VERTICAL LAND MOVEMENT FOR THE ITALIAN COASTS BY ALTIMETRIC AND TIDE GAUGES MEASUREMENTS

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ABSTRACT

The difference between the sea surface height observed by satellite altimetry and tide gauges gives an estimation of vertical land movements. We use this approach for determining vertical crustal movements along Italian coasts.

The major problem with the altimetry is to acquire data near to the coastlines. We explore satellite data statistically to understand in which tide gauge stations the methodology of comparison with the satellite observations can be applied. We analyze the two different datasets (tide gauges and satellite altimetry) in order to determine under which circumstances it is possible to calculate the tectonic rates from the sea level trends differences.

We try to approach the coast as much as possible and we determine the apparent tectonic rates in 12 selected stations along Italian coastlines. We found subsidence in Puglia coasts and in Lampedusa station, uplift in Liguria Sea littoral and stability along the central coasts of Italy, like in Civitavecchia and in Ancona. The results are complementary to vertical land movements achievable with GPS.

1. SATELLITE ALTIMETRY DATASET

The satellite altimeter refers to a geocentric reference frame, that is it records sea surface height variation with respect to an ellipsoidal reference system.

The satellite Topex-Poseidon (launched in 1992) and Jason-1 (launched in 2002) are altimetric missions for sea level observations and together cover a time period of at least 17 years. The Jason-1 satellite samples the same tracks of Topex/Poseidon and guarantees continuity in the observations (Fig.1). Precision of the single observation is estimated to be near to 4 cm [1].

Envisat altimeter is an Earth observation satellite, which is equipped with a dual-frequency Nadir pointing Radar (RA-2, Radar Altimeter 2) operating in the K_u band and S bands, used to define ocean topography as well as mapping/monitoring sea ice and measuring land heights. It provides data since when it was launched (March 2002). We used it to compare our results obtained using Topex and Jason-1 altimeters, taking the different repetition period (35 days for Envisat, 10 days for Topex and Jason-1) and the different track coverage (Fig. 2) into account.

The altimetric data are available on the website of Delft University Database RADS (Radar Altimetry Database System) [2] and they have been corrected for the delays caused by atmospheric refraction, sea state bias and tides, as summarized in Tab. 1. The choices are standard and follow the investigations of [3].

Every satellite track is identified by a specific number. In our case, the tracks of interest are: 9, 44, 59, 85, 120, 135, 146, 161, 196, 211, 222, and 237. They cover the area of the study, which is defined by latitude 30°÷47° and longitude 5°÷22°.

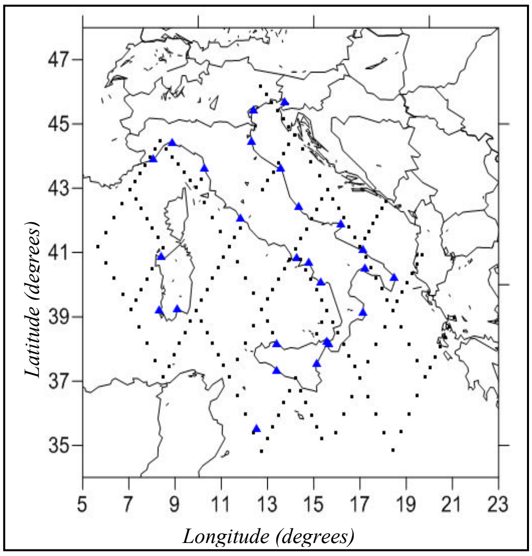

Figure 1: Altimetric grid points in the area of interest (black points). Blue triangles: 26 tide gauge stations of ISPRA network. Topex-A and Jason-1 sample the same tracks.

Altimetric 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 day sampling interval at discrete locations with the criterion of covering the whole investigation area in the Central Mediterranean. We choose discrete points along the tracks which are represented in Fig. 1 as black dots. The points coincide with all crossovers and 3 or 5 midpoints between two crossovers; 5 midpoints are considered when approaching the coastline. The satellite observations which are within a spatial window of 7 km side length centred on the

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altimetric grid point and are comprised in the 10 days interval are averaged to produce one data point. By this way we obtain one time series for each observation point.

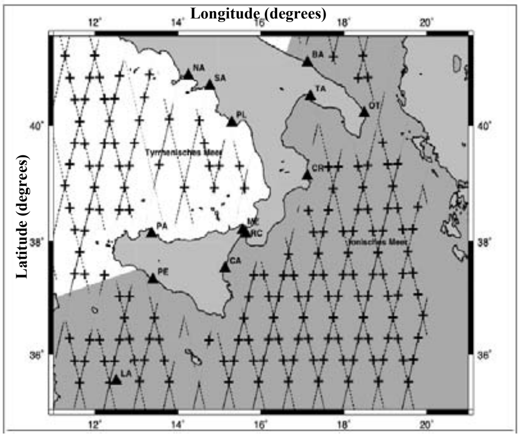

Figure 2: Envisat tracks in Southern Italy. Triangles represent the tide gauge stations. Grey and white oceanic domains: define two distinct areas used for the gridding procedure: separate gridding avoids leakage across independent basins.

The same was done for Envisat data, considering a sampling interval of 35 days and a time interval from 2002 to 2009.05 (Fig.2).

1.1. Statistical analysis of altimetric data

We obtain 233 time series of altimetric data, one for each altimetric observation point, applying Matlab routines to the data downloaded from the RADS database. We have considered the time interval for Topex-A and Jason-1-A, from 1992.7 to 2009.05.

We carry out a check, in order to discard those time series in which the number of available data makes trend estimation insignificant, due to the lack of data near to the coast. Also the outliers have been eliminated. We explore the data statistically in order to quantify the loss when approaching the coast. In Fig. 3 an example of the histogram of the amount of available data is shown. We found the loss near the coast is stronger for Jason-1 altimeter, which shows a considerable cutback in the number of available data at distances less than 45 km from the coast.

The following step includes a correlation coefficient analysis between altimetric data and tide gauges data for the time interval 1998.6-2009.05. We rely on the ISPRA tide gauges network [4], which counts 26 stations homogeneously distributed along the Italian coastline.

The correlation coefficient between two time series is a quantitative measure of their similarity. We calculate the correlation coefficient between the tide gauge and the surrounding altimetric grid points. We take care to resample tide gauge daily data at the 10-days satellite passage. We compute the correlation coefficients for each altimetric observation point with respect to the tide gauge. In Fig. 4 the results are shown.

We note that the correlation coefficient ranges between 0.45 and 0.85, but normally it is quite high: about 0.6÷0.7. It does not necessarily depend on the distance between tide gauge and altimetric point. It seems to have a pattern similar to that caused by ocean currents. In the Adriatic Sea, for instance, the correlation increases in the central area, while it decreases in the Northern and in the Southern sectors. This situation is clearly visible for Vieste and Ortona, but also for Ancona, Bari and Venezia (see Fig. 4).

If we compare this map with a map of the Mean Dynamic Topography of the Mediterranean [5], or with Sea Level Anomaly maps [6] we can note that the distribution of the coefficients presents an analogue pattern. We can speculate that the correlation coefficients are influenced by oceanic circulation and

Table 1: corrections applied to Topex and Jason-1 altimetric data

	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*

sea currents. The currents could provoke differences in the sea level rates measured at the altimeter observation points and at the tide gauges. Presently the knowledge of these phenomena in the Mediterranean does not allow this effect to be quantified. In our work we try to avoid the problem trying to approach the coast as much as possible, even with interpolation methods.

We carry out a correlation coefficients analysis also for the Envisat data for the period 2002-2009.05. We notice a low correlation zone in the Tyrrhenian Sea estending North from tide gauge station Palermo (PA) as shown in Fig. 5. It indicates a poor correlation area with respect to all the tide gauges in the neighborhoods.

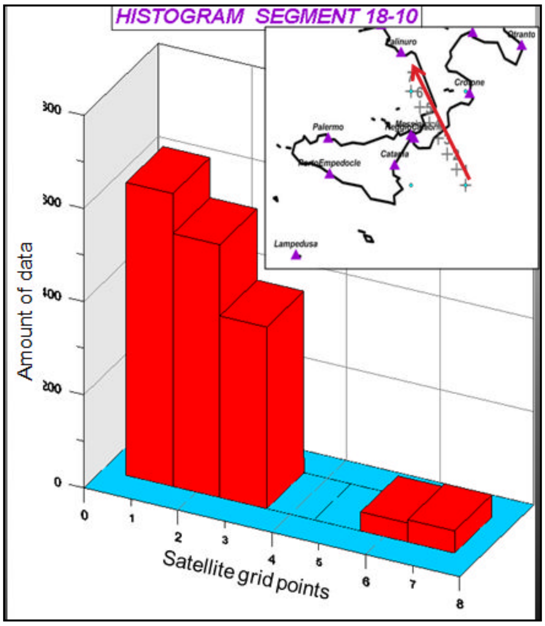

Figure 3. Histogram of the amount of available altimetric data along a satellite track. The lack of data near the coast stands out.

2. SATELLITE ALTIMETRY AND TIDE GAUGE STATIONS

Tide gauges measure sea level but, as they are fixed to the coast, they sense both sea surface height variations and vertical crustal movements [3], [7], [8], [9]. 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. They can be used to correct the tide gauge sea level rates for the sea surface rate inhomogeneities.

The linear trend determination is the first step to do. We calculate the linear trend for every satellite observation point and secondly we compare it with the trend obtained for the tide gauges. We calculate linear trends for every tide gauge station of ISPRA network, which provides continuous data from 1998.6.

We also proceed to limit the altimetric time series to obtain an identical time interval both for altimetry and tide gauge time series (1998.6 – 2009.05), in order to avoid a bias in the trends due to changes in time intervals. The apparent crustal movement is derived from the trend difference.

In the following paragraph we calculate the annual altimetric trend for every available altimetric time series and we try to approach the coast as much as possible in order to minimize the distance between the altimeter point and the tide gauge.

3. TREND ESTIMATION

We estimate the trend for each altimetric observation point. We model the linear sea level variation as the linear coefficients in the function:

$$y(t) = a_0 + a_1 \sin\omega t + a_2 \cos\omega t + a_3 t + n(t) \qquad (1)$$

where ω is the angular frequency of the yearly oscillation, n(t) is noise, y(t) is the observed series, a_3 is the linear increase rate.

We calculate the average linear sea surface increase for the interval 1998.6-2009.05. We interpolate the linear trends of altimetric data on a regular grid in order to minimize the distance between the altimeter and the tide gauge. We use a regular grid with 0.5° grid-spacing using near neighbor algorithm [10]. 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 is w(r) = 1/(1 + d^2), where d = 3r/R, r is distance from the node and R is the search-radius.

By this way, we have two types of data available for the determination of vertical crustal motions: a) the altimetric trend calculated in the observed point as near as possible to the coast, b) the altimetric trend calculated by interpolation in the grid point nearest to the tide gauge station.

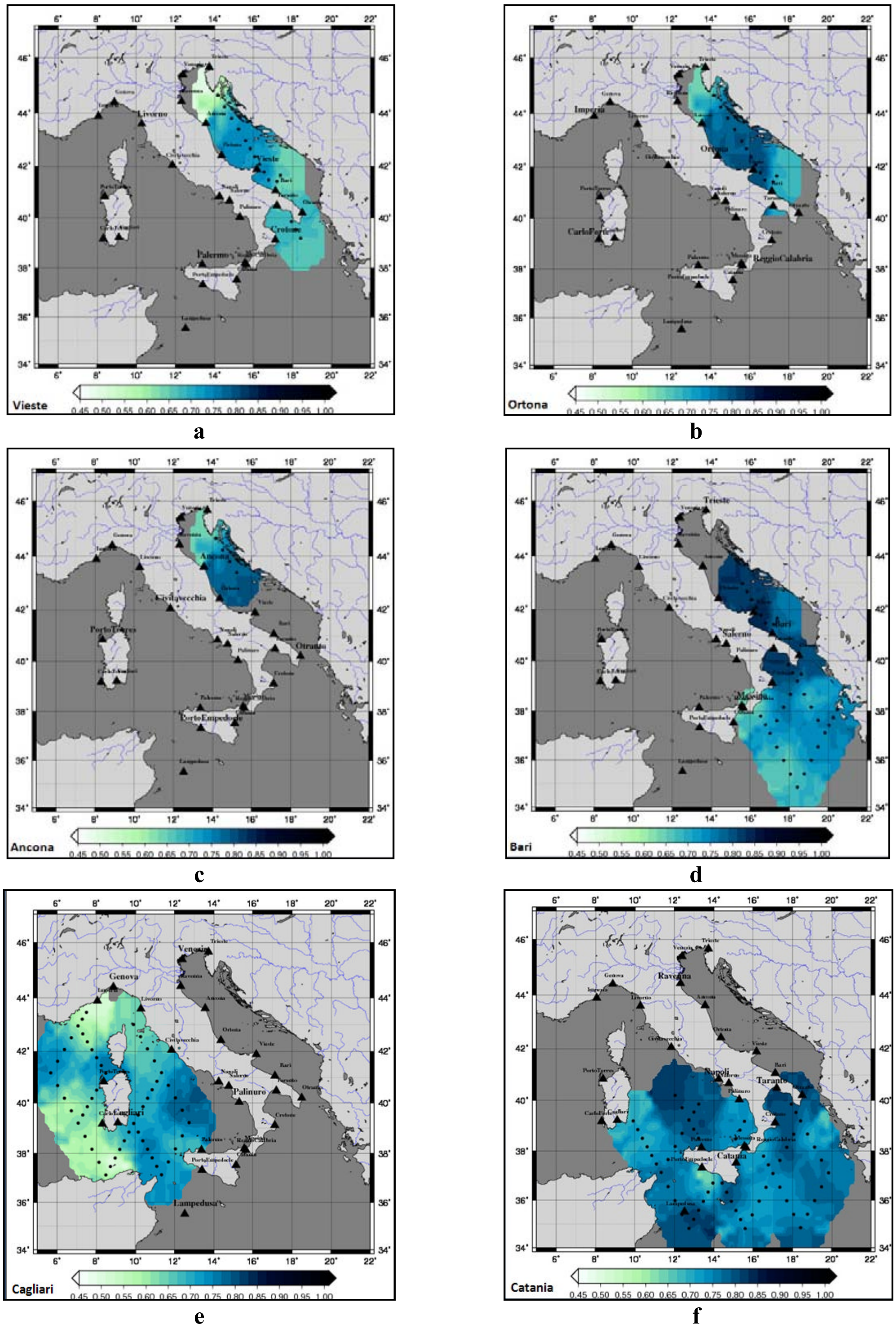

Figure 4. Correlation coefficients between satellite altimetric points and one reference tide gauge station. Each map refers to one particular tide gauge station, which are: a) Vieste, b) Ortona, c) Ancona, d) Bari, e) Cagliari, f) Catania. Time interval of analysis: 1998.6-2009.05

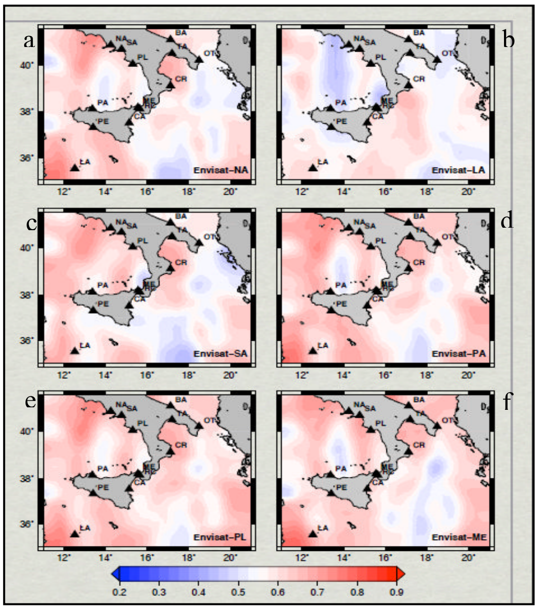

Figure 5: Correlation coefficients of Envisat data in the Tyrrhenian Sea with respect to selected tide gauge stations: a) Naples, b) Lampedusa, c) Salerno, d) Palermo, e) Palinuro, f) Messina. Time interval of analysis: 2002-2009.05

The map of sea level trends from altimetric data for the Central Mediterranean is illustrated in Fig. 6. The areas around Bari and East of Corsica are the only zones where the sea level rate is almost null or slightly negative. The sea level trends show strongly positive sea level rise especially around Crotone, Reggio Calabria, Catania and Otranto. The sea level rise is particularly strong in the Ionian basin , confirmed also in the Envisat data (Fig. 7).

4. APPARENT TECTONIC RATES

Apparent tectonic rate is defined as sea level change observed by the altimeter minus sea level change observed by the tide gauge in the same time interval (1998.6 - 2009.05 in our study). If it is positive, it corresponds to an apparent station uplift, while if it is negative it corresponds to a subsidence (Eq.2):

$$T_{tett} = T_{sat} - T_{tg} \qquad (2)$$

where T_{tett} is the apparent tectonic rate, T_{sat} is the altimetric trend, T_{tg} is the tide gauge rate.

For the determination of T_{tg} we could rely on the 26 tide gauge stations of ISPRA database, which provides hourly data. We reduce them to daily sampling and eliminate the tide variation. We calculate linear trends for every tide gauge using the daily data, obtaining the results illustrated in Fig. 8.

The distance of the satellite tracks from tide gauge stations is quite far (with distances greater than 95 km) for 14 out of 26 stations. Therefore we select only those stations in which the satellite track flies over the tide gauge station (or at least close to it), that is the stations in which the altimetric sea level rate exists and in which the calculated altimetric trend is available.

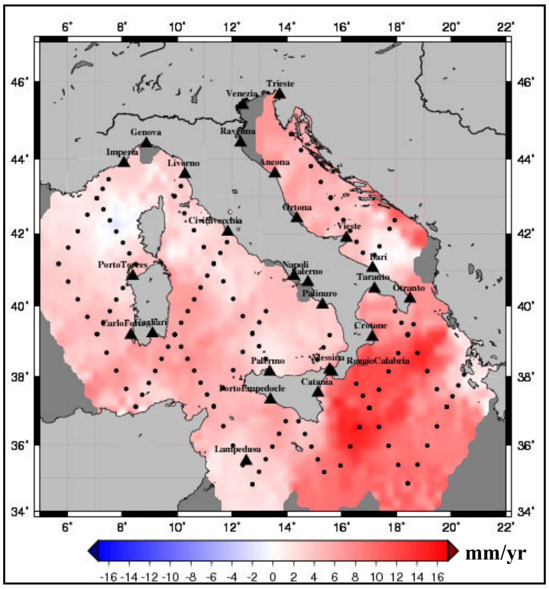

Figure. 6: Altimetric trends in the central Mediterranean. Time interval of analysis: 1998.6-2009.05. Altimeters used: Topex and Jason-1.

We obtain the apparent tectonic rates in 12 tide gauge stations, as shown in Tab.2.

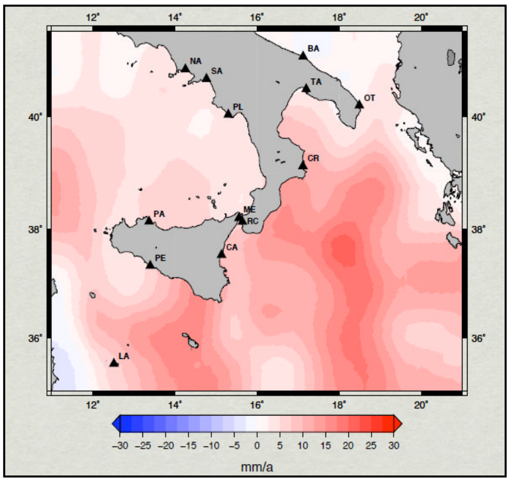

Figure. 7: Altimetric trends in the central Mediterranean with Envisat data. Time interval of analysis: 2002-2009.05.

In Fig. 9 the rates are illustrated on a colour coded map. The positions of the altimetric grid points used in the calculation are shown in orange colour. We found uplift along the Ligurian coast, subsidence in the South Adriatic coast, and stability along the central Italian coasts and in Palermo station.

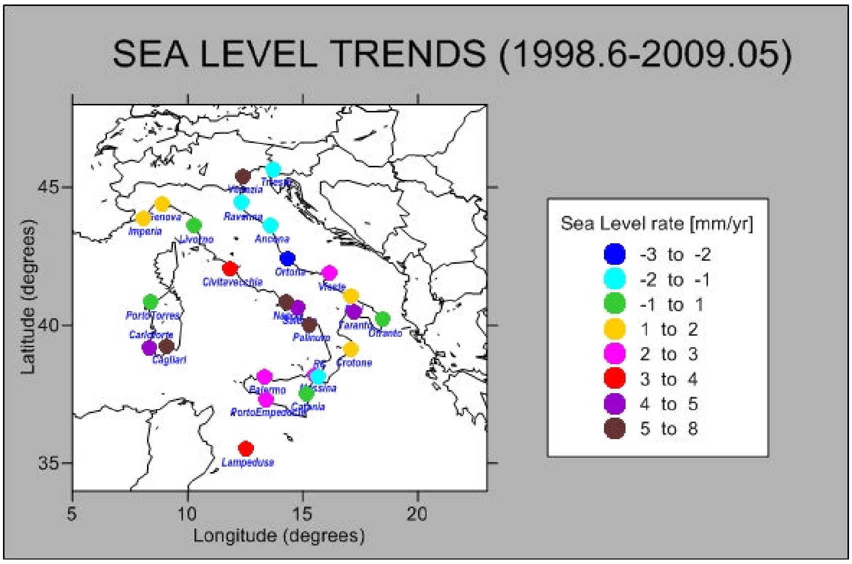

Figure. 8: Colour coded map of sea level trends for the 26 tide gauges stations of ISPRA network. Time interval of analysis: 1998.6-2009.05, except Porto Torres (2000-2009.05).

Table 2: Apparent tectonic rates in 12 selected locations along the Italian coastline. Time interval of analysis: 1998.6 – 2009.05, except Porto Torres (2000-2009.05). Reported are: station names (column 1); altimetric trends at the grid point (column 2) and respective errors (column 3); tide gauge rates (column 4) and respective errors (column 5); apparent tectonic rates (column 6) and respective errors (column 7); distance altimetric grid point / tide gauge (column 8); time interval of analysis (column 9).

Station name	***Altimetric rate***	***Error (mm/yr)***	***Tide gauge rate***	***Error (mm/yr)***	***Apparent tectonic rate***	***Error (mm/yr)***	***Distance altimeter/tide gauge (km)***	***Time interval (years)***
Ancona	-1,8	2,6	-1,8	0,6	0,1	2,7	21	1998.6-2009.05
Bari	-0,7	1,6	1,5	0,5	-2,2	1,7	24	1998.6-2009.05
Cagliari	5,2	1,3	7,1	0,4	-1,8	1,3	65	1998.6-2009.05
Carloforte	5	1,6	4,2	0,4	0,8	1,6	94	1998.6-2009.05
Civitavecchia	3,2	1,4	3,6	0,4	-0,4	1,5	31	1998.6-2009.05
Imperia	3,2	1,7	1,8	0,4	1,4	1,7	66	1998.6-2009.05
Lampedusa	2,3	1,4	3,9	0,4	-1,6	1,5	17	1998.6-2009.05
Livorno	3,4	1,8	0,6	0,5	2,9	1,9	37	1998.6-2009.05
Palermo	1,6	1,4	2,3	0,3	-0,8	1,4	44	1998.6-2009.05
Otranto	5,4	1,4	-0,4	0,4	-1,9	1,1	50	1998.6-2009.05
Porto Torres	1	1,9	-2	0,5	3.01	1,5	37	2000-2009.05
Vieste	-2,4	1	2,5	0,5	2,4	1,7	24	1998.6-2009.05

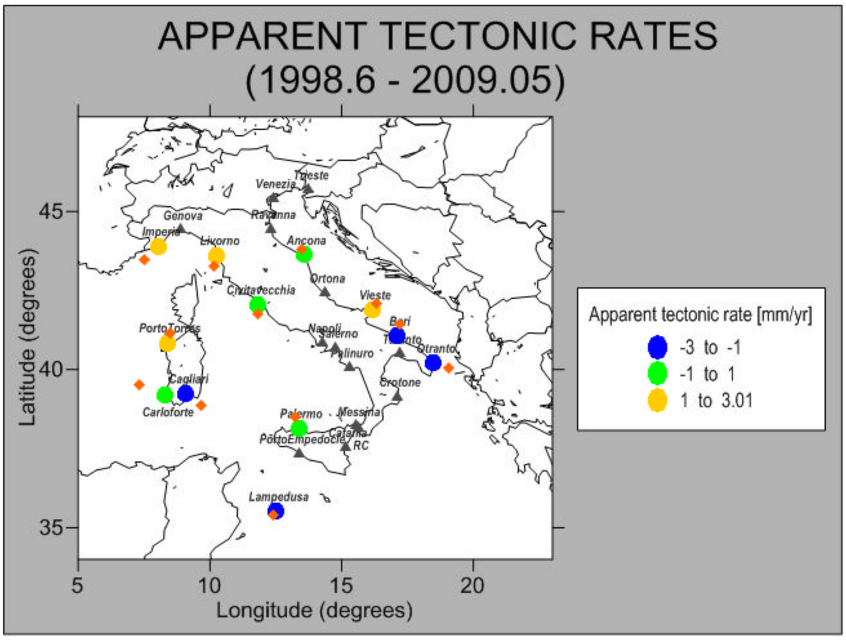

Figure 9: Map distribution of the apparent tectonic rates in 12 selected locations along Italian coasts. The positions of the altimetric grid points used for the calculation are represented as orange rhombus. Time interval of analysis: 1998.6-2009.05. Porto Torres interval of analysis: 2000-2009.05.

Sardinia merits a separate discussion. It is known to be tectonically stable, while we found an anomalous positive value in Porto Torres. We check the satellite and tide gauge data and we noticed a significant interruption of tide gauge data in 1999, that can be the cause for the anomalous value. If we consider Porto Torres data from 2000, we obtain an apparent tectonic rate of 3.01 mm/yr, quite high. It is less reliable compared to the other stations due to the reduction in the time interval.

5. Discussion

If we compare our tectonic rates along the Ligurian coast with previous works (considering GPS [11] or tide gauges and satellite altimetry [4]), we find agreement on the small uplift observed. Another confirmation of our results comes from [12] which published a review of the last 12 ka relative sea level changes in Italy using the elevation of MIS (Marine Isotope Substage) 5.5 marker, of 125 ka, as a benchmark to assess tectonic stability. Along the Tyrrhenian coast a large area of tectonic stability is detected. This is in agreement with our work, in which we find a relative stability for Civitavecchia station.

Reference [13] considers the tectonic vertical movements in more than 100 locations along Italian coasts by using geologic and archeological markers of Holocene age and making some small corrections for residual post glacial isostatic movements. A Holocene stability is indicated for the eastern Adriatic coast and it is in reasonable agreement with our results for Ancona station, although we found a subsidence in the southern part of the Adriatic coastline. On the western coast of the peninsula, [14] and [9] find another substantial stability area, and we find a similar result in Civitavecchia station.

6. Conclusions

Vertical movements of the Earth crust may be due to several causes: volcanism, isostatic adjustment, tectonics, subsidence both natural and anthropogenic.

Recent investigations [4], [9] have demonstrated it is possible to combine satellite altimetry and tide gauge data in order to estimate vertical motions of the Earth's crust. In our work we apply this methodology to the Italian coasts, but it is generally applicable to any other parts of the world.

It is known that near the coast there are some problems: loss of data and degradation in data accuracy due to contamination of the radiometer and of the altimeter echo by the littoral. Errors associated with altimeter and radiometer drawbacks can cumulate: for this reason, altimeter data within 0–20 km from the coast are rejected [8]. We note this is particularly true for Jason-1 altimeter, rather than Topex-Poseidon. Nevertheless, in selected locations, we could approach the coast within 20-30 km from the littoral, as in the case of Lampedusa, Ancona, Bari and Vieste. It is recommended to select the stations where the satellite tracks fly over the tide gauge. We calculate the sea level trend difference between altimetry data and tide gauges data to estimate the apparent tectonic rates. The dedicated satellite altimeter data are available continuously since 1992. Tide gauges data are continuous since 1998.

It is possible to calculate the tectonic rates from the sea level trends differences, but we found that the altimetric point should not be farther than 95 km from the tide gauge. The comparison of records of the two instruments is a powerful tool, but it depends on the length of the available data. The sea level trends vary in space and time. We note that longer time intervals generally correspond to smaller rate values, which shows that the rates stabilize with larger time intervals.

Altimetric trends show a larger variability with respect to tide gauges rates. Presently the 10 years of tide gauges data available are a relatively short time period for the study. In the future, with longer time periods, more reliable results will be achievable. The methodology can be used to complement the network of observation points for the vertical crustal movement rates obtainable by GPS and repeated leveling.

7. Acknowledgments

Altimetric data of Topex-Poseidon and Jason-1 altimeters are available on the RADS Database (Delft University), while hourly data are achievable from ISPRA Database. This research 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.

8. References

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