b_1, b_2 from Eq. (5). In the last column the differences between trends and the error is given.

Let us first consider the differential rates obtained for the recent ISPRA data (19995.5–2009.1). The rms of the residual ($\Delta t_{t\text{-Pal}}$) of

Table 4
Correlation coefficient between tide gauge stations (upper right triangle of table) and mutual distances (km) (lower left triangle of table).

		PA	ME	CA	PE	RC	CR
		Correlation coefficient					
PA		–	0.89	0.94	0.96	0.91	0.89
ME		191.4	–	0.88	0.89	0.89	0.82
CA	Distance (km)	169.0	89.4	–	0.95	0.97	0.96
PE		89.8	212.9	154.6	–	0.86	0.89
RC		198.7	104.0	80.8	216.4	–	0.92
CR		343.7	170.4	248.4	381.4	169.5	–

the differential regression is less than half (15–31 mm) the value found in the regression of a linear function and a yearly and half-yearly oscillation. The parameter b_1 is about 1 in all cases, which shows that all stations have very similar amplitude. The value b_2 is systematically 10% of b_1 or less, which shows that the phase shift is very small. The differential rates obtained from the two methods are very similar, and differ by 0.8 mm/yr at most. The uncertainty is greater than the formal error of the trend, but is representative of the actual uncertainty on the differential trends due to different methodological approaches. We find that all stations except Porto Empedocle have negative sea level rates with respect to Palermo.

We now consider the older records from the PSMSL database (monthly sampling), that concern Reggio Calabria, Catania and Genova (Fig. 2B). We have one result for the differential rate between Catania and Palermo (1896.5–1920), with the result of 0 ± 1 mm/yr. The Catania data are not completely reliable, because they are classified as "metric" and not "RLR" by the PSMSL database. The PSMSL defines "metric" the raw data received from the local authority. The RLR (Revised Local Reference) data have been reduced to a common datum by the PSMSL making use of the tide gauge history provided by the supplying authority. For Catania only the "metric" data are available, which means that only incomplete information is present on possible datum shifts or other problems. Two more historic rates have been calculated (Catania and Reggio Calabria), but we are obliged to substitute Palermo with Genova as a reference station, because Palermo is unavailable. The differential sea level rates are given in Table 5. We find again that the two stations Catania and Reggio Calabria have a negative differential sea level rate with respect to the stable reference station.

We now proceed with the differential rates between the tide gauge and the nearest altimeter point. The location of the altimetric sampled point is the one shown in Fig. 1. For the mutual analysis both time series have identical sampling, so we sample the tide gauge at the time of passage of the satellite with a rate of 1 sample every 10 days. We do not average the tide gauge series over the 10-day interval, because the altimeter also samples the sea surface without any time averaging. In Table 6 we give the results for the regression parameters between the tide gauge and the altimetric points. Again we report the values of the rms residual ($\Delta_{\text{t-A}}$), the differential rate of the tide gauge with respect to the satellite altimeter data ($b_{\text{t-A}}$, error $\Delta b_{\text{t-A}}$), and the in phase and out of phase coefficients and their errors (b_1, Δb_1, b_2, Δb_2). Besides all relevant regression parameters, we give the correlation coefficient ($\rho_{\text{t-A}}$) and distance between the tide-gauge station and the satellite altimeter point. The Reggio Calabria station has a higher correlation coefficient with the Ionian Sea than with the Tyrrhenian Sea. The mutual distances (D) are between 44 and 126 km. The differential rates between altimeter and tide gauge are systematically higher than the differential rates of the tide gauges and the stable Palermo or Genova stations. The tide gauge-altimeter differential rates are between 0 and 9 mm/yr, values which are comparable to those found in previous works (e.g. Fenoglio-Marc et al., 2004). Assuming that Palermo is stable and has no vertical movement, we would expect the differential rates from Tables 5 and 6 to coincide, as they would both be equal to the local crustal movement. Instead we find systematically greater values for the altimetric derived differential trends, which poses a paradox and may indicate a general problem. Analyzing the different values it is evident that the inconsistencies cannot be relieved by a possible vertical movement of the Palermo station. The differential trends we obtain between tide gauges seem more realistic, as they compare better to the rates derived from geological investigations. In our case it is therefore inadvisable to calculate the differential rates between the tide gauges and the altimetric observations, but to use the altimetry extrapolated to the coast to determine the general variation of the rates of sea surface change. The altimetric data show that a negative trend of the Reg-

Table 5
Differential sea level trends between tide gauges and the stable station Palermo or Genova. All relevant parameters of the regression analysis: starting and ending year, number of equations (N), correlation coefficient, rms prediction error (Δt), linear trend (b_{dt}), in-phase and out-of-phase amplitude coefficients (b_1, b_2), correlation coefficient, distance between stations.

Differential rates of tide gauges with respect to Palermo station. ISPRA data											Difference of rates
Station	Starting year	Ending year	N values	$\rho_{\text{t-Pal}}$	$\Delta t_{\text{t-Pal}}$ (mm)	$b_{\text{t-Pal}}$ (mm/yr)	b_1	Δb_1	b_2	Δb_2	$a_t - a_{\text{Pal}}$ (mm/yr)
Catania	1999.5	2009.1	3488	0.95	20	-1.8 ± 0.1	1.2	0.007	−0.06	0.007	-1.3 ± 0.6
Crotone	1999.5	2009.1	3488	0.89	31	-2.5 ± 0.2	1.2	0.010	−0.13	0.010	-2 ± 0.6
Genova	1999.5	2009.1	3488	0.93	20	-1.2 ± 0.1	1.1	0.006	−0.2	0.007	-0.9 ± 0.6
Porto Empedocle	1999.5	2009.1	3488	0.97	15	0.43 ± 0.9	1.1	0.005	0.04	0.005	0.5 ± 0.6
Reggio Calabria	1999.5	2009.1	3488	0.94	22	-2.0 ± 0.1	1.2	0.007	0.06	0.007	-1.9 ± 0.6

Differential rates of tide gauges with respect to Palermo station. PSMSL data											Difference of rates
Station	Starting year	Ending year	N values	$\rho_{\text{t-Pal}}$	$\Delta t_{\text{t-Pal}}$ (mm)	$b_{\text{t-Pal}}$ (mm/yr)	b_1	Δb_1	b_2	Δb_2	$a_t - a_{\text{Pal}}$ (mm/yr)
Catania	1896	1920	280	0.78	36	0.15 ± 0.33	0.81	0.039	−.0690	0.040	0 ± 0.57

Differential rates of tide gauges with respect to Genova station. PSMSL data											Difference of rates
Station	Starting year	Ending year	N values	$\rho_{\text{t-Gen}}$	$\Delta t_{\text{t-Gen}}$ (mm)	$b_{\text{t-Gen}}$ (mm/yr)	b_1	Δb_1	b_2	Δb_2	$a_t - a_{\text{Gen}}$ (mm/yr)
Catania	1960	1972	120	0.80	38	-1.5 ± 0.95	0.84	0.052	−.065	0.052	-1.5 ± 1.98
Reggio Calabria	1951.2	1965.9	178	0.55	60	-4.0 ± 1.1	0.70	0.073	−0.09	0.072	-4.8 ± 1.60

Table 6
Differential sea level trends between tide gauges and nearest altimeter points.

Tide gauge station	Satellite point	Starting year	Ending year	D (km)	N values	$\Delta t_{t\text{-}A}$ (mm)	$\rho_{t\text{-}A}$	$b_{t\text{-}A} \pm \Delta b_{t\text{-}A}$ (mm/yr)	b_1	Δb_1	b_2	Δb_2	Trend difference
Catania	CA_pass120_3	1999.5	2009.1	126	360	57	0.67	−8.2 ± 1.2	0.66	0.034	−.0281	0.0321	−12.3 ± 1.8
Crotone	CR-Pass 135_2	1999.5	2009.1	97.0	412	56	0.72	−9.0 ± 1.1	0.70	0.029	−.0138	0.0278	−12.2 ± 1.6
Palermo	PA-Pass 44_3	1999.5	2009.1	44	380	51	0.64	1.0 ± 1.0	0.49	0.030	0.00268	0.0305	−0.9 ± 1.5
Porto Empedocle	PE-Pass 44_6	1999.5	2009.1	114.3	392	54	0.65	−1.6 ± 1.0	0.59	0.035	−.657	0.0350	0.1 ± 1.4
Reggio Calabria	RC-Pass 120_2 I.	1999.5	2009.1	126.1	360	53	0.68	−8.7 ± 1.1	0.65	0.032	0.0612	0.0299	−12.8 ± 1.6
Reggio Calabria	RC-Pass 59_3 T.	1999.5	2009.1	59.9	404	66	0.52	−3.1 ± 1.2	0.48	0.039	0.122	0.0386	−4.1 ± 1.6

All relevant parameters of the regression analysis: starting and ending year, number of equations (N), correlation coefficient, rms prediction error (Δt), linear trend (b_{dt}), in-phase and out-of-phase amplitude coefficients (b_1, b_2), correlation coefficient, distance between stations.

gio Calabria and Catania stations with respect to Palermo cannot be explained by variations in sea surface rates, as the Ionian Sea has a higher rate than the sea in front of Palermo. Also if the Reggio Calabria and Catania stations detect variations of the Tyrrhenian Sea, the altimeter shows that the eastern northern Sicilian coastline has a higher rise than Palermo, and thus cannot be responsible of the rate deficit of the tide gauge.

7. Discussion

Our goal is to use existing historical tide gauge stations to determine the vertical crustal movements along the Sicilian-Calabrian coastline. The existing continuous data cover the interval 1999.5–2009.1 (ISPRA database; stations Crotone, Catania, Porto Empedocle, Palermo, Messina, Reggio Calabria) and 1950–1970 (PSMSL database; Catania, Reggio Calabria, Genova). For the recent data we have not considered the Messina station for the crustal movement analysis, because the pier on which the station was set may be influenced by a land-slide discovered in Messina harbour (Monaco et al., 2008).

Good functioning of the stations can be verified by the calculation of the mutual correlation coefficient of the sea level record, which is high when two stations record the same sea level signal. We find very high correlation coefficients between the stations, with values up to 0.97; we are therefore confident of good data quality.

For each station we determine a linear rate of sea level change, which is the sum of the geocentric sea surface change and the vertical coastal movement. We have shown that the linear sea level rate varies in time and space, when calculated on a time base of 10 years, due to atmospheric and oceanic currents (for a detailed discussion see, e.g. Tsimplis et al., 2005).

Geologically, the Palermo station has been shown to be relatively tectonically stable (Ferranti et al., 2006), so we calculate the differential sea level trends with respect to this station. In the time intervals in which the Palermo station is unavailable we use the Genova station, which is the reference station for the Italian height system, and tectonically stable (e.g. Salvioni, 1957; Ferranti et al., 2006; Serpelloni et al., 2006). The present day sea level change is assumed to be caused partly by an isostatic crustal subsidence which affects all Mediterranean stations and may account to up to 40% of the signal (Stocchi and Spada, 2009; Lambeck et al., 2004). For the Sicilian-Calabrian stations the difference in the isostatic contribution is 0.1 mm/yr at most (Stocchi and Spada, 2009; Lambeck et al., 2004), so we need not consider it is as a significant differential crustal movement in our study.

We find that Catania, Reggio Calabria and Crotone have a systematically negative sea level rate with respect to Palermo. Porto Empedocle has a slightly positive differential rate. The older records confirm that Reggio Calabria and Catania have negative rates with respect to the stable Genova station.

The analysis of satellite altimetric data has shown that the Ionian sea is affected by a strong sea level anomaly, that manifested itself in the first decade of the 1990's with a negative sea level change up to −21 mm/yr (trend for 1992–2002 time interval). In the subsequent years the Ionian sea level trends have been steadily rising, inverting the tendency to a strongly positive sea level rise, when considering the last decade (1999–2009). The Ionian sea level anomaly is important in the context of our study, as it may affect the Reggio Calabria and Catania stations. The location of the Reggio Calabria station is close to the Messina straits, so it could also be influenced by sea level variations in the Tyrrhenian sea. The mutual correlation analysis with satellite altimetry shows that the correlation coefficient for Reggio Calabria is higher for the Ionian satellite locations than for the Tyrrhenian locations, which means that Reggio Calabria follows the Ionian Sea rather than the Tyrrhenian Sea. Presently we cannot ascertain whether the negative Ionian anomaly was present in the years 1950–1970, the interval used for the trend analysis of the PSMSL data for the two stations Reggio Calabria and Catania. We are confident that the recent negative differential rates of Reggio Calabria and Catania with respect to Palermo cannot be explained by the different sea surface rates, as in the interval of analysis (1999.5–2009.1) the Ionian anomaly was positive and not negative, with high positive increase values (10 mm/yr), whereas the rates at the Palermo station are stable in time and lower (3 mm/yr for the same time interval). In cases in which the satellite tracks pass close to the tide gauge stations, differential trends between the two instruments can be used directly to find the crustal rates. We have considered a less favourable case, where the satellite measurements are far from the tide gauge stations. The distances are dictated by two factors: the first one is due to the fixed position of the satellite passes, the second one due to the fact that the altimetric data are obtainable only up to a distance of 10 km or more from the coastline. A closer approach of the remote sea level observation is in theory possible, but requires a retracking of the reflected satellite signals, which is presently available only for a very limited time period (e.g. COASTALT, see http://www.coastalt.eu/). In our case, the difference in the satellite and tide-gauge derived sea level trends reflects the greater variability of the sea level trends in the open ocean with respect to the trends observed at the coast. Nevertheless the altimetric observations are necessary in estimating regional characteristics of the sea level rates, which are extrapolated to the coastline. We may speculate that Reggio Calabria and Catania are only mildly affected by the Ionian sea level anomaly, and that the observed negative sea level trend is due to an effective tectonic uplift. The uplift would fit the geologic vertical crustal rates very well. They predict uplift in both locations Catania and Reggio Calabria (Antonioli et al., 2009; Ferranti et al., 2007).

8. Conclusions

We examine tide gauge and satellite altimetric observations of sea level with the aim of obtaining crustal vertical movement rates. The methodology is useful as it gives complementary rates to those obtainable from archaeological and geological approaches (Flemming and Webb, 1986; Antonioli et al., 2007, 2009) and the GPS geodetic measurements (Bennett and Hreinsdottir, 2007; Serpelloni et al., 2007). We think that the use of these data is important, as a multitude of freely accessible tide-gauge data exist, covering several decades of observations. The dedicated satellite altimeter data are available continuously since 1992. We have executed the data analysis in a specific region of the Mediterranean, but the methodology we propose is generally applicable and can be used in any other part of the world. The sea level trends vary in space and in time, with values between −15 mm/yr and 15 mm/yr when calculated for intervals of a decade in the open sea by the altimeter. The scatter is barely smaller when considering the trends calculated for tide gauges over time intervals of 10 years. The scatter reduces greatly when the time interval of calculation is increased. Differential sea level trends at tide gauges give information on differential crustal movement at two stations, provided the regional variations in sea surface rates can be controlled. For the Sicilian-Calabrian area we find Reggio Calabria, Catania and Crotone have a significantly lower sea level rise than that found at Palermo. This observation holds for different time intervals between 1950 and today. The differential rates with respect to Palermo range between -1.3 ± 0.6 to -1.8 ± 0.1 for Catania and -1.9 ± 0.6 to -2.0 ± 0.1 for Reggio Calabria, with an uncertainty of less than 1 mm/yr. As mentioned above, in principle we cannot exclude the possibility that the deficit in sea level change could be an expression of the lateral variations of sea surface change, rather than due to a relative tectonic uplift. Contemporaneous satellite altimetric data are available for the most recent time interval, and show that the deficit cannot be explained by a slower sea surface change at Reggio Calabria and Catania. We were interested in using the satellite derived sea level trends as an absolute reference for the tide gauge derived trends, but find that the short overlapping time interval (10 years) allows only qualitative considerations. The satellite derived trends deviate from the tide gauge derived trends too much to be used for determination of the vertical crustal movements. One problem may be due to the fact that our satellite data are only available at distances greater than about 44 km offshore, where the sea surface rates seem to be larger offshore than at the coast. In future the comparison may be made in a more quantitative way, when the data time interval is larger and the average sea level trends have smaller scatter. A future improvement could be achieved with a dedicated and tailored data analysis of the reflected satellite altimetric signal that may allow us to obtain data nearer to the shoreline. We interpret the deficit in sea level rise at Reggio Calabria and Catania as due to tectonic uplift. Geological studies have shown that at Catania the tectonic Late Holocene rate is 0.6 mm/yr and the Late Pleistocene rate is 1.27 mm/yr (Antonioli et al., 2006); for Reggio Calabria the Holocene rate has been estimated to be 2.1 mm/yr and the Late Pleistocene (past 125 kyr) rate to be 1.23 mm/yr (Antonioli et al., 2006). The geologically determined movement can differ from the present-day rate, because the current slip rate corresponds to a particular phase of the seismic cycle, whereas the average geological rate contains the pre- and post-seismic continuous as well as the coseismic movement (Ferranti et al., 2007).

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