Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 51 (2013) 1019–1028

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Coastal sea level changes in Europe from GPS, tide gauge, satellite altimetry and GRACE, 1993–2011

Guiping Feng [a,b], S. Jin [a,*], T. Zhang [a,b]

[a] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Available online 21 September 2012

Abstract

Sea level changes are threatening the human living environments, particularly along the European Coasts with highly dense population. In this paper, coastal sea level changes in western and southern Europe are investigated for the period 1993–2011 using Global Positioning System (GPS), Tide Gauge (TG), Satellite Altimetry (SA), Gravity Recovery and Climate Experiment (GRACE) and geophysical models. The mean secular trend is 2.26 ± 0.52 mm/y from satellite altimetry, 2.43 ± 0.61 mm/y from TG+GPS and 1.99 ± 0.67 mm/y from GRACE mass plus steric components, which have a remarkably good agreement. For the seasonal variations, annual amplitudes of satellite altimetry and TG+GPS results are almost similar, while GRACE Mass+Steric results are a little smaller. The annual phases agree remarkably well for three independent techniques. The annual cycle is mainly driven by the steric contributions, while the annual phases of non-steric (mass component) sea level changes are almost a half year later than the steric sea level changes.

Keywords: Sea level change; Satellite altimetry; Tide gauge; GRACE; GPS

1. Introduction

Due to global warming recently, the average global sea level was rising through the 20th century with thermal expansion of water and fresh water input from the melting of continental ice sheets and land basins (Douglas, 2001; Peltier, 2001; Miller and Douglas, 2004; Holgate and Woodworth, 2004; Cazenave and Nerem, 2004; Leuliette et al., 2004; Church and White, 2006; Meyssignac and Cazenave, 2012). Global sea level variations are highly non-uniform around the world and some regional sea level changes are several times larger than the global mean value, which are affected by climate variability and local environments, such as associated with El Niño and North Atlantic Oscillation (NAO). Therefore, it is important to monitor regional sea level changes, which is directly related to our living environments, marine ecosystems, coastal erosion and marsh destruction, particularly in denser population areas, e.g. European Coasts and islands.

Traditional measurements of sea level changes primarily rely on two techniques: tide gauge (TG) and satellite altimetry (SA). The tide gauge has been used to measure the changes in sea level for almost two centuries (Barnett, 1984).With the development of satellite altimetry since 1993, satellite altimetry has been widely used to measure the global sea level variations with high accuracy and high spatial-temporal resolution. Satellite altimetry measures the absolute sea level variations, whereas TG provides the relative sea level variations with respect to the TG land.

Recently, a number of vertical coastal motions have been investigated using satellite altimetry and tide gauges data (Fenoglio-Marc et al., 2004; Wöppelmann and Marcos, 2012; Braitenberg et al., 2010; Garcia et al., 2011). On the contrary, tide gauge will provide an opportunity to measure the absolute coastal sea level changes when the vertical land movements are precisely observed by the co-located Global Positioning System (GPS). In this paper, the sea level changes along the western and southern

* Corresponding author. Tel.: +86 21 34775292.
E-mail addresses: gpfeng@shao.ac.cn (G. Feng), gnss.jin@gmail.com (S. Jin).

0273-1177/$36.00 © 2012 COSPAR. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.asr.2012.09.011

European Coasts are measured and analyzed from multi-techniques, including satellite altimetry, tide gauge and GPS for the period 1993–2011. Since the absolute sea level variations contain the steric and mass components. The steric sea level changes are caused by the temperature and salinity variations, and the mass sea level changes are mainly derived from fresh water input and output, which could be measured by the Gravity Recovery and Climate Experiment (GRACE) mission launched in August 2002 (Tapley et al., 2004). Therefore, each contribution to the sea level changes along the European Coasts are further assessed and discussed.

2. Observation data

2.1. Satellite altimetry

The global merged Maps of Sea Level Anomaly grid data are used from French Archiving, Validation and Interpretation of the Satellite Oceanographic data (AVISO). The data set is a combined solution, which merged the ERS-1/2, Topex/Poseidon (T/P), ENVISAT and Jason-1/2 altimetric satellites. The altimetric data set is 7-day time resolution at $0.25 \times 0.25°$grids from January 1993 to December 2011 (AVISO, 1996). Necessary geophysical and atmospheric corrections are applied to the data set, such as ionospheric delay, dry and wet tropospheric corrections, solid Earth and ocean tides corrections, electromagnetic bias corrections, ocean tide loading corrections, pole tide corrections, sea state bias corrections, instrumental corrections and the Inverted Barometer (IB) response of the ocean (Ducet et al., 2000). In order to compare with GRACE and TG result, the monthly satellite altimetric data set is obtained from the weekly data at the closest points to the TG location and GRACE grid.

2.2. Tide gauge

The tide gauge (TG) at the coast can measure relative sea level variations with respect to the coast (Woodworth and Player, 2003). Here the 31 tide gauges at co-located GPS stations with the time span larger than 10 years are selected from the Permanent Service for Mean Sea Level (PSMSL) global network of tide gauges (Fig. 1). The time series of monthly TG averages from the revised local reference data are used to analyze the relative sea level changes. Since several TG time series missed some observations, here the data with less than 4 consecutive missing months in one year are used through linearly interpolating for some gaps and other data with missing more months are not used.

2.3. GPS data

In order to obtain the absolute coastal sea level changes, the vertical crustal motions at TG stations should be considered. GPS could precisely monitor the land motions (Jin et al., 2007; Jin and Wang, 2008). Here the 31 GPS stations co-located with Tide Gauges are used from the Système d'Observation du Niveau des Eaux Littorales (SONEL), whose distances between co-located GPS and TG stations are less than 3 km.

These solutions are expressed in the global ITRF2008 reference frame and covered from 1993 to 2011 with weekly intervals (Fig. 1). Details about the GPS data processing are available at the SONEL website (http://www.sonel.org/-GPS,28-.html?lang=en). In order to compare with satellite altimetric results, we also consider the impact of the glacial isostatic adjustment (GIA) on the vertical ground motion (Paulson et al., 2007).

2.4. GRACE Mass and Steric components

The global sea level changes from satellite altimetry include the steric and mass variations. In order to estimate the mass sea level changes along the European Coasts, ocean mass are estimated from the monthly GRACE solutions (Release-04) from the Center for Space Research (CSR) at the University of Texas, Austin for August 2002–December 2011, excluding June 2003, January 2004, January 2011 and June 2011 which don't have observed data. The degree 2 order 0 (C_{20}) coefficients are replaced by Satellite Laser Ranging (SLR) solutions (Cheng and Tapley, 2004); the degree 1 coefficients (C_{11}, S_{11}, and C_{10}) are used from Swenson et al. (2008); in order to minimize the effect of measurement and correlated errors, we use the 300 km width of Gaussian filter and de-striping filter (Swenson and Wahr, 2006).The de-striping filter is that the lower 11×11 set of harmonics was left unchanged, and a 5th order polynomial is fit as a function of even or odd degree (n) to the remaining coefficients for each order (m) greater than 2 from $n = 12$ up to $n = 60$. The postglacial rebound signals in the data have been removed according to the GIA model of Paulson et al. (2007). The leakage from land signals onto ocean signals have been reduced as much as possible by Wahr's method (Wahr et al., 1998). In order to compare with altimetric results, we have to add back the GAD coefficients to the GRACE GSM coefficients (Flechtner, 2007) and remove the time-variable mass of the atmosphere averaged over the global ocean (Willis et al., 2008). Finally, we can calculate the mass-induced sea level changes with the gravity coefficients anomalies (Chambers, 2006) as

$$\Delta\eta_{ocean}(\phi,\lambda,t) = \frac{a_e\rho_e}{3\rho_w}\sum_{n=0}^{60}\sum_{m=0}^{n}\frac{(2n+1)}{(1+k_n)}W_nP_{nm}(\sin\phi) \left\{ \begin{array}{c} (\Delta C_{nm}(t) + \Delta C_{nm}^{GAD}(t) - \Delta C_{nm}^{GAA}(t))\cos(m\phi) + \\ (\Delta S_{nm}(t) + \Delta S_{nm}^{GAD}(t) - \Delta S_{nm}^{GAA}(t))\sin(m\phi) \end{array} \right\} \quad (1)$$

where ϕ is latitude, λ is longitude, a_e is the equatorial radius of the Earth, ρ_e is the average density of the Earth (5517 kg/m^3), ρ_w is the density of fresh water (1000 kg/m^3), $\Delta C_{nm}, \Delta S_{nm}$ are dimensionless Stokes coefficients,

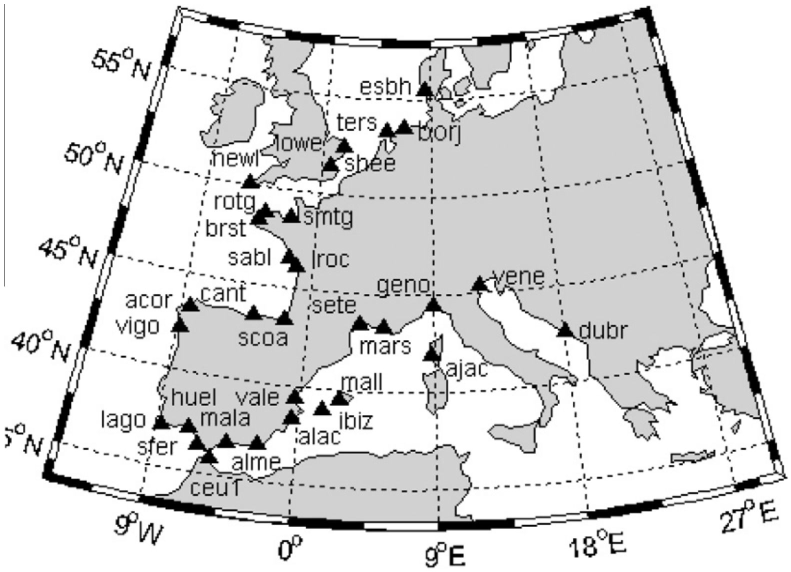

Fig. 1. The location of co-located Tide Gauge and GPS stations used in this study.

P_{nm} is the fully-normalized Associated Legendre Polynomials of degree n and order m, k_n is the Love number of degree n (Han and Wahr, 1995), W_n is the Gaussian smoothing.

Oceanographic temperature and salinity data provided by Ishii are used to estimate the steric sea level changes in the Europe (Ishii et al., 2006). The data set consists of monthly 1°grid point's temperature and salinity down to 700 m from 1993 to 2011. The steric sea level variations for monthly 1°×1°grid are calculated by converting the temperature and salinity values into density (Ishii et al., 2006).

$$\Delta\eta_{steric}(\phi,\lambda,t) = -\frac{1}{\rho_0}\int_{-h}^{0}[\rho(\phi,\lambda,t,S,T,P) - \overline{\rho}(\phi,\lambda,\overline{S},\overline{T},\overline{P})]dz \quad (2)$$

where ρ_0 is the mean density of seawater (1028 kg/m^3), h is the maximum depth, ρ is the density as a function of latitude (ϕ), longitude (λ), observation epoch (t), temperature (T), salinity (S) and pressure (P), which can be obtained by the depth. Mean seawater density ($\overline{\rho}$) is determined by the average salinity ($\overline{S}$), temperature ($\overline{T}$) and pressure ($\overline{P}$).

3. Results and discussions

3.1. Seasonal variations of sea level

The sea level change time series are obtained from satellite altimetry, Tide Gauge+GPS, and GRACE Mass+Steric. For example, Fig. 2 shows the sea level variations at the ceu1 TG station. It has shown that the sea level change time series have a strong seasonal signal and long-term trend, which agree remarkably well for three independent techniques. So we use a model including the annual, semi-annual and a linear trend to adjust the TG+GPS, satellite altimetry and GRACE Mass+Steric time series.

$$SLR(t) = A_a\cos(\omega_a t - \phi_a) + A_{sa}\cos(\omega_{sa} t - \phi_{sa}) + B + C\cdot t + \varepsilon \quad (3)$$

where t is time, A_a, ϕ_a, ω_a is annual amplitude, phase and frequency, respectively, A_{sa}, ϕ_{sa}, ω_{sa} is semi-annual amplitude, phase and frequency. C is the long-term trend and ε is the un-modeled residual item. We use least-squares method to fit the time series of sea level variations for every station and estimate the annual, semi-annual items and the long-term trend of sea level variations.

Since the semiannual amplitude is not higher than 10% of the annual amplitude, we mainly focus on the annual variations and secular trend (Table 1). Fig. 3 shows annual amplitudes and phases of sea level changes along the European Coasts at the 31 Tide Gauge Stations from satellite altimetry (red), Tide Gauge+GPS (blue), and GRACE Mass+Steric sea level changes (green) for the period of 1993 to 2011 (GRACE mass component just from 2002 to 2011). It has found that the three independent observations of sea level variations along the European Coasts have a good agreement both on annual amplitude and annual phase. The mean amplitude at all TG stations is 58.82 mm and the mean annual phase at all TG stations is 276.2° from satellite altimetry. The Tide Gauge+GPS results show that the mean amplitude is 57.99 mm and the mean annual phase is 282.4°. The difference of annual phase between satellite altimetry and TG+GPS results is from 0.7° to 33.8°. The GRACE Mass+Steric results show that the mean amplitude at all TG stations is 40.87 mm and the mean annual phase at all TG stations is 270.9°. The difference of annual phase between satellite altimetry and GRACE Mass+Steric results is from 4.3° to 47.6°. The annual amplitude of GRACE Mass+Steric results is

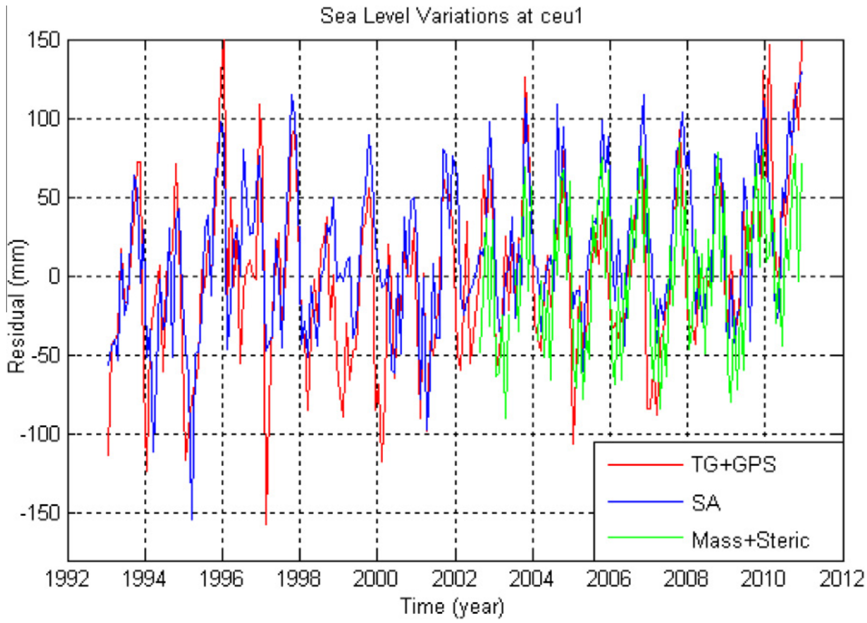

Fig. 2. Sea level change time series at ceu1 station. SA is the sea level change from satellite altimetry (blue), TG+GPS is the sea level change from tide gauge and GPS (red), Mass+Steric is the sea level change from GRACE mass plus steric components (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Secular trend, annual amplitude and phase of sea level variations at TG stations from multi-technique observations: Satellite altimetry, Tide Gauge and GPS, and GRACE Mass+Steric results.

TGsites	Satellite altimetry			Tide Gauge+GPS			GRACE Mass+Steric		
	Trend	Amplitude	Phase	Trend	Amplitude	Phase	Trend	Amplitude	Phase
sabl	1.33 ± 0.33	47.68	−75.86	2.67 ± 0.96	54.26	−47.39	0.67± ± 0.48	35.27	−89.9
lroc	1.02 ± 0.45	50.24	−70.64	1.40 ± 1.37	43.45	−46.98	0.67 ± 0.48	35.27	−89.9
cant	1.92 ± 0.26	45.54	−82.8	1.59 ± 0.94	55.85	−66.06	1.27 ± 0.67	34.67	−73.13
scoa	0.70 ± 0.31	49.1	−76.28	4.47 ± 0.90	40.49	−59.66	1.07 ± 0.63	33.67	−70.31
acor	1.94 ± 0.29	42.08	−74.15	−0.31 ± 0.28	40.79	−50.47	1.30 ± 0.64	29.78	−82.14
vigo	1.74 ± 0.29	42.04	−59.01	−2.06 ± 0.98	47.97	−30.32	2.34 ± 0.63	21.36	−63.42
huel	2.85 ± 0.30	45.41	−83.1	0.85 ± 0.68	57.12	−116.91	3.79 ± 0.90	31.99	−73.88
lago	1.94 ± 0.31	44.41	−67.9	0.46 ± 0.28	38.37	−75.85	3.74 ± 0.67	26.14	−77.42
sfer	2.78 ± 0.36	48.62	−85.93	0.84 ± 0.59	45.24	−100.32	3.79 ± 0.90	31.99	−73.88
ceu1	2.64 ± 0.44	45.56	−86.5	2.12 ± 0.55	41.53	−89.85	2.86 ± 1.27	40.21	−78.83
ters	2.89 ± 0.97	72.46	−76.79	3.91 ± 1.22	94.31	−70.44	5.78 ± 0.79	45.66	−80.44
shee	1.85 ± 0.91	69.91	−94.99	3.97 ± 1.17	51.52	−79.52	3.85 ± 0.49	22.55	−97.06
esbh	2.50 ± 1.01	83.99	−70.6	2.81 ± 1.99	95.8	−72.29	3.52 ± 1.02	50.7	−83.83
lowe	3.57 ± 0.93	67.96	−90.08	3.44 ± 0.64	63.83	−72.65	4.71 ± 0.6	38.06	−106.88
brst	0.64 ± 0.45	53.18	−61.51	0.34 ± 0.56	56.56	−48.55	0.70 ± 0.54	39.24	−86.84
smtg	2.04 ± 0.99	59.46	−83.1	2.36 ± 0.93	56.94	−63.63	1.72 ± 0.49	69.78	−105.02
rotg	0.69 ± 0.54	59.3	−70.25	2.65 ± 0.72	49.12	−53.07	1.63 ± 0.49	56.97	−100.64
newl	1.78 ± 0.60	58.87	−66.93	4.31 ± 0.85	57.6	−59.37	1.71 ± 0.51	33.26	−85.96
borj	2.60 ± 1.04	75.62	−78.11	4.9 ± 1.85	83.18	−77.43	5.71 ± 0.82	49.06	−94.2
ajac	1.87 ± 0.37	70.24	−109.7	6.29 ± 2.01	60.95	−95.33	1.95 ± 0.65	50.58	−102.09
alac	2.41 ± 0.31	65.9	−100.1	3.52 ± 0.65	67.57	−100.47	0.19 ± 0.55	54.42	−92.88
alme	2.95 ± 0.37	59.38	−94.69	3.75 ± 1.23	70.28	−102.77	0.26 ± 0.33	45.87	−112.63
dubr	3.38 ± 0.44	54.9	−70.32	3.27 ± 0.66	43.67	−65.08	1.57 ± 0.71	27.54	−89.08
geno	3.51 ± 0.34	55.87	−99.23	2.69 ± 0.94	45.18	−98.63	1.40 ± 0.76	27.77	−94.34
ibiz	2.32 ± 0.35	67.96	−104.8	3.36 ± 1.49	66.65	−110.54	0.21 ± 0.56	58.21	−95.29
mala	2.87 ± 0.46	67.27	−97.72	1.83 ± 0.90	59.44	−95.97	1.57 ± 1.32	39.69	−63.51
mall	0.73 ± 0.34	79.3	−105.6	1.61 ± 0.58	76.13	−109.47	−0.11 ± 0.66	57.83	−95.26
mars	3.01 ± 0.35	56.65	−91.94	2.72 ± 0.74	51.39	−72.14	0.88 ± 0.56	41.17	−102.67
sete	3.14 ± 0.38	56.73	−88.45	4.31 ± 1.27	44.33	−74.45	1.59 ± 0.43	39.67	−108.9
vale	2.48 ± 0.3	68.24	−102.7	4.64 ± 1.58	86.74	−111.15	−0.04 ± 0.64	53.79	−92.25
vene	4.01 ± 0.43	59.65	−78.69	2.79 ± 0.76	51.47	−87.65	1.25 ± 0.46	44.78	−97.81
mean	2.26 ± 0.52	58.82	−83.82	2.43 ± 0.61	57.99	−77.56	1.99 ± 0.67	40.87	−89.04

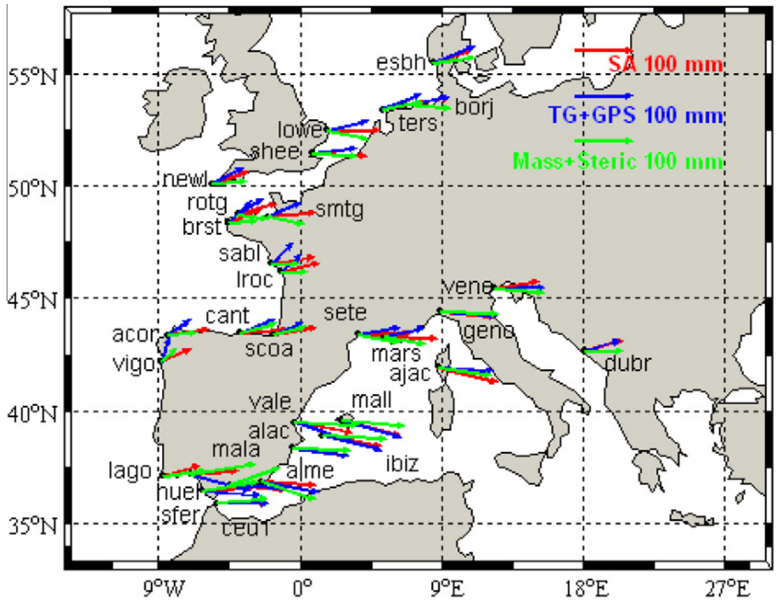

Fig. 3. Annual amplitudes and phases of sea level changes at 31 TG stations along the European coasts (satellite altimetry (red), TG+GPS (blue), GRACE Mass+Steric results (green)). The arrow lengths stand for the amplitudes and the phases are counted as clockwise from the north. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

smaller than the satellite altimetry results, while the annual amplitude of TG+GPS results is similar to the satellite altimetry results. For the annual phase, the GRACE Mass+Steric results have larger deviations in comparison with satellite altimetry than the TG+GPS results.

Fig. 4(a)–(d) show the correlation between SA and TG+GPS amplitude (a), SA and GRACE Mass+Steric amplitude (b), SA and TG+GPS phase (c) and SA and GRACE Mass+Steric phase (d). For the annual amplitude, the correlation between SA and TG+GPS time series is

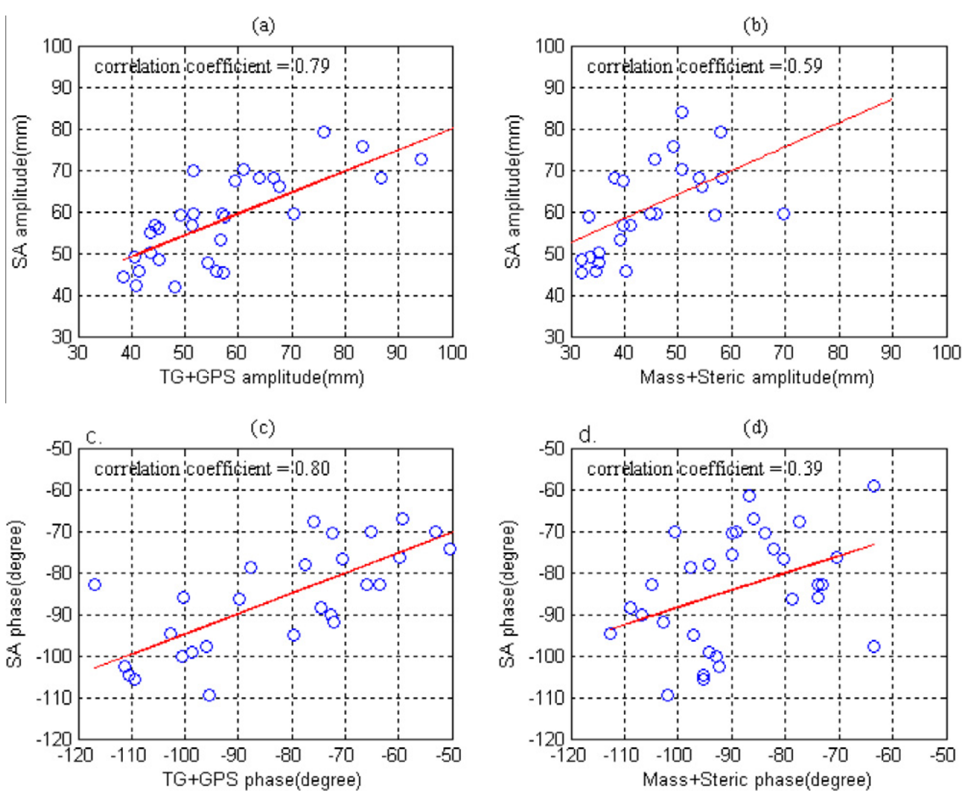

Fig. 4. Correlation coefficients of SA and TG+GPS amplitude (a), SA and GRACE Mass+Steric amplitude (b), SA and TG+GPS phase (c), SA phase and GRACE Mass+Steric phase (d).

Table 2
Annual amplitudes and phases of sea level change components along the European Coasts for the period of 1993 to 2011 (GRACE mass component for 2002 to 2011).

	Annual amplitude(mm)	Annual phase(degree)
Satellite Altimetry	58.82 ± 6	276.2 ± 10
TG+GPS	57.99 ± 7	282.4 ± 12
Steric sea level	44.21 ± 6	233.8 ± 7
GRACE Mass	14.14 ± 3	4.9 ± 12
Total (Mass+Steric)	40.87 ± 8	270.9 ± 15

0.79 and the correlation between SA and GRACE Mass+Steric time series is 0.59. For the annual phase, the correlation between SA and TG+GPS time series is 0.80 and the correlation between SA and GRACE Mass+Steric time series is 0.39. It has shown that TG+GPS results agree much better with altimetry results both in annual amplitude and phase than the GRACE Mass+Steric results. We further evaluate the mass and steric contributions to the sea level changes, respectively. Table 2 shows the results of annual amplitudes and phases of different sea level changes components along the European Coasts. These results are the averaged time series from all the time series along the European Coast. We can find that the annual cycle of sea level changes along the European Coasts is mainly driven by the steric contributions. The annual cycle of mass sea level changes measured by GRACE reaches the maximum value in January, almost half year later than the steric sea level changes with the peak in August. The maximum annual amplitude of steric sea level changes occurs in August with one month earlier than the altimetric results. The differences of GRACE Mass + Steric results with respect to the SA and TG+GPS probably come from the GRACE solutions due to the low resolution and land-ocean linkage effects.

3.2. Secular sea level changes

The secular trend of sea level changes at the 31 Tide Gauge Stations along the European coastline is analyzed from multi-technique observations. Fig. 5 shows the results from satellite altimetry (red), Tide Gauge+GPS (blue), and GRACE Mass+Steric sea level changes (green) at the 31 Tide Gauge Stations for the period of 1993 to 2011 (GRACE mass component just from 2002 to 2011). It has clearly shown that at most TG stations, the satellite altimetry, TG+GPS and GRACE Mass+Steric results have a good agreement in secular trend. The mean secular trend of sea level variations along the European Coasts is 2.26 ± 0.52 mm/y from satellite altimetry, 2.43 ± 0.61 mm/y from TG+GPS, and 1.99 ± 0.67 mm/y from GRACE Mass+Steric results. The secular trends between satellite altimetry and TG+GPS are much close at most stations, such as cant, esbh, lowe, brst, dubr, mars stations and so on, and at three stations, the differences between TG+GPS and altimetry results are larger than 1 mm/y. The secular trends from satellite altimetry and GRACE Mass + Steric results have a good agreement at some stations, such as sabl, lorc, cant, huel stations and so on, but still have some larger differences and the largest difference is up to 3.11 mm/y at borj station. The specific reasons will be discussed in Section 3.3. We calculate the correlation coefficient between the three measured values. For the secular trend, the correlation coefficient between SA and TG+GPS time series is 0.51 and the correlation coefficient between SA and GRACE Mass + Steric time

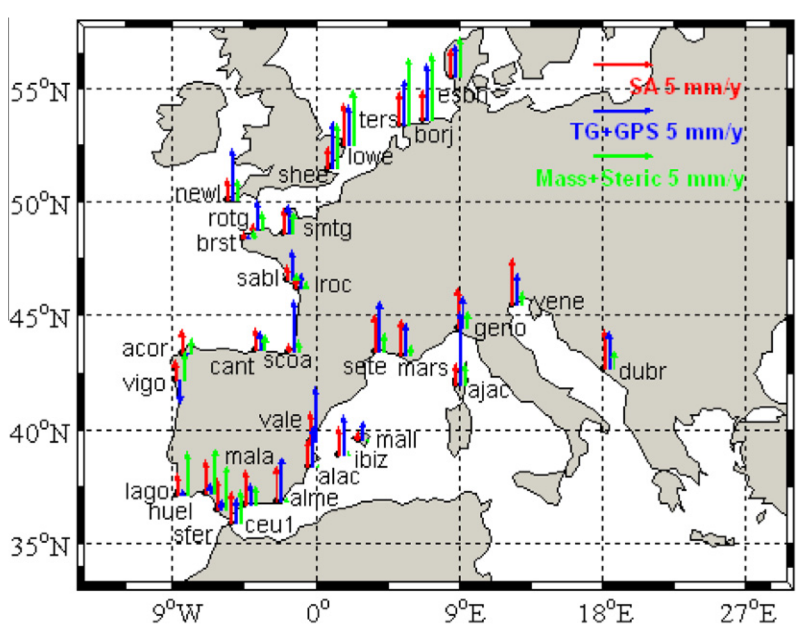

Fig. 5. Secular trend of sea level variations at the 31 Tide Gauge Stations along the Europe coastlines (satellite altimetry (red), TG+GPS (blue), GRACE Mass+Steric (green)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

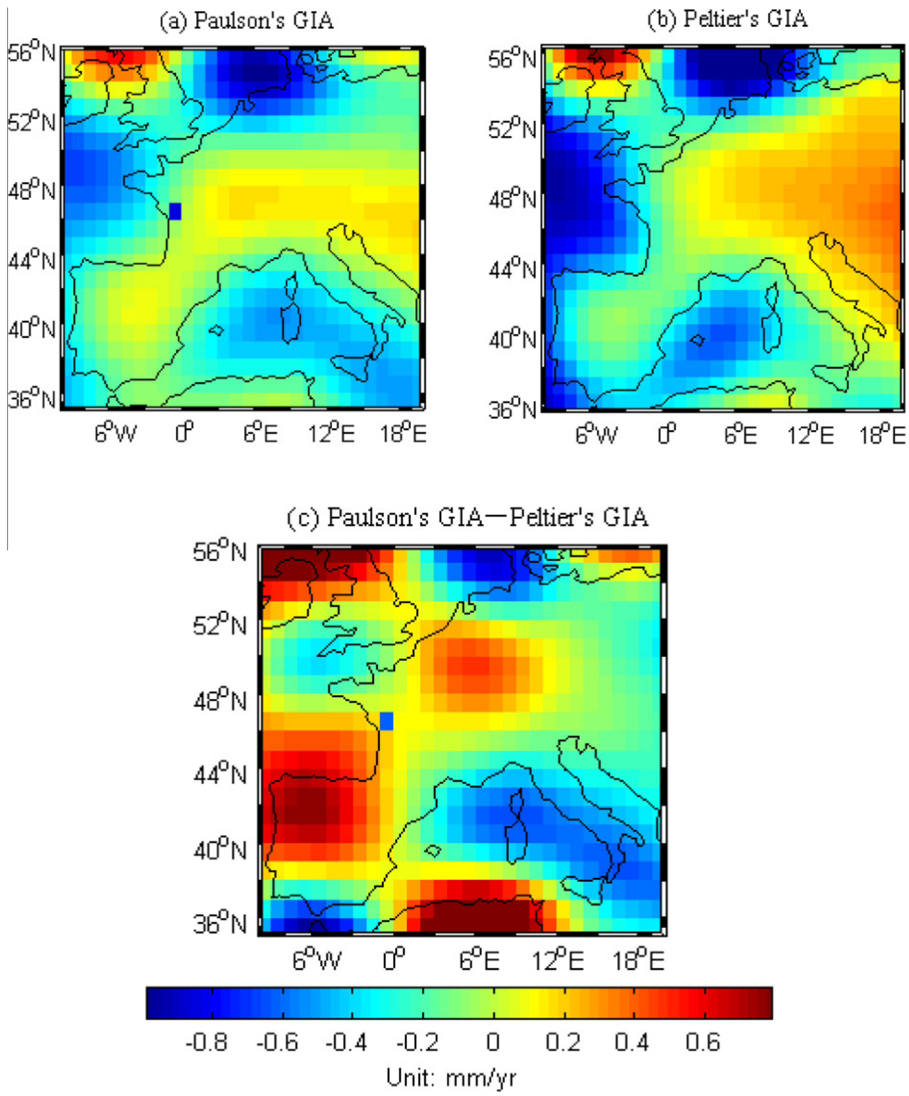

Fig. 6. Secular trend of sea level variations along the European Coasts predicted from GIA model: (a) Paulson's GIA model and (b) Peltier's GIA model (c) difference between two models.

series is 0.30. At most stations, the secular trend of sea level variations matches well between TG+GPS and satellite altimetry, while the GRACE Mass+Steric secular trend has a larger deviations. So TG+GPS are able to well capture the secular trend of sea level changes.

3.3. Effects and discussions

The main purpose of this work is to estimate and evaluate the sea level changes along the European Coasts from multi-techniques, including satellite altimetry, TG+GPS and GRACE Mass+Steric sea level measurements. Generally speaking, the results have good agreements in annual variations and secular trend between satellite altimetry, TG+GPS and GRACE Mass+Steric sea level variations along the European Coasts during 1993–2011 period, but some differences still exist, particularly in GRACE mass components.

When we use GRACE harmonic coefficients to estimate the mass sea level changes, many factors will affect the GRACE results. The first one is GRACE instruments noises and measurement errors; the second one is the errors from the atmosphere and ocean models (Han et al., 2004); the third one is noises and correlated errors in the GRACE harmonic coefficients (Swenson and Wahr, 2006); and the fourth one is due mainly to the low resolution and land-ocean linkage effects. The GPS results also still have lots of errors, such as tropospheric and ionospheric delays, mapping functions, bedrock thermal expansion and contraction, the antenna phase center influence, multi-path effects and orbital errors, etc. Penna et al. (2008) reported that the impact of ocean tide models is larger than 1mm in the time series of displacement. Horwath (2010) found that GPS satellite orbital errors, such as solar radiation pressure, Earth albedo can affect the results and GPS satellite wing's pointing error has a significant annual cycle.

Table 3
Secular trend of sea level variations at TG stations from multi-technique observations in the same time-span: Satellite altimetry, Tide Gauge and GPS, and GRACE Mass+Steric results.

TGsites	GRACE Mass+Steric			Tide Gauge + GPS		
	Time-span	Trend (GRACE Mass+Steric)	Trend (Satellite altimetry)	Time-span	Trend (Tide Gauge + GPS)	Trend (Satellite altimetry)
sabl	2002–2011	0.67 ± 0.48	0.99 ± 0.42	1993–2011	2.67 ± 0.96	1.33 ± 0.33
lroc	2002–2011	0.67 ± 0.48	1.16 ± 0.59	1998–2011	1.40 ± 1.37	1.26 ± 0.57
cant	2002–2011	1.27 ± 0.67	1.72 ± 0.67	1993–2009	1.59 ± 0.94	2.28 ± 0.37
scoa	2002–2011	1.07 ± 0.63	1.17 ± 0.89	1993–2011*	4.47 ± 0.90	0.70 ± 0.31
acor	2002–2011	1.30 ± 0.64	1.98 ± 0.78	1993–2011	-0.31 ± 0.28	1.94 ± 0.29
vigo	2002–2011	2.34 ± 0.63	2.28 ± 0.78	1993–2011	-2.06 ± 0.98	1.74 ± 0.29
huel	2002–2011	3.79 ± 0.90	2.91 ± 0.81	1997–2006	0.85 ± 0.68	2.39 ± 1.42
lago	2002–2011	3.74 ± 0.67	2.51 ± 0.76	1993–1999*	0.46 ± 0.28	1.75 ± 0.68
sfer	2002–2011	3.79 ± 0.90	2.92 ± 1.00	1993–2011	0.84 ± 0.59	2.78 ± 0.36
ceu1	2002–2011	2.86 ± 1.27	2.82 ± 1.11	1993–2011	2.12 ± 0.55	2.64 ± 0.44
ters	2002–2011	5.78 ± 0.79	2.91 ± 1.53	1993–2011	3.91 ± 1.22	2.89 ± 0.97
shee	2002–2011	3.85 ± 0.49	1.69 ± 1.54	1997–2009	3.97 ± 1.17	1.35 ± 1.21
esbh	2002–2011	3.52 ± 1.02	2.86 ± 2.68	1993–2011	2.81 ± 1.99	2.50 ± 1.01
lowe	2002–2011	4.71 ± 0.6	3.79 ± 1.24	1993–2011	3.44 ± 0.64	3.57 ± 0.93
brst	2002–2011	0.70 ± 0.54	0.57 ± 0.57	1993–2011	0.34 ± 0.56	0.64 ± 0.45
smtg	2002–2011	1.72 ± 0.49	2.23 ± 1.04	2006–2011	2.36 ± 0.93	2.42 ± 1.25
rotg	2002–2011	1.63 ± 0.49	0.95 ± 0.66	1993–2011*	2.65 ± 0.72	0.69 ± 0.54
newl	2002–2011	1.71 ± 0.51	1.88 ± 0.69	1993–2011	4.31 ± 0.85	1.78 ± 0.60
borj	2002–2011	5.71 ± 0.82	2.97 ± 1.24	1993–2008	4.9 ± 1.85	4.99 ± 1.37
ajac	2002–2011	1.95 ± 0.65	1.96 ± 0.59	2003–2011*	6.29 ± 2.01	1.52 ± 1.03
alac	2002–2011	0.19 ± 0.55	2.35 ± 0.63	1993–1997	3.52 ± 0.65	3.07 ± 1.87
alme	2002–2011	0.26 ± 0.33	1.66 ± 0.58	1993–1997	3.75 ± 1.23	3.51 ± 1.56
dubr	2002–2011	1.57 ± 0.71	2.9 ± 0.74	1993–2008	3.27 ± 0.66	3.29 ± 0.54
geno	2002–2011	1.40 ± 0.76	2.74 ± 1.13	1993–1997*	2.69 ± 0.94	3.25 ± 2.73
ibiz	2002–2011	0.21 ± 0.56	1.18 ± 1.12	2003–2009	3.36 ± 1.49	1.43 ± 1.18
mala	2002–2011	1.57 ± 1.32	2.19 ± 0.85	2003–2011	1.83 ± 0.90	2.07 ± 0.91
mall	2002–2011	-0.11 ± 0.66	0.49 ± 0.56	1997–2010	1.61 ± 0.58	0.94 ± 0.47
mars	2002–2011	0.88 ± 0.56	2.13 ± 0.89	1993–2011*	2.72 ± 0.74	3.01 ± 0.35
sete	2002–2011	1.59 ± 0.43	2.2 ± 0.78	1996–2010*	4.31 ± 1.27	2.42 ± 0.42
vale	2002–2011	-0.04 ± 0.64	2.28 ± 0.96	1995–2005	4.64 ± 1.58	2.75 ± 0.37
vene	2002–2011	1.25 ± 0.46	3.57 ± 1.18	1993–2000	2.79 ± 0.76	4.75 ± 1.56
mean		1.99 ± 0.67	2.13 ± 1.02		2.43 ± 0.61	2.31 ± 1.05

*Shows some data at stations are not available in some year.

Van Dam et al. (2007) reported that mismodeling the semidiurnal ocean tidal signal on GPS data processing at European coastal sites can result in spurious annual signals. In addition, the different processing softwares and strategies, also affect the GPS solutions in seasonal and secular changes.

For the secular trend of sea level variations estimated by TG+GPS and satellite altimetry, another effect is glacial isostatic adjustment (GIA). Due to locating at the early Alpine and Fennoscandian ice sheets, the European Coasts are potentially affected by the GIA (Stocchi et al., 2005). An accurate GIA estimate depends on about both the melting history of continental ice sheets since the Last Glacial Maximum (LGM) and the viscoelastic response of the solid Earth (Peltier, 2004). Fig. 6 shows the two different GIA models' estimates in the European Coasts. The Fig. 6(a) is the estimate from Paulson's GIA model which depends on the ICE-5G deglaciation model and 4-layered approximation to VM2 mantle model (Paulson et al., 2007); the Fig. 6(b) is the estimate from Peltier's GIA model, which depends on the ICE-5G deglaciation model and VM2 mantle model (Peltier, 2004); the Fig. 6(c) is the difference between Fig. 6(a) and 6(b). The GIA-induced rate of sea level variations in the Celtic sea, Bay of Biscay and North Sea produces a subsidence sea level changes with up to −0.98 mm/y, almost −0.3 mm/y in the western Mediterranean and around 0.8 mm/y in the Northern United Kingdom. However, the two GIA models have great differences in some places (Fig. 6(c)). In the southwestern coast of France (in the Bay of Biscay), the difference between each other is around 0.35 mm/y. For example, the difference is 0.38 mm/y in the cant station and 0.36 mm/y in the acor station. In the western Mediterranean and central Mediterranean, the difference is up to 0.49 mm/y. For example, the difference is 0.27 mm/y at the lago station and is 0.30 mm/y at the ceu1 station. At the esbh station, the difference reaches 0.40 mm/y. The GIA accounts for around 30% of the secular sea level variations at quite stable sites, such as ters and esbh station. So the GIA model's uncertainty is one of main error sources in estimating the secular trend of sea level variations using the GPS and Tide Gauges.

In addition, observation time of three kinds of techniques cannot completely overlap, which is also an effect in the secular trend. As GRACE results' time span is from

2002 to 2011, in order to evaluate the time-span affects, we calculate the satellite altimetric trend for 2002–2011. And for the TG time series, because different stations have different time spans, so we calculate the satellite altimetric trend at the same time-span at each TG station. The results are shown in Table 3.

Table 3 has shown the secular trend with the same time span. The mean secular trend of sea level variations along the European Coasts has no big changes. For the secular trend, the correlation coefficient between SA and TG+GPS time series is improved from 0.51 to 0.61 and the correlation coefficient between SA and GRACE Mass+Steric time series is improved from 0.30 to 0.45. Furthermore, using the same the time-span, the discrepancies between satellite altimetry and GRACE Mass+Steric decrease from 13.5% to 7.9% and the discrepancies between satellite altimetry and GRACE Mass+Steric decrease from 7.0% to 5.3%. In addition, the tide gauge and GPS stations do not locate exactly at the same place, which also affect the estimated results.

4. Conclusion

In this paper, the sea level variations along the European Coasts are investigated from satellite altimetry, tide gauges, GPS, GRACE (satellite gravimetry) and Ishii oceanographic data. For the annual changes of sea level, the TG+GPS results are consistent with satellite altimetry with annual amplitude correlation of 0.79 and annual phase correlation of 0.80 at total 31 co-located TG and GPS stations for the period 1993–2011. The annual phases of the three independent techniques agree remarkably well at most stations, with difference of only 6 degrees. Furthermore, the annual cycle of sea level changes along the European Coasts is mainly driven by the steric contributions. The annual amplitude of mass sea level variations from GRACE is just a quarter of steric sea level changes.

For the secular trend, the sea level variations along the European Coasts is 2.26 ± 0.52 mm/y from satellite altimetry, 2.43 ± 0.61 mm/y from TG+GPS, and 1.99 ± 0.67 mm/y from GRACE Mass + Steric results. The correlation coefficient between SA and TG + GPS time series is 0.51 and the correlation coefficient between SA and GRACE Mass + Steric time series is 0.30. The secular trend between satellite altimetry and TG+GPS is much close at most stations, while GRACE Mass+Steric results have some larger differences with respect to satellite altimetry and TG+GPS, and the largest difference is at borj station with up to 3.11 mm/y. On one hand, a number of factors affect GPS and GRACE estimates, such as the glacial isostatic adjustment (GIA), orbital errors, errors of data processing strategies and models, and the low resolution and land-ocean linkage effects of GRACE. On the other hand, due to the Tide Gauge and GPS stations do not exactly locate at the same places.

Therefore, these results indicate that the co-located tide gauge and GPS well estimate the annual signals and secular trend of sea level changes with wide potentials. Due to limitations of spatial resolution and land-ocean linkage errors of GRACE along the European Coasts, the GRACE cannot capture mass sea level changes well. In the future, with the launch of the next generation of gravity satellites, measuring more high-precision global sea level variations are expected with improving the measurement accuracy, extending the observation time, enhancing data processing procedure and geophysical models (e.g., tide and GIA models).

Acknowledgments

We are grateful to thank the Système d'Observation du Niveau des Eaux Littorales (SONEL) and the Permanent Service for Mean Sea Level (PSMSL) for providing GPS and Tide Gauges data. This research is supported by the National Basic Research Program of China (973 Program) (Grant No. 2012CB720000), Main Direction Project of Chinese Academy of Sciences (Grant No. KJCX2-EW-T03), Shanghai Science and Technology Commission Project (Grant No. 12DZ2273300), Shanghai Pujiang Talent Program Project (Grant No. 11PJ1411500) and National Natural Science Foundation of China (NSFC) Project (Grant No. 11173050).

References

AVISO, AVISO User Handbook: Merged TOPEX/Poseidon Products, Romonville St-Agne, France, p. 201, 1996.

Barnett, T.P. The estimation of "global" sea level change: a problem of uniqueness. J. Geophys. Res. 89 (C5), 7980–7988, 1984.

Braitenberg, C., Mariani, P., Tunini, L. Vertical crustal motions from differential tide gauge observations and satellite altimetry in southern Italy. J. Geodyn., http://dx.doi.org/10.1016/j.jog.2010.09.003, 2010.

Cazenave, A., Nerem, R.S. Present-day sea level change: observations and causes. Rev. Geophys. 42 (3), RG3001, http://dx.doi.org/10.1029/2003RG000139, 2004.

Chambers, D.P. Evaluation of new GRACE time-variable gravity data over the ocean. Geophys. Res. Lett. 33 (17), LI7603, 2006.

Cheng, M., Tapley, B. Variations in the Earth's oblateness during the past 28 years. J. Geophys. Res. 109, B09402, http://dx.doi.org/10.1029/2004JB003028, 2004.

Church, J.A., White, N.J. A 20th century acceleration in global sea-level rise. Geophys. Res. Lett. 33, L01602, http://dx.doi.org/10.1029/2005GL024826, 2006.

Douglas, B.C. Sea level change in the era of the recording tide gauges, in: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), Sea Level Rise: History and Consequences. Academic Press, New York, pp. 37–64, 2001.

Ducet, N., Le Traon, P., Reverdin, G. Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. J. Geophys. Res. 105 (C8), 19477–19498, 2000.

Fenoglio-Marc, L., Groten, E., Dietz, C. Vertical land motion in the Mediterranean Sea from altimetry and tide gauge stations. Mar. Geod. 27 (3–4), 683–701, 2004.

Flechtner, F. AOD1B Product description document for product releases 01 to 04, GRACE 327–750, CSR publ. GR-GFZ-AOD-0001 Rev. 3.1, University of Texas at Austin, p. 43, 2007.

Garcia, F., Vigo, M.I., Garcia-Garcia, D. Combination of multisatellite altimetry and tide gauge data for determining vertical crustal movements along Northern Mediterranean Coast. Pure Appl. Geophys. 169, 1411–1423, http://dx.doi.org/10.1007/s00024-011-0400-5, 2011.

Han, D., Wahr, J. The viscoelastic relaxation of a realistically stratified earth, and a further analysis of post-glacial rebound. Geophys. J. Int. 120, 287–311, 1995.

Han, S.C., Jekeli, C., Shum, C.K. Time-variable aliasing effects of ocean tides, atmosphere, and continental water mass on monthly mean GRACE gravity field. J. Geophys. Res. 109, B04403, 2004.

Holgate, S.J., Woodworth, P.L. Evidence for enhanced coastal sea level rise during the 1990s. Geophys. Res. Lett. 31, L07305, http://dx.doi.org/10.1029/2004GL019626, 2004.

Horwath, M., Mass variation signals in GRACE products and in crustal deformations from GPS: a comparison. In: Flechtner, F., et al. (Eds.), System Earth via Geodetic-Geophysical Space Techniques, Advanced Technologies in Earth Sciences, part 5, pp. 399–406, http://dx.doi.org/10.1007/978-3-642-10228-8_34, 2010.

Ishii, M., Kimoto, M., Sakamoto, K., et al. Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses. J. Oceanogr. 62, 155–170, 2006.

Jin, S.G., Park, P., Zhu, W. Micro-plate tectonics and kinematics in Northeast Asia inferred from a dense set of GPS observations. Earth Planet. Sci. Lett. 257 (3-4), 486–496, http://dx.doi.org/10.1016/j.epsl.2007.03.011, 2007.

Jin, S.G., Wang, J. Spreading change of Africa-South America plate: insights from space geodetic observations. Int. J. Earth Sci. 97 (6), 1293–1300, http://dx.doi.org/10.1007/s00531-007-0220-0, 2008.

Leuliette, E.W., Nerem, R.S., Mitchum, G.T. Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. Mar. Geodesy. 27 (1–2), 79–94, 2004.

Meyssignac, B., Cazenave, A. Sea level: a review of present-day and recent-past changes and variability. J. Geodyn. 58 (96–109), http://dx.doi.org/10.1016/j.jog.2012.03.005, 2012.

Miller, L., Douglas, B.C. Mass and volume contributions to 20th century global sea level rise. Nature 428, 406–409, 2004.

Paulson, A., Zhong, S.J., Wahr, J. Inference of mantle viscosity from GRACE and relative sea level data. Geophys. J. Int. 171 (2), 497–508, 2007.

Peltier, W.R. Global glacial isostatic adjustment and modern instrumental records of relative sea level history, in: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), Sea Level Rise: History and Consequences. Academic Press, San Diego, pp. 65–95, 2001.

Peltier, W.R. Global glacial isostasy and the surface of the ice-age earth: the ICE-5G(VM2) Model and GRACE. Ann. Rev. Earth Planet. Sci. 32, 111–149, 2004.

Penna, N.T., Bos, M.S., Baker, T.F., Scherneck, H.G. Assessing the accuracy of predicted ocean tide loading displacement values. J. Geod. 82, 893–907, http://dx.doi.org/10.1007/s00190-008-0220-2, 2008.

Stocchi, P., Spada, G., Cianetti, S. Isostatic rebound following the Alpine deglaciation: impact on the sea level variations and vertical movements in the Mediterranean region. Geophys. J. Int. 162, http://dx.doi.org/10.1111/j.1365-246X.2005.02653.x, 2005.

Swenson, S.C., Wahr, J. Post-processing removal of correlated errors in GRACE data. Geophys. Res. Lett. 33, http://dx.doi.org/10.1029/2005GL025285, 2006.

Swenson, S., Chambers, D., Wahr, J. Estimating geocenter variations from a combination of GRACE and ocean model output. J. Geophys. Res. 113, B08410, http://dx.doi.org/10.1029/2007JB005338, 2008.

Tapley, B.D., Bettadpur, S., Watkins, M., Reigber, C. The gravity recovery and climate experiment: mission overview and early results. Geophys. Res. Lett. 31, L09607, http://dx.doi.org/10.1029/2004GL019920, 2004.

Van Dam, T., Wahr, J., Lavallée, D. A comparison of annual vertical crustal displacements from GPS and Gravity Recovery and Climate Experiment (GRACE) over Europe. J. Geophys. Res. 112, B03404, http://dx.doi.org/10.1029/2006JB004335, 2007.

Wahr, J., Molenaar, M., Bryan, F. Time-variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J. Geophys. Res. 103 (32), 205–229, 1998.

Willis, J.K., Chambers, D.P., Nerem, R.S. Assessing the globally averaged sea level budget on seasonal to interannual time-scales. J. Geophys. Res. 113, C06015, http://dx.doi.org/10.1029/2007JC004517, 2008.

Woodworth, P.L., Player, R. The permanent service for mean sea level: an update to the 21st century. J. Coastal Res. 19, 287–295, 2003.

Wöppelmann, G., Marcos, M. Coastal sea level rise in southern Europe and the non-climate contribution of vertical land motion. J. Geophys. Res. 117, C01007, http://dx.doi.org/10.1029/2011JC007469, 2012.