NEW ANALYSIS OF TIDE GAUGES MONTHLY TIME SERIES FOR VARNA AND BURGAS SPANNING 1928 - 2011

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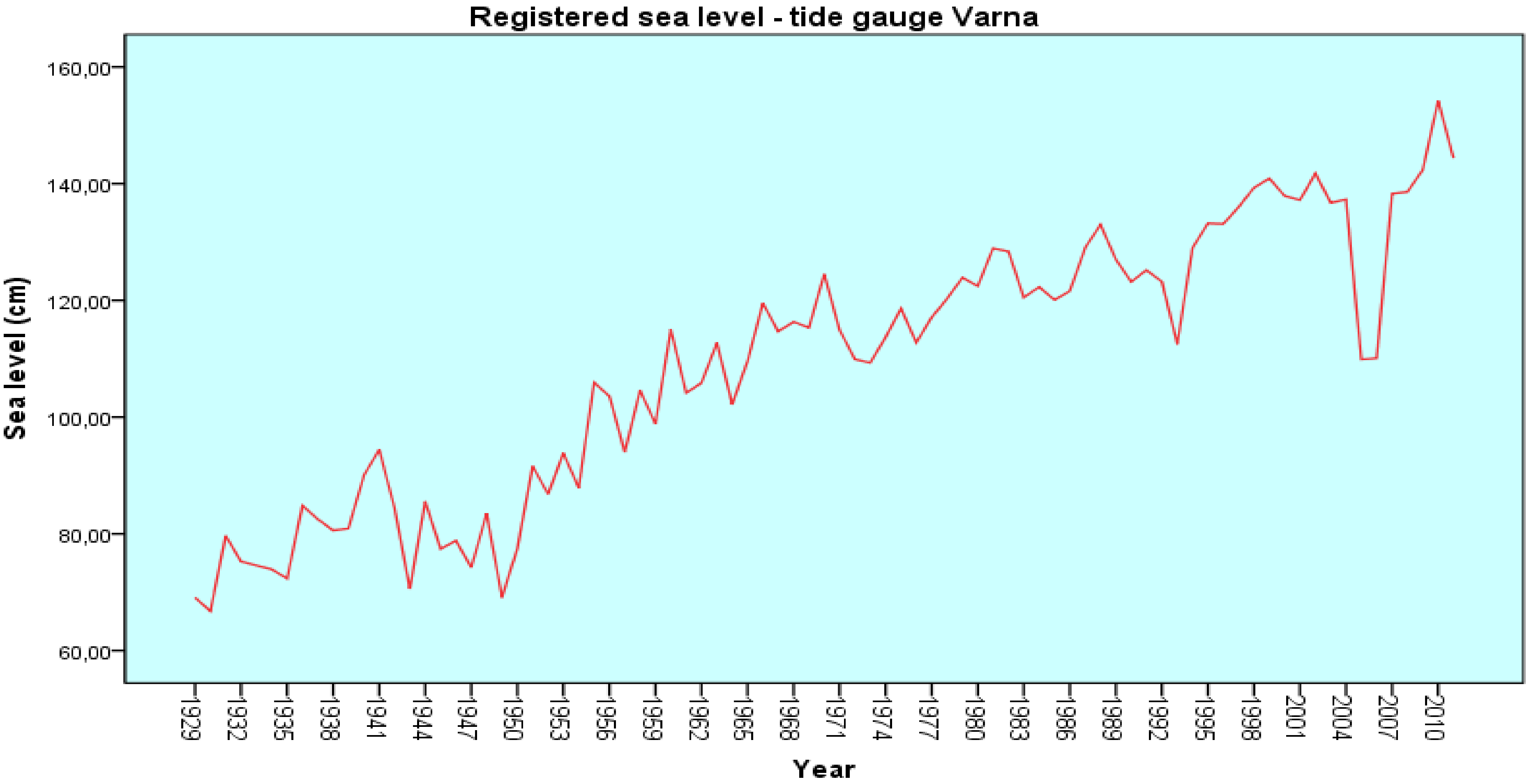
The tide gauges along the Bulgarian Black Sea coast are four: Varna, Burgas, Irakli and Ahtopol. Their main goal is to monitor permanently the sea level. The tide gauges in Varna and Burgas are in operation till 1928.

Tide gauge "Varna"

The "Varna" tide gauge is basic monitoring station. It is located in the naval base in front of the harbor station. The tide gauge is in operation from 1928. The tide gauge is of mechanical type, made by the German company „A.Ott" (Kempten) and is established in a small building on the pier. The tide gauge itself is located above the draw-well directly connected with the sea by pipe with length 5 m. In the well a metal staff is mounted to visually monitor the sea level and to control the sea level registrations. The sea level is depicted by continuous wavy line on a diagram set up on cylinder tube. The tube makes one revolution for 24 hours by clockwork mechanism. Additional processing is needed to calculate the mean daily sea level.

The permanent registration of the sea level at the tide gauges gives the opportunity to analyze **daily**, **monthly** and **yearly** data. The daily and monthly time series, including mean sea level and tidal components, are analyzed to provide the sea level trend at tide gauge stations.

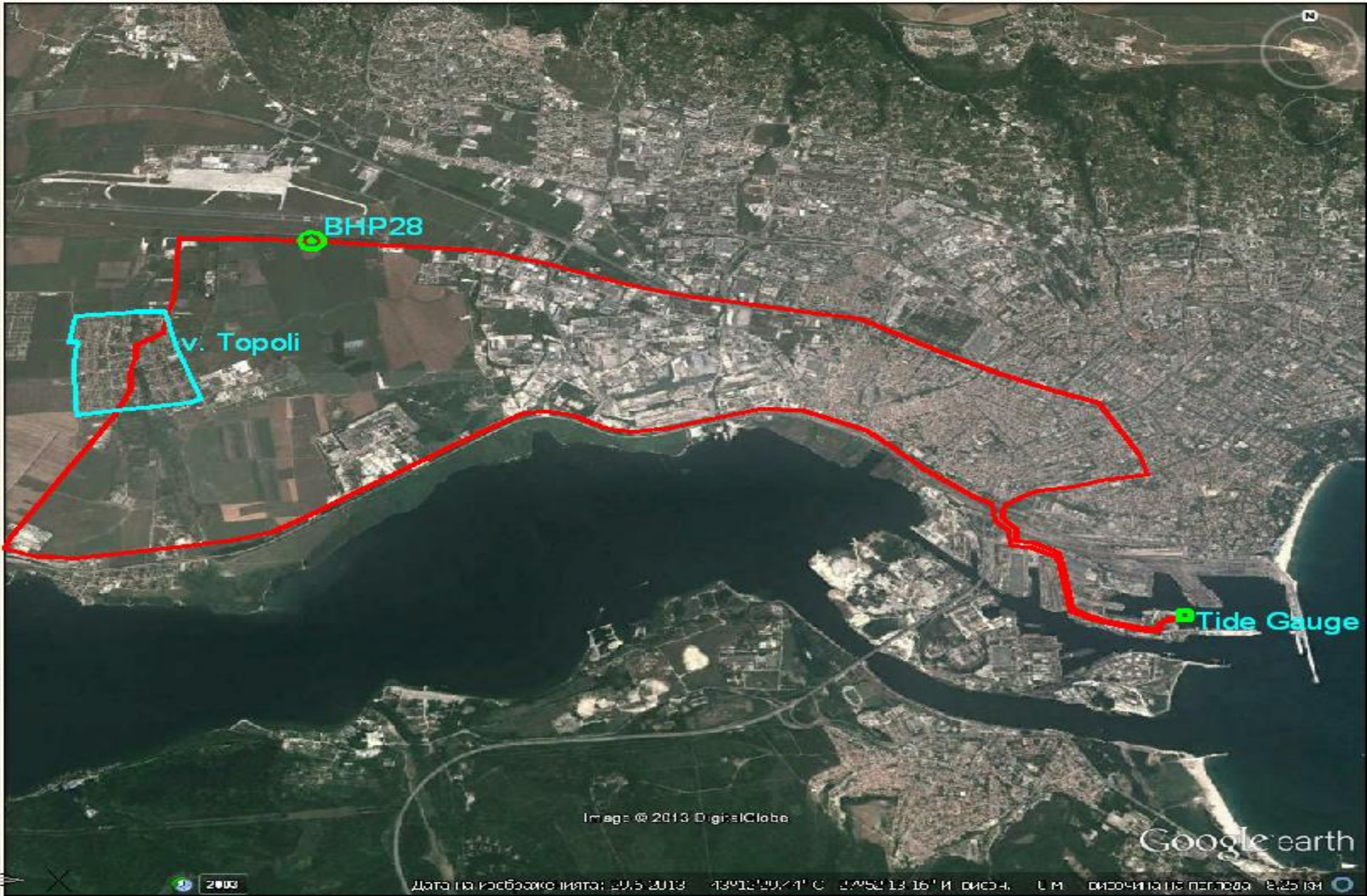
As there are significant data gaps in the daily registrations which need additional attention we use, at this stage of analysis, the **monthly sea level data** obtained by averaging daily values.



The sea level registrations are contaminated by the subsidence of the tide gauge staff associated with the secular and local vertical crustal motion at the tide gauge station.

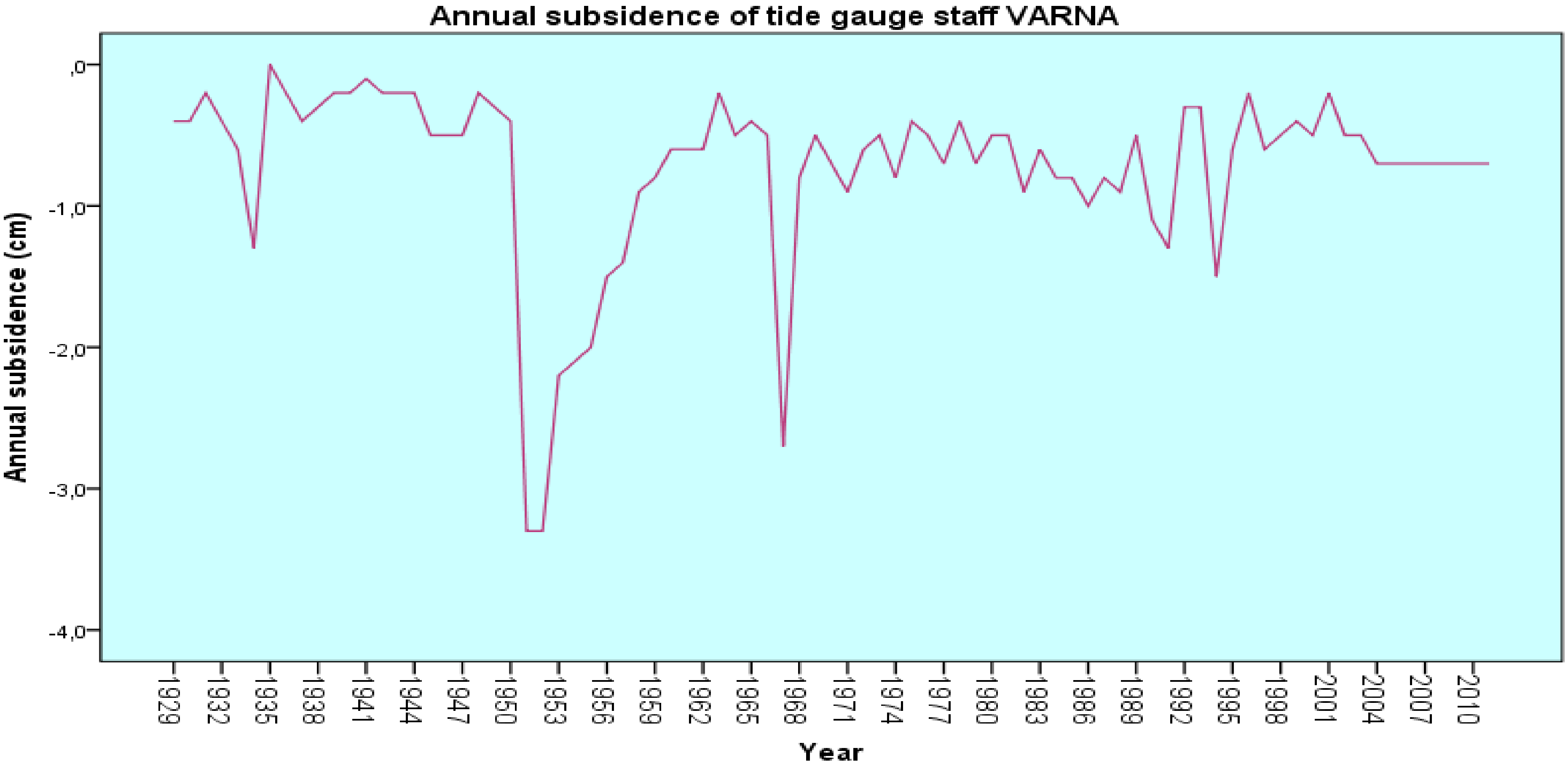
That's why to separate the sea level registration from vertical motion at tide gauges precise spirit leveling is performed every year of the control leveling loop connecting the tide gauge and Secular Leveling Benchmark 28 located outside the active subsidence zone.

Control Leveling Loop in Varna – length 28 km



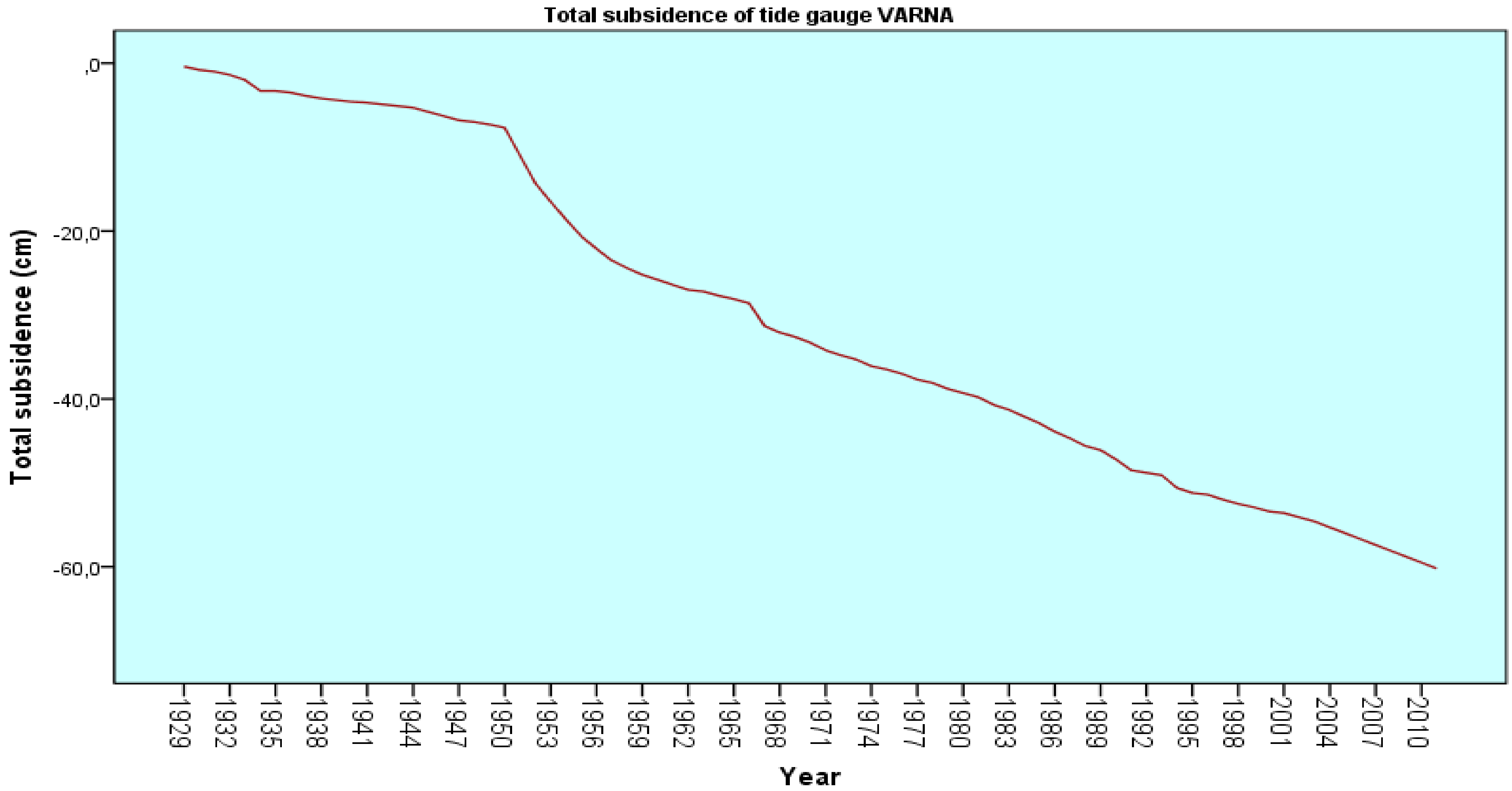
Subsidence of the tide gauge staff in Varna:

- To obtain the subsidence every year precise leveling is performed of the control leveling loop in the period 1928 – 2003.
- The total subsidence for the period 1928 – 2003 is 54.6 cm.

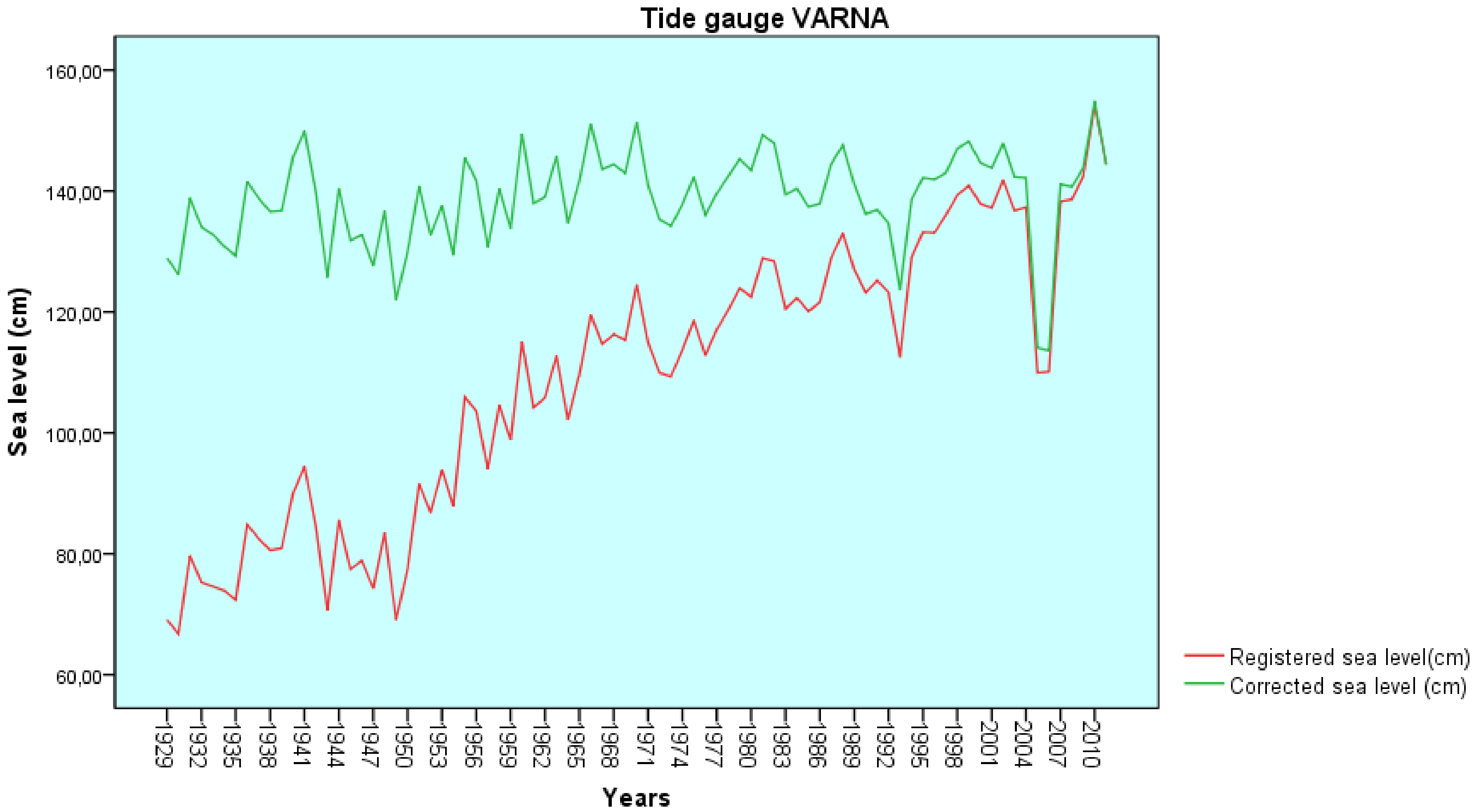


Annual data of the tide gauge staff subsidence

The peak value of about -3.0 cm/yr for the period 1951 – 1953 is associated with the building a massive structure near by the tide gauge station.



The tide gauge staff subsidence is approximately stable and roughly linear in time with the exception of the peak in the period 1951 - 1953.



Tide gauge sea level registrations corrected for the tide gauge staff subsidence. The values are obtained by interpolation from the yearly subsidence data for the whole period.

For the time series analysis we use the regression model :

$$Y(t) = a_0 + a_1 t + \sum_{j=1}^{3} A_j \cos(\varpi_j t - \varphi_j) + \varepsilon(t),$$

where :

a_0 – mean sea level;

a_1 – secular trend;

A_j – amplitude of the seasonal variations;

ω_j – angular frequency;

φ_j – phase of the wave;

$\varepsilon(t)$ – errors.

The included seasonal component accounted for semiannual, annual and long period tides (the long period tide is associated with the Moon's declination) – the indexes 1,2 and 3):

$$\sum_{j=1}^{3} A_j (\cos\varpi_j t - \varphi_j) = a_1 \cos\varpi_1 t + b_1 \sin\varpi_1 t + a_2 \cos\varpi_2 t + b_2 \sin\varpi_2 t + a_3 \cos\varpi_3 t + b_3 \sin\varpi_3 t$$

The solve for parameters are obtained by least squares where:

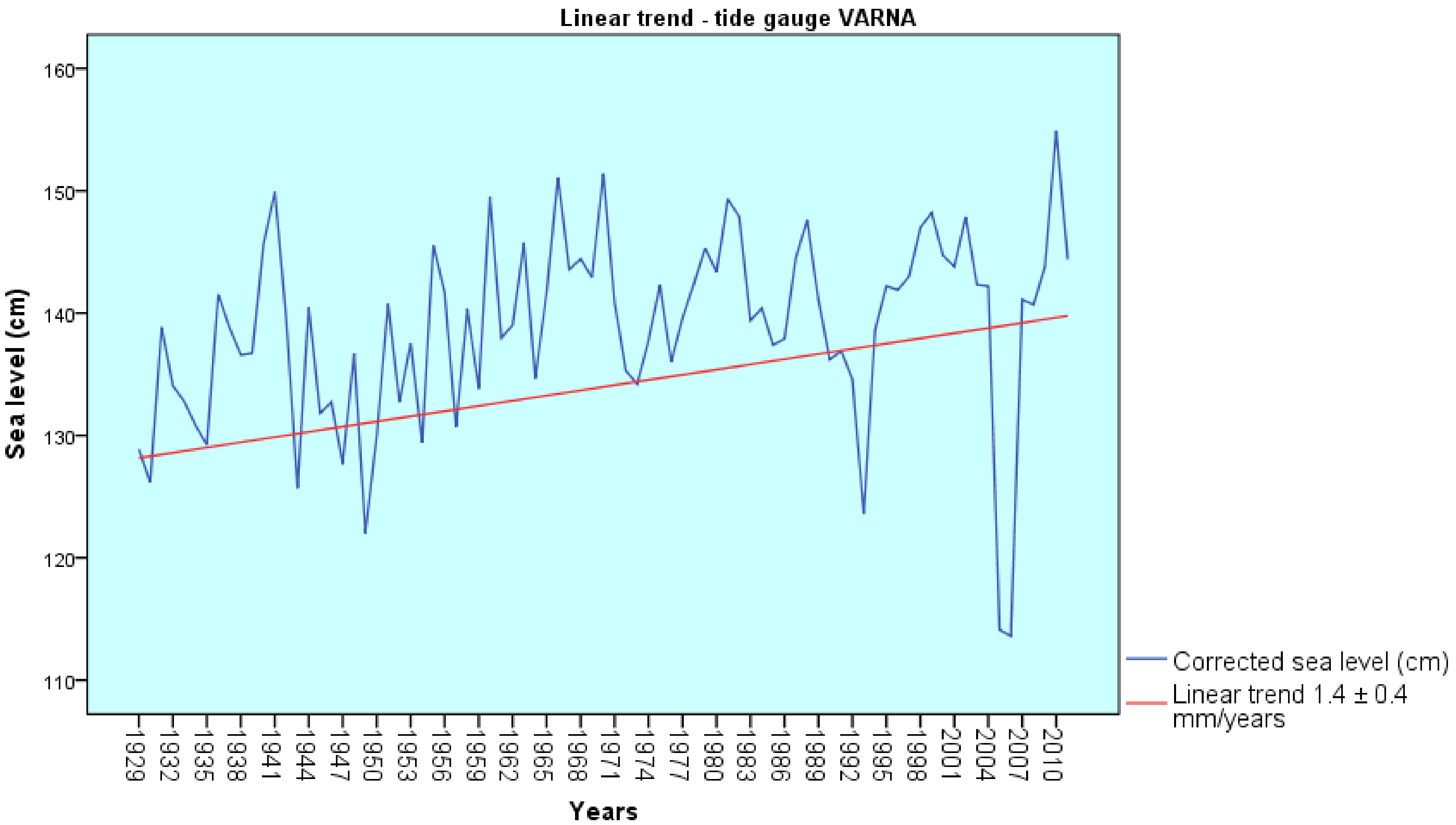
$l_{1,m}$- matrix of the observations;
$X_{1,k}$- unknown parameters;
$A_{k,n}$ – design matrix;
P – weights of the observations.

The solution is of the form:

$$X = (A^T P A)^{-1} A^T P l$$

$m^2 = (V^T P V)(n - r)^{-1}$ mean square error for the unit weight;

$m_x = m (A^T P A)^{-1}$ mean square errors of the unknown parameters.



Obtained secular trend at the tide gauge Varna

Unknown parameters:

Varna				σ
Mean sea level (cm)		a_0	128.16	5.62
Secular trend mm/yr		a_1	1.42	0.40
Amplitude (mm)	*Semiannual (cosine)*	a_2	16.37	3.98
	Semiannual (sine)	b_2	6.74	3.98
	Annual (cosine)	a_3	-61.13	3.98
	Annual (sine)	b_3	29.15	3.98
	18,6 years (cosine)	a_4	-0.73	3.98
	18,6 years (sine)	b_4	-19.85	4.06

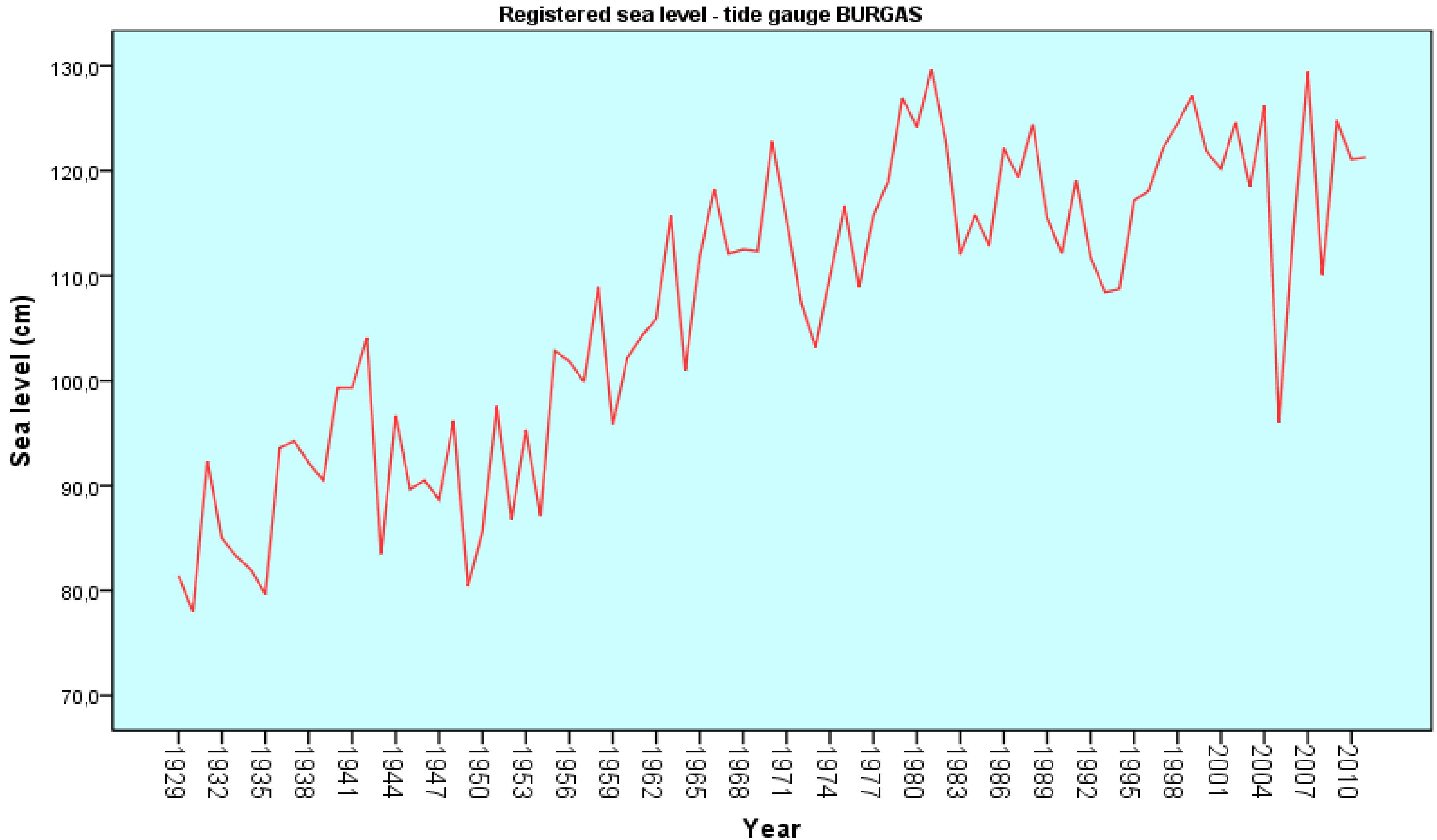
Tide gauge Burgas

The tide gauge station is located in the territory of port Burgas.

The station is in operational from 1928 and the primary goal have been to control the Varna tide gauge station.

The tide gauge is the same as in Varna - „A.Ott” (Kempten).

The visual metal staff are established in outside draw-well which connect the sea with the inside well. The whole pipe connection with the sea is about 20 m.



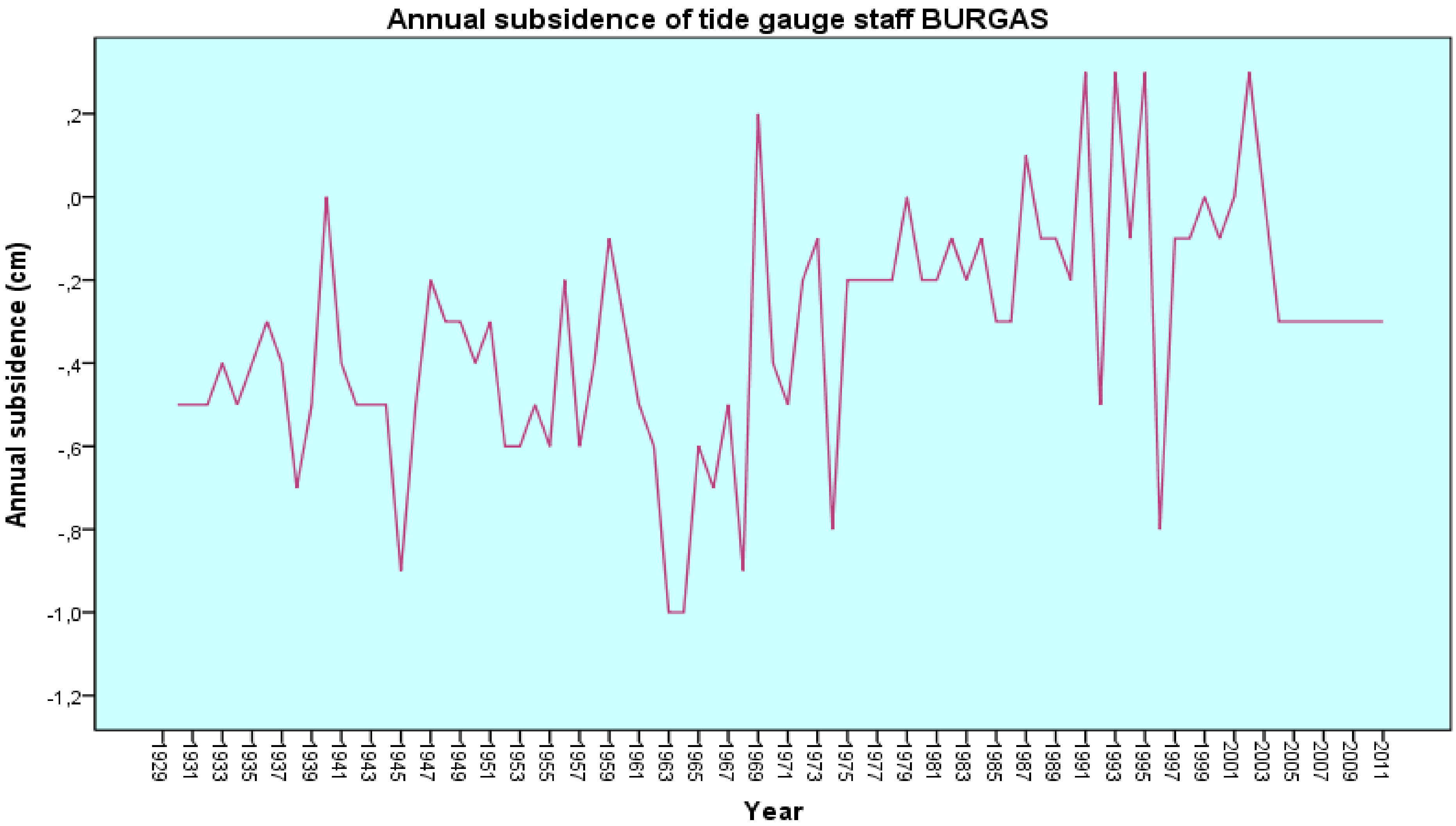
Separation the sea level registration from vertical motion at tide gauges is performed by precise spirit leveling every year of the control leveling loop connecting the tide gauge and Secular Leveling Benchmark 63 located outside the active subsidence zone.

Control Leveling Loop in Burgas – length 24 km

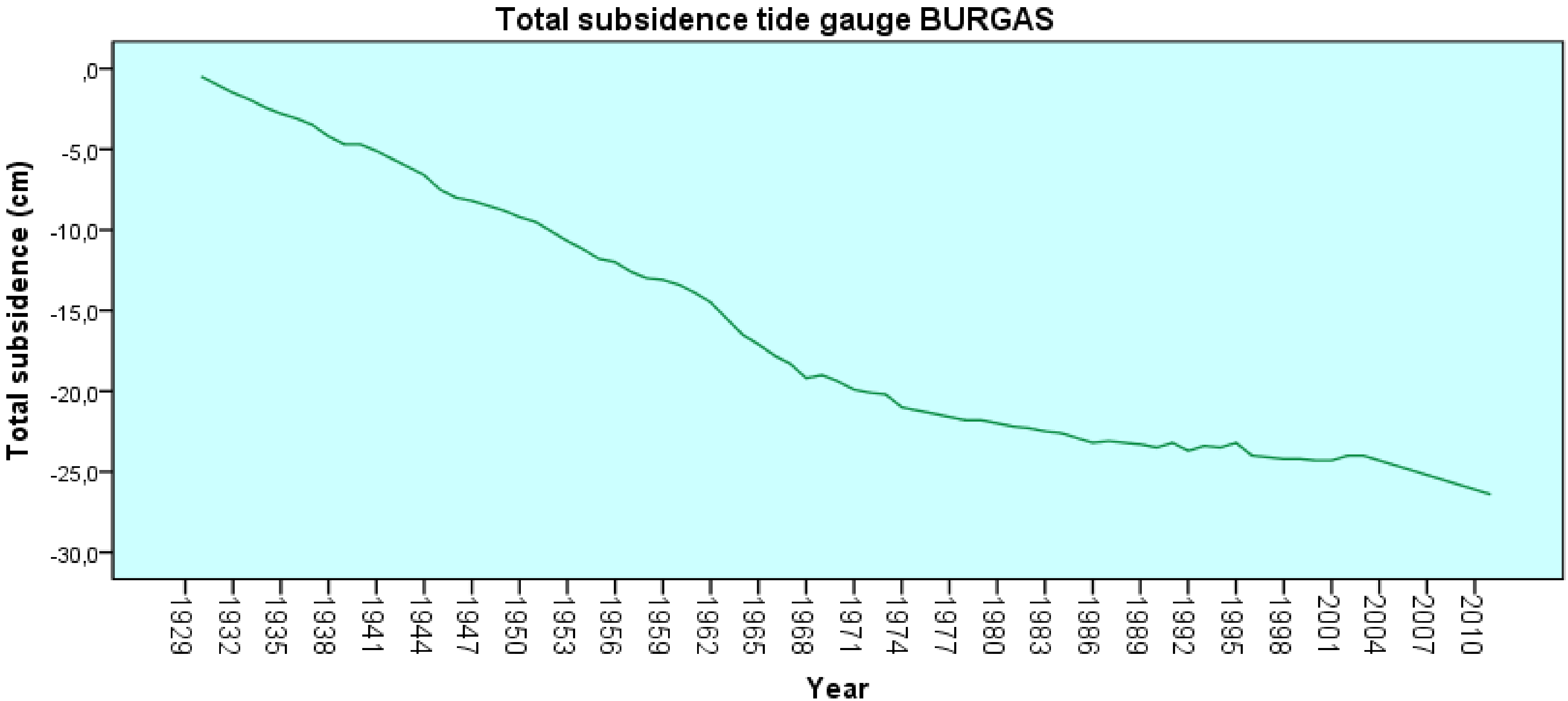
Tide gauge Burgas

Subsidence of the tide gauge staff Burgas:

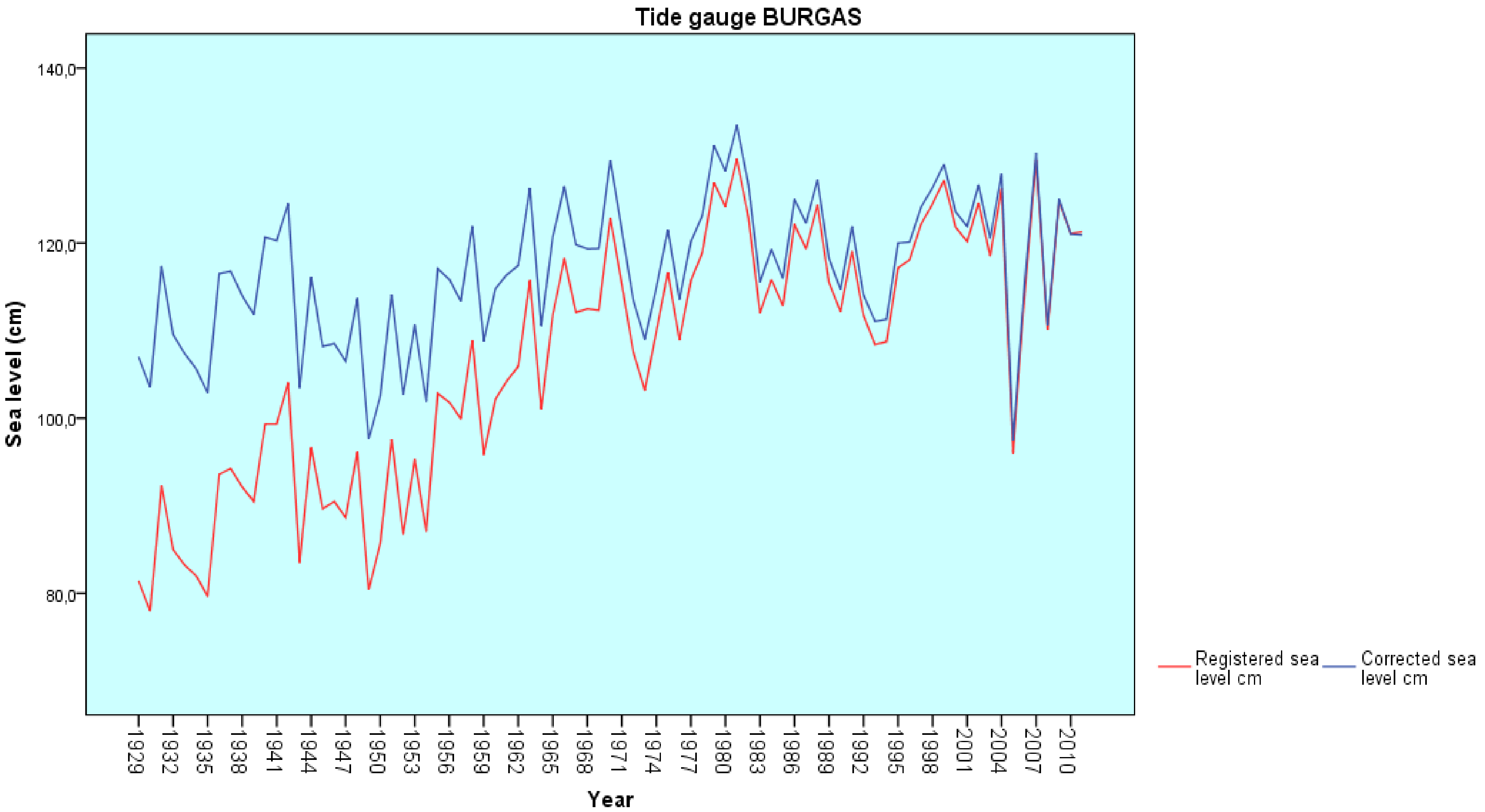
- Every year precise leveling of the control leveling loop for the period 1928 - 2003.
- The total subsidence for the period 1928 – 2003 is 24.3 cm.



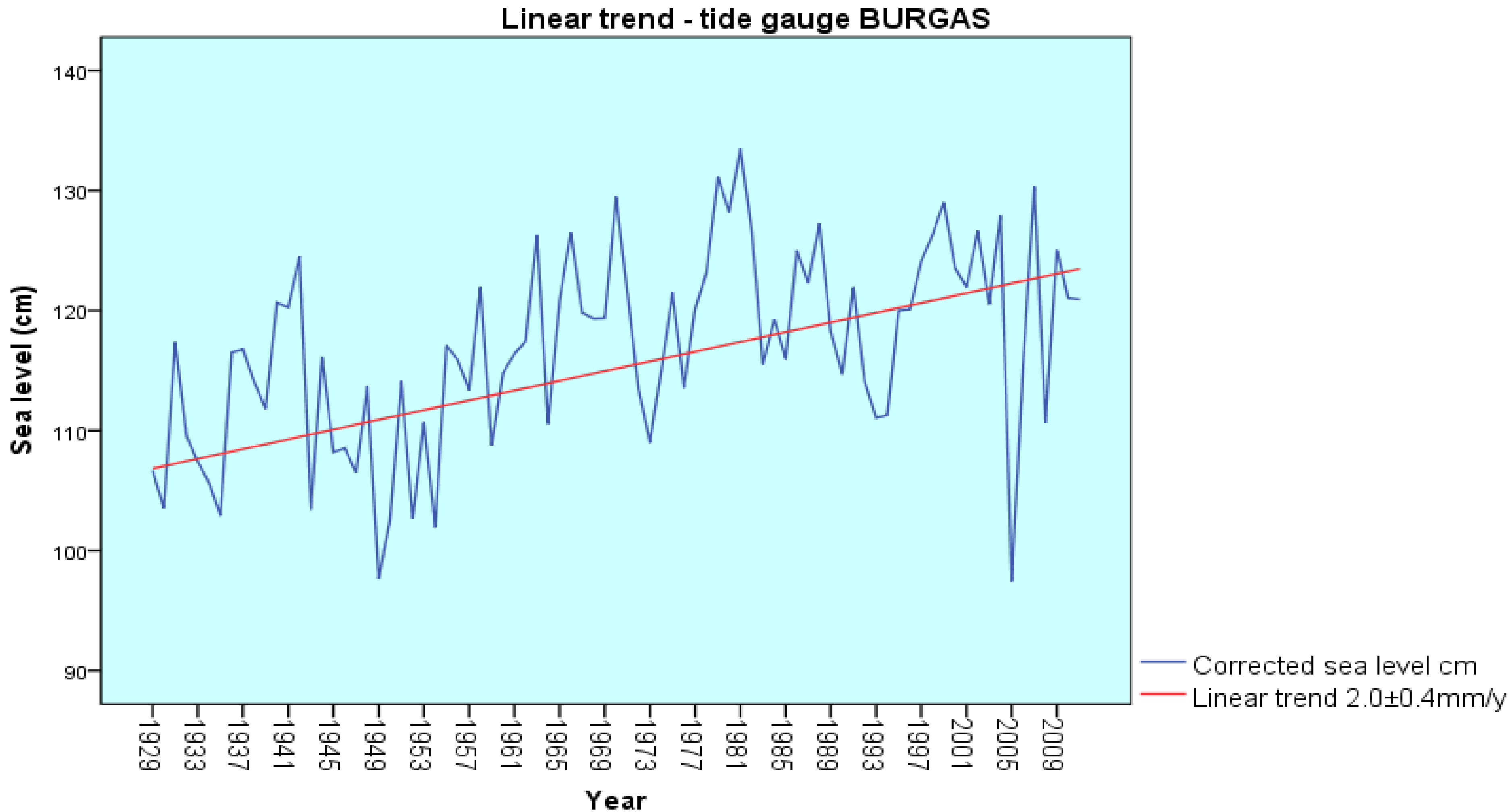
The tide gauge annual staff subsidence in Burgas



The tide gauge subsidence is approximately stable in time. The total subsidence for the period 1928 – 2003 is 24.3 cm.



Tide gauge sea level registrations corrected for the tide gauge staff subsidence. The values are obtained by interpolation from the yearly subsidence data for the whole period.



Obtained secular trend for the tide gauge Burgas

Solve for parameters:

Burgas				σ
Mean sea level (cm)		a_0	106.85	5.62
Secular trend mm/yr		a_1	2.028	0.40
Amplitude (mm)	***Semiannual (cosine)***	a_2	17.76	3.98
	Semiannual (sine)	b_2	10.90	3.98
	Annual (cosine)	a_3	-62.35	3.98
	Annual (sine)	b_3	30.00	3.98
	18,6 years (cosine)	a_4	4.40	3.98
	18,6 years (sine)	b_4	-30.02	4.06

The precise leveling at the tide gauges control leveling loops at Varna and Burgas has been performed every year in the period 1928 - 2003. After that precise leveling is not performed, so, the values for the tide gauge staff subsidence are extrapolated for the time span after 2003. The extrapolation is performed by using ARIMA model with parameters (1,0,0). For Varna tide gauge data the level of significance of this model is 93,7%.

For the Burgas tide gauge station for the staff subsidence the data for the period 1928 – 2003 are fitted exponential smoothing (alpha= 1; gamma=0,996) because for the last few years the observations show significant values for the subsidence of the tide gauge staff.

For comparison we calculate the unknown parameters once for the period 1928 – 2003 and twice for the period 1928 – 2011 using extrapolated values for the staff subsidence.

Tide gauge station/years		Varna 2003	Varna 2011	Burgas 2003	Burgas 2011
Mean sea level cm		128.16	134.40	106.80	110.40
Secular trend mm/yr		1.42	1.10	2.02	1.58
Amplitude (mm)	Semiannual (cosine)	16.367	16.19	17.75	19.15
	Semiannual (sine)	6.74	7.04	10.89	11.66
	Annual (cosine)	-61.12	-60.43	-62.35	-62.83
	Annual (sine)	29.15	27.88	30.00	29.30
	18,6 years (cosine	-0.72	-9.89	4.40	1.13
	18,6 years (sine)	-19.85	-27.53	-30.02	-39.44

We plan to repeat this year the control leveling at both tide gauges and this will reveal the actual subsidence of the tide gauge staff's at Varna and Burgas.

The obtained components of the tide waves for the tide gauges at Varna and Burgas are in good agreement themselves and are statistically significant.

The values for the secular trend for Varna and Burgas obtained in this study and published by other authors are also in good agreement:

	Secular trend	
Pashova, Belijashky (2006)	Varna ***1,5 mm/yr***	Burgas ***1,8 mm/yr***
Belijasky (2000)	Varna ***1,5 mm/yr***	Burgas ***2,3 mm/yr***
This study	Varna ***1,4 mm/yr***	Burgas ***2,0 mm/yr***

From the mid 2013 at the tide gauges at Varna and Burgas two radar tide gauges are in operational.

The old tide gauges will work along with the new radar tide gauges for the period 6 – 12 months simultaneously. This will be the base for synchronization the registrations between the old and new tide gauges and to continue the long time series data as one homogeneity time series.

We have obtained transformations between two types tide gauges as a prerequisite to continue the monitoring the sea level.

Thank you for your attention