Sea Level Changes in the Black Sea Using Satellite Altimetry and Tide-Gauge Observations

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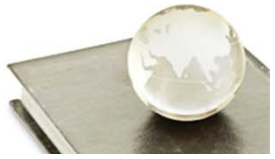
June 28, 2015



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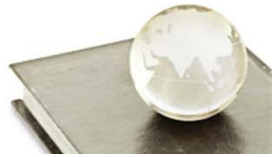
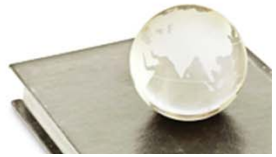


Introduction…

- Black Sea is an isolated sea in the ocean system.
- It has strong temporal mass variations in relation to its wide drainage area covering a large part of Europe.

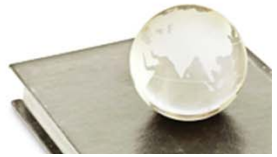


Introduction

- Mean sea level of the Black Sea has risen rapidly (Cazenave et al. 2002; Kubryakov and Stanichyni 2013; Vigo et al. 2005).
- Aim of this study;

Seasonal variations of sea level	Satellite altimetry data
Secular sea level changes	Tide-gauge stations data

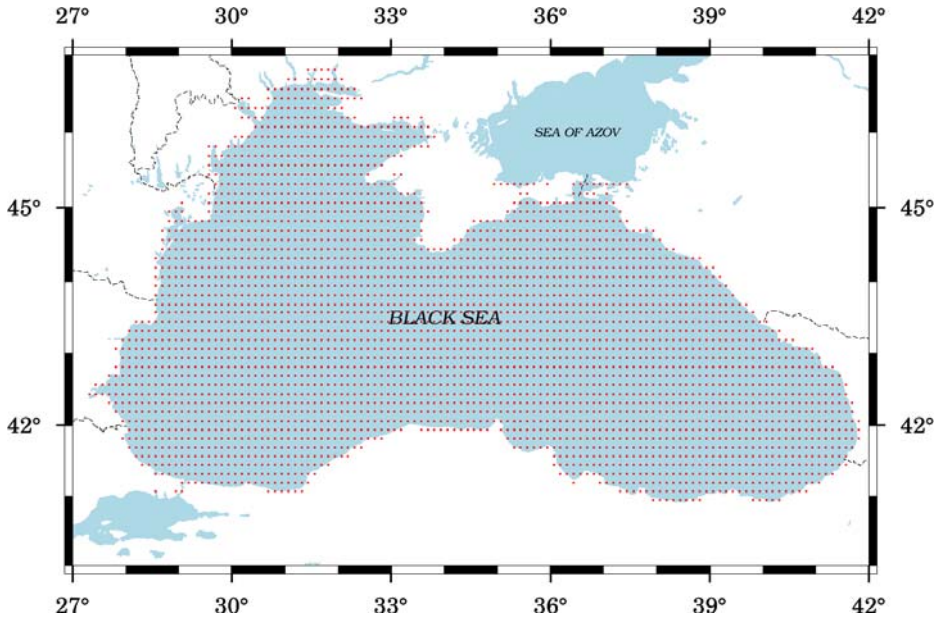
- Sea level changes along the Black Sea coasts at the same time-span for satellite altimetry and tide-gauge time series.



Data Sets (1)…

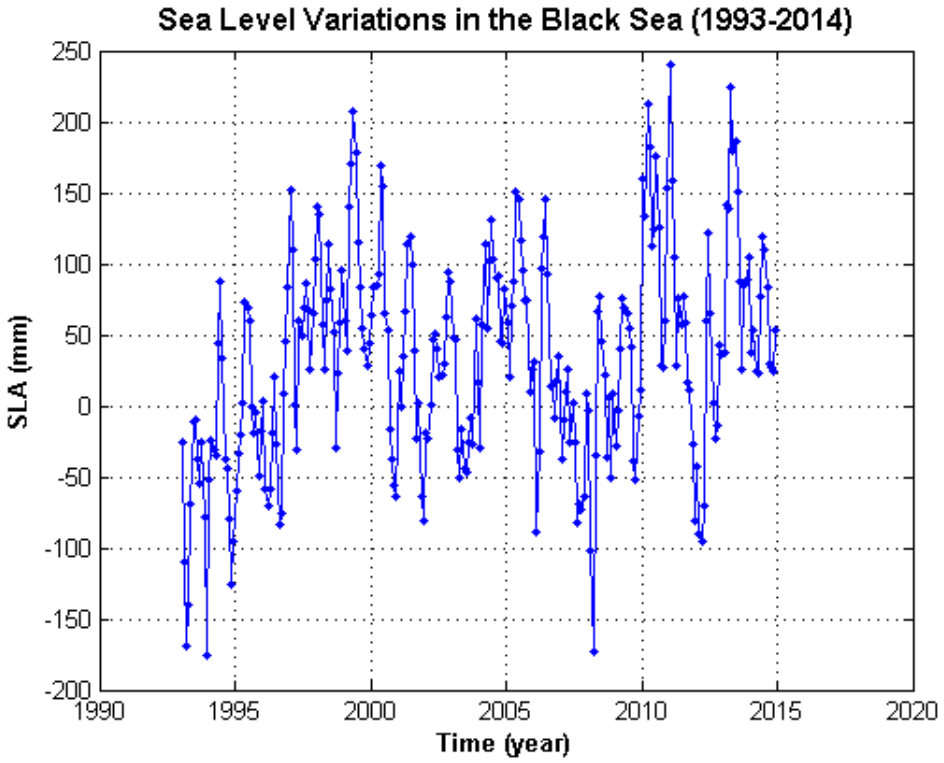
Altimetric data set:

- All-sat-merged Maps of Sea Level Anomaly (MSLA) gridded data in delayed time (from AVISO).
- Daily data at 0.125° x 0.125° grids.
- Time-span: from 1 January 1993 to 27 December 2014.



Total 3249 grid points

Data Sets (1)



- Monthly satellite altimetric data set is obtained from the daily data at all the grid points. These values are spatially averaged over all the Black Sea.

Data Sets (2)…

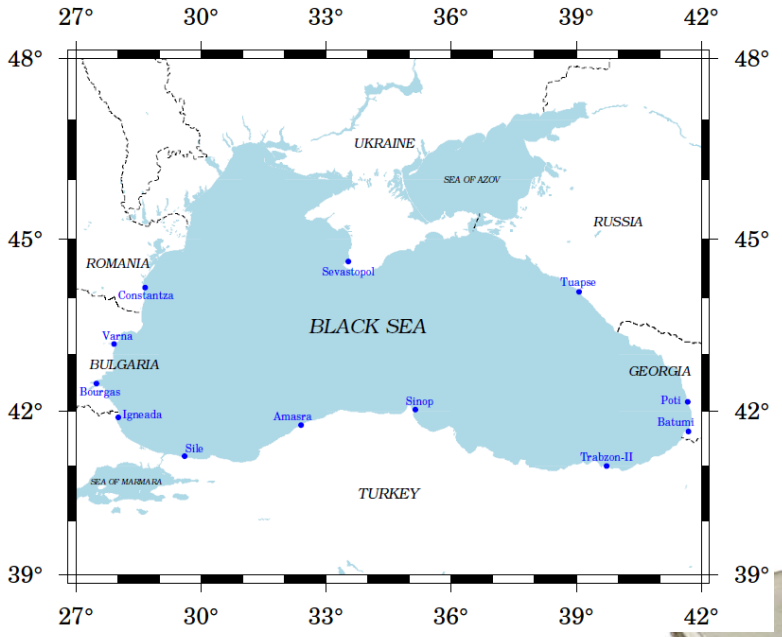
Tide-gauge stations along the Black Sea coasts:

- 7 tide-gauge stations data from the Permanent Service for Mean Sea Level (PSMSL),
- 5 tide-gauge stations data from Turkish Sea Level Monitoring System (TUDES)

Tide-gauge station	Country	Date of the first data	Time-span
[1] Poti	Georgia	January 1874	1874-2013
[1] Batumi	Georgia	January 1882	1882-2013
[1] Sevastopol	Ukraine	January 1910	1910-1994
[1] Tuapse	Russia	January 1917	1917-2011
[1] Varna	Bulgaria	January 1929	1929-1996
[1] Bourgas	Bulgaria	January 1929	1929-1996
[1] Constantza	Romania	January 1933	1933-1997
[2] Amasra	Turkey	13 June 2001	2001-2014
[2] Igneada	Turkey	29 June 2002	2002-2014
[2] Trabzon-II	Turkey	14 July 2002	2002-2014
[2] Sinop	Turkey	18 June 2005	2005-2014
[2] Sile	Turkey	16 July 2008	2008-2014

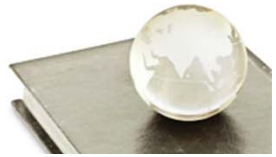
[1] PSMSL

[2] TUDES stations



Data Sets (2)

- Tide-gauge stations data from PSMSL.
  - Time series of monthly mean sea level data from revised local reference datum.
- Sea level data from TUDES tide-gauge stations.
  - Provided at 15-minute intervals.
  - Referred to Turkish National Vertical Control Network - TUDKA99.
- Missing observations are eliminated.

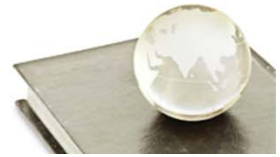


Analysis of Sea Level Change Time Series

- Sea level change time series have a strong seasonal signal and long-term trend.
- A model including the annual, semi-annual variations and a linear trend to adjust the satellite altimetry and tide-gauge time series (*Feng et al. 2012*).

$$\boldsymbol{MSL(t) = A_a\, cos(\omega_a t - \emptyset_a) + A_{sa}\, cos(\omega_{sa} t - \emptyset_{sa}) + B + Ct + \varepsilon}$$

$\boldsymbol{MSL}$: Mean Sea Level, $\boldsymbol{t}$: time,
$\boldsymbol{A_a, A_{sa}}$: annual and semi-annual amplitude, respectively,
$\boldsymbol{\emptyset_a, \emptyset_{sa}}$: annual and semi-annual phase, respectively,
$\boldsymbol{\omega_a, \omega_{sa}}$: annual and semi-annual angular frequency, respectively,
$\boldsymbol{B}$: mean sea level at t_0,
$\boldsymbol{C}$: long–term trend,
$\boldsymbol{\varepsilon}$: un-modeled residuals



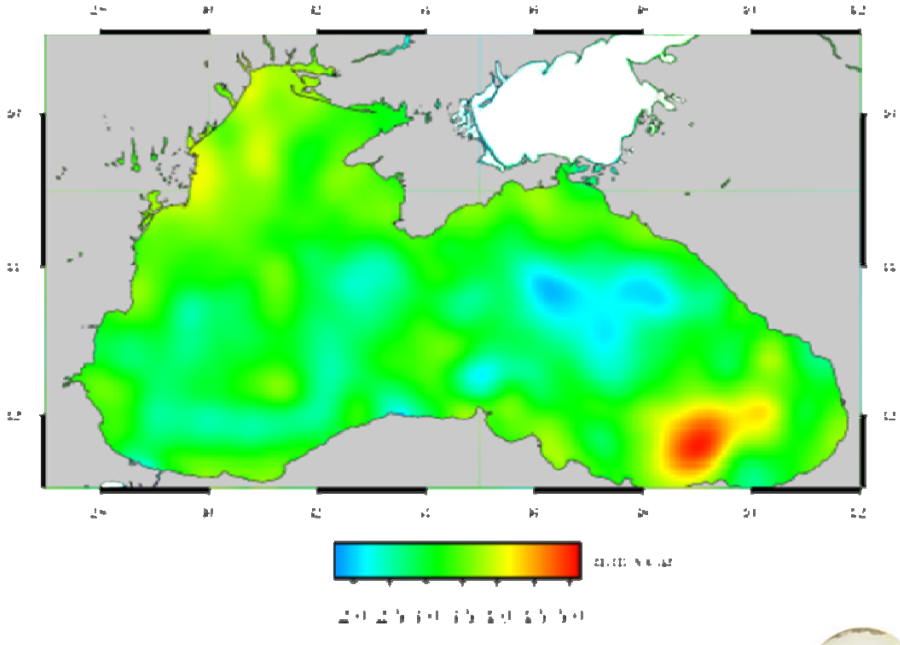
From Satellite Altimetry

Black Sea level variations for the period of 1993 to 2014:

- Trend: 3.16 ± 0.77 mm/year
- Annual amplitude: 36.08 ± 6.39 mm
- Semi-annual amplitude: 22.86 ± 6.39 mm
- Annual phase: 325.16 ± 0.19°
- Semi-annual phase: 341.33 ± 0.29°

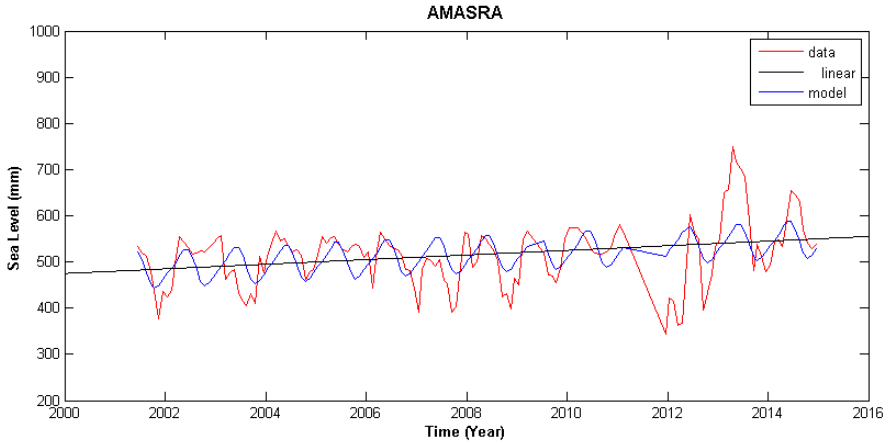
* The annual cycle of sea level change reaches the maximum value in November.

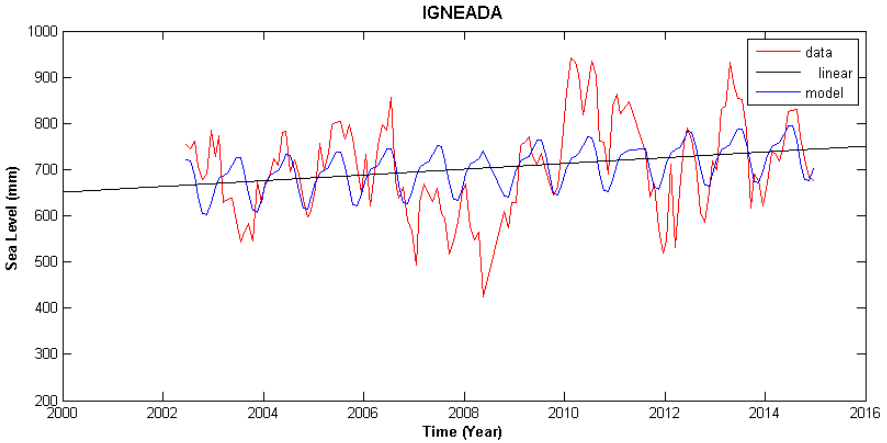
Map of the Black Sea level trends



From Tide-Gauge Stations…

Sea level change time series for 2 TUDES tide-gauge stations



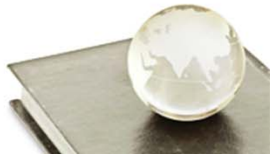


From Tide-Gauge Stations

Tide-gauge station	Trend (mm/year)
Poti	6.65±0.07
Batumi	1.97±0.08
Sevastopol	1.31±0.13
Tuapse	2.41±0.11
Varna	1.27±0.18
Bourgas	1.79±0.20
Constantza	1.22±0.21
Amasra	5.01±1.33
Igneada	6.23±2.25
Trabzon-II	2.26±2.06
Sinop	-0.02±3.16
Sile	4.54±5.54

Tide-gauge station	Time-span
Poti	1874-2013
Batumi	1882-2013
Sevastopol	1910-1994
Tuapse	1917-2011
Varna	1929-1996
Bourgas	1929-1996
Constantza	1933-1997
Amasra	2001-2014
Igneada	2002-2014
Trabzon-II	2002-2014
Sinop	2005-2014
Sile	2008-2014

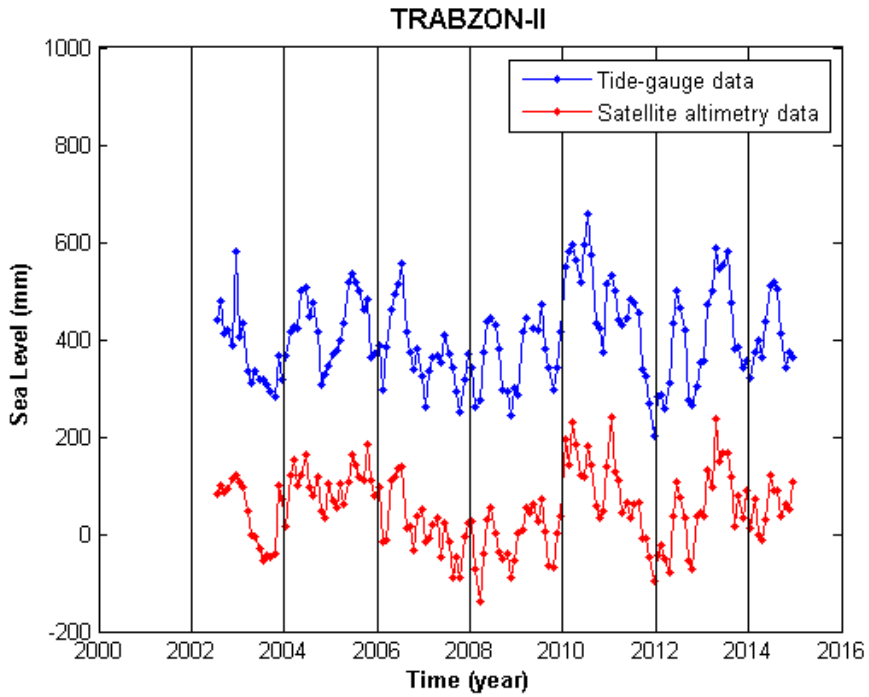
- Trends, annual/semi-annual amplitudes and phases of relative sea level variations at 12 tide-gauge stations.
- The trend estimations are sensitive to length of record!!!



Coastal Sea Level Changes in the Black Sea…

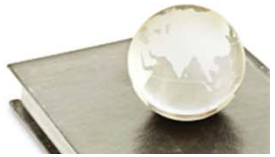
- Comparision of sea level change time series at the tide-gauge stations and the nearest altimetric grid points to these stations.

- Estimations for same time-span.



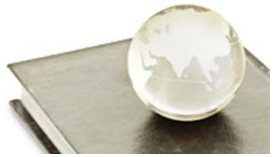
Coastal Sea Level Changes in the Black Sea…

Tide-gauge station / Altimetric grid point	Distance (km)	Same time-span	Trend (mm/year)	Annual		Semi-annual	
				Amplitude (mm)	Phase (°)	Amplitude (mm)	Phase (°)
Constantza	3.270	January 1993	14.46±5.93	37.38±10.49	-64.99±0.28	25.03±10.38	-19.91±0.42
The nearest point		December 1997	24.72±4.76	27.10±6.28	-83.39±0.23	15.55±6.28	-41.78±0.40
Amasra	7.924	June 2001	-0.31±1.52	27.11±6.69	-61.39±0.24	9.36±6.52	-8.24±0.71
The nearest point		December 2012	0.84±1.79	24.57±8.08	-60.07±0.33	20.46±8.05	-16.48±0.40
Igneada	7.876	June 2002	6.23±2.25	51.83±10.79	-38.93±0.21	22.41±10.80	43.36±0.48
The nearest point		December 2014	2.02±1.69	24.51±5.97	-51.33±0.24	13.78±5.94	-10.20±0.43
Trabzon-II	8.603	July 2002	2.26±2.06	62.62±8.92	-26.38±0.14	27.28±8.95	17.16±0.33
The nearest point		December 2014	-0.38±1.71	27.28±6.10	-48.95±0.22	25.96±6.10	2.26±0.23
Sinop	5.953	June 2005	-0.02±3.16	48.99±11.15	-44.16±0.23	29.49±11.17	11.95±0.38
The nearest point		December 2014	6.85±2.65	29.06±5.98	-66.34±0.21	30.48±3.80	-11.78±0.25
Sile	5.523	July 2008	4.54±5.54	62.74±12.66	-51.00±0.20	22.84±12.66	48.96±0.55
The nearest point		December 2014	3.45±4.76	19.47±6.02	-62.79±0.31	18.08±6.01	-16.82±0.33



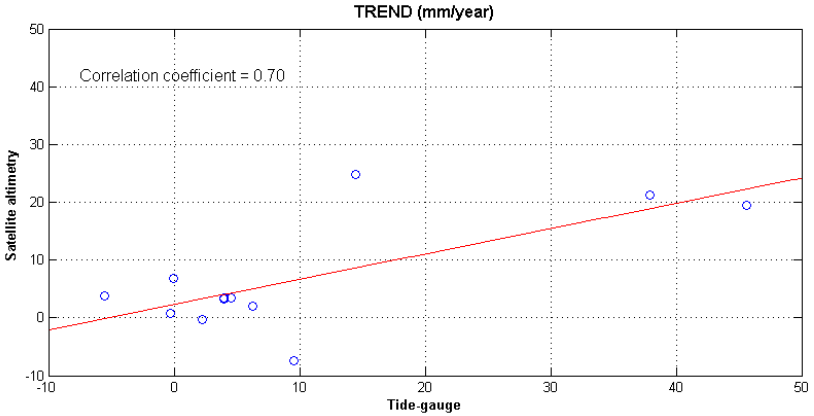
Coastal Sea Level Changes in the Black Sea…

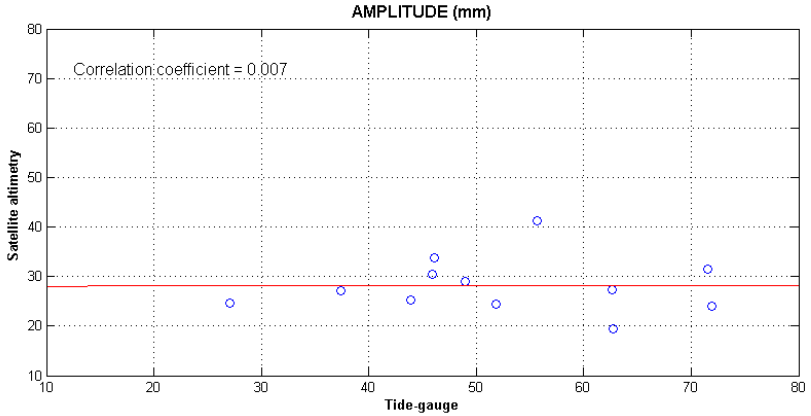
Tide-gauge station	Distance (km)	Same time-span	Trend (mm/year)	Annual		Semi-annual	
Altimetric grid point				Amplitude (mm)	Phase (°)	Amplitude (mm)	Phase (°)
Poti	2.358	January 1993	4.00±0.85	45.95±6.83	-30.33±0.15	17.21±6.84	43.13±0.40
The nearest point		December 2013	3.38±0.82	30.49±6.38	-37.82±0.21	23.65±6.38	-12.98±0.27
Batumi	6.171	January 1993	-5.55±1.12	46.11±10.18	35.88±0.22	1.18±10.16	37.68±8.60
The nearest point		December 2013	3.86±0.83	33.69±6.33	-35.60±0.19	24.30±6.33	-16.17±0.26
Sevastopol	6.829	January 1993	9.55±22.85	71.56±9.23	-29.08±0.13	28.66±9.23	-11.06±0.22
The nearest point		December 1994	-7.35±16.78	31.53±6.12	-76.24±0.19	18.40±6.12	-16.32±0.33
Tuapse	4.188	January 1993	3.95±1.02	55.63±6.82	-42.99±0.12	26.78±6.80	18.66±0.25
The nearest point		December 2011	3.19±0.95	41.29±6.17	-74.24±0.15	20.23±6.17	-0.31±0.31
Varna	2.358	January 1993	37.94±10.87	43.91±15.19	-84.37±0.33	17.47±15.09	-37.93±0.82
The nearest point		December 1996	21.22±6.54	25.33±5.92	-52.30±0.23	15.62±5.92	-23.67±0.38
Bourgas	7.194	January 1993	45.64±11.98	71.88±4.83	-52.56±0.26	22.34±11.86	-26.94±0.55
The nearest point		December 1996	19.42±7.04	23.95±5.75	-47.05±0.24	16.97±5.75	-22.81±0.34

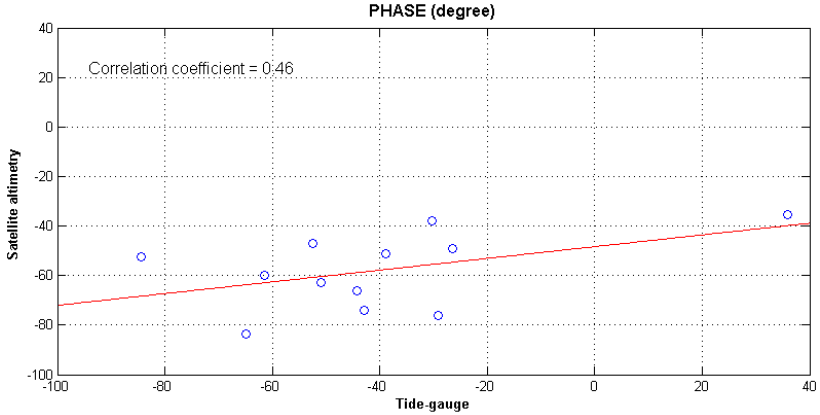


Coastal Sea Level Changes in the Black Sea…

- The correlation coefficients between tide-gauge and satellite altimetry time series:

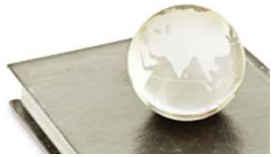






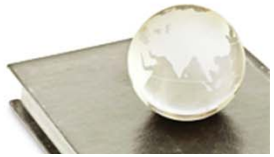
Coastal Sea Level Changes in the Black Sea

- Results for long-term time-series are agreed remarkably consistent.
- Nevertheless, at most stations, the results have large differences at most stations.
- Differences may be related to;
  - Data outliers,
  - Data gaps,
  - Too short time series,
  - Vertical land motions,
  - A loss of quality in the satellite altimetry measurements near the coastlines,
  - Distance between the tide-gauge stations and the altimetric grid points.



Conclusions

- The Black Sea level has been rising at a rate of 3.16 mm/year according to the satellite altimerty data.
- This rate varies from the coast to the coast.
- Trend estimations, detected with comparision of absolute and relative sea level variations along the Black Sea coasts, are consistent.
- For more accurate analysis, the data outliers should be detected and eliminated.
- Data gaps should be taken into consideration.
- Vertical land motion should be measured near the tide-gauge stations.



Thank you for your attention…

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