

BOOK REVIEW (PART I)

BLACK SEA LEVEL : PAST, PRESENT, FUTURE

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This study, carried out by researchers at the Marine Hydrophysical Institute of the Ukrainian National Academy of Sciences offers an unique insight into the understanding of the past, present and future of the Black Sea water level changes. The authors show that the survey of the Black Sea Level goes back nearly a century and a half. There are over 300 references, two-thirds of them in Russian. Most of the literature on which this study is based dates back to 1960-1980. That was a time when the study of the wind setup generated by sea-storms was given special attention, considering its impact on navigation and other coastal activities.

The last 15 years have shown new trends in the study of the Black Sea level changes like the long-term sea level oscillations and forecast data. Those are largely influenced by the present-day rise of the World Ocean level that triggers flooding of low coastal land and adversely influences coastal morphological processes. Therefore, to know the causes and analyse the processes that produce the sea level changes, is imperative to a rational economic management of coastal natural resources. The higher the sea level rise speed, in the 21st century, the more significant the topic.

Remarkably, Black Sea level changes are studied not only by researchers from the Black Sea riparian countries but also by those living in the United States, United Kingdom, France, Germany, Spain, Greece and so on. Certainly, not accidentally. The Black Sea has a unique geographic position as the most isolated internal sea in the Atlantic Ocean system. The Straits (*i.e.* Bosphorus, Dardanelles and Gibraltar) connecting the Black Sea to the Mediterranean and the World Ocean, is a real

buffer that filter many processes taking place in the World Ocean, which produce signals of sea levels changes related to the climate changes.

There is a dense network of sea level gauge around the Black Sea. Some of these stations have been supplying monitoring data for more than a century. This has created good conditions for tracking climate change in sea levels. The purpose of this monograph consists in the generalization of the Black Sea level change research results obtained by the authors. The authors quote the sources of the results obtained by other researchers during the whole period of study related to the Black Sea.

This study of Black Sea level changes is structured as follows:

1. CONTENT

Foreword

- Cap.1. Factors which influence sea level changes in the Black Sea.
 - 1.1. Rivers discharge.
 - 1.2. Rainfall over the sea.
 - 1.3. Sea surface evaporation.
 - 1.4. Global Black Sea freshwater budget.
 - 1.5. Spatial distribution of river discharges, rainfall and evaporation.
 - 1.6. Water exchanges through straits.
 - 1.7. Atmospheric pressure.
 - 1.8. Steric effects.
 - 1.9. Alluvia discharges.
 - 1.10. Present – day tectonics.
- References for chapter 1.

- Cap. 2. Black Sea level changes.
- 2.1. Long term periodic sea level oscillations.
 - 2.2. Multiannual sea level oscillations.
 - 2.3. Seasonal sea level oscillations.
 - 2.4. Synoptic sea level oscillations.
 - 2.5. Extreme values of sea level.
 - 2.6. Mesoscale sea level oscillations.
 - 2.7. Contributions of the different oscillation aspects to the overall sea level changes.
 - 2.8. Tsunami waves.
 - 2.9. Sea level oscillations in the Bosphorus Strait.
 - 2.10. Sea level changes in the Black – Marmara – Aegean seas system.
 - 2.11. Use of altimetry data for interannual and seasonal Black Sea level oscillations.
- References for chapter 2.
- Cap. 3. Sea level changes and possible consequences.
- 3.1. Climate change scenarios.
 - 3.2. Sea level change scenarios.
 - 3.3. Consequences of climate and relative sea level changes.
- References for chapter 3.

Conclusions

- Appendix 1. Observations on the Black Sea level changes.
- 1.1. Short history of the Black Sea level changes.
 - 1.2. Present day situation of the sea level gauges network in the Black Sea.
- References for appendix 1.
- Appendix 2. Sea level. Glossary (in Russian, Ukrainian and English).

As shown above, Chapter I examines the factors that influence Black Sea level changes.

The second chapter is devoted to level change at time scales from seiche to long term oscillations. Level oscillations are examined separately for the straits and also for the Black – Marmara - Aegean seas system. The contribution of various types of level oscillations to global change are shown. The possibility of using satellite data to study the level regime and to monitor it is considered.

The third chapter examines mainly the likely consequences of sea level change on coastal morphology processes.

Appendix 1 consists of a brief history of the Black Sea level observations up to the current state of the network of level observation points.

Appendix 2 is a Russian and Ukrainian dictionary of terms used in obtaining, processing and analyzing level data, adapted to international standards.

The authors claim that the conclusions of this work are not exhaustive and think that their results will be refined, completed, and even revised. One of the aims of this monograph is to highlight the Black Sea level changes issue and foster the research in this field.

2. RESEARCH RESULTS

The main themes of the chapters are detailed as follows:
2.1. In Chapter 1, „Factors that influence sea level changes in

the Black Sea“, the authors define the water level, as a surface that coincides, to a first approximation, with the multiannual mean global ocean level, considered as the surface of the geoid. This level is not idle and is constantly changing under the action of various forces, diverging from the geoid. The Black Sea level is affected by factors leading to change in the volume of water.

The eustatic factors leading to variation in Black Sea volume are river discharges, sea surface evaporation, rainfall, water exchange through straits, anthropogenic discharges, sediment accumulation and their compaction. The changes in volume triggered by tectonic movements seem to be insignificant and could be neglected to a first approximation.

The factors that rule the Black Sea level fluctuations are more or less studied and known. A major difficulty is the lack of reliable and long-term data series about evaporation, precipitation and water exchange through straits. Indirect methods of assessment are used to solve the problem. The other (anthropogenic and sediment accumulation) factors have not been yet analyzed.

The main factors influencing the distribution in time and space of the Black sea water are the wind, atmospheric pressure, water density and water surface fluctuations related to water flow generated by coastal winds. Wave generating processes bear a certain impact on sea level fluctuations. Geodynamic forces leading to secular changes in sea level are dealt with separately.

They are produced by slow vertical movements of the Earth's crust (uplifting or subsidence). These level changes are significant for economic activities.

The contribution of various factors to create the Black Sea level regime changes is treated as thickness of water layers:

- The contribution of river water is evaluated to a multi-annual mean of 336 km³, corresponding to a layer of water 79 cm/year thick, with a maximum and a minimum of 120 and 56 cm/year, respectively. About 80% of the water influx belongs to the Danube, Dnieper and Dniester rivers. Thus, the river water supply highly impacts the Black Sea level fluctuations. The river water supply trend is positive with a rate of about 0.126 km³/year. This does not explain the Black Sea level rise.
- Unlike the river water supply assessed on the basis of measurements, the precipitations were mainly determined indirectly using data from monitoring coastal stations. The evaluation for the interval 1923-1998 showed that a multi-annual mean of 570 mm water equivalent to a volume of water equal to 241 km³ fell on the Black Sea surface. In the above-mentioned interval, the yearly precipitations increased with a rate of 0.167 cm /year.
- The evaporation on the Black Sea surface was also evaluated indirectly by theoretical and empirical methods. The result was that the mean multi-annual evaporation, during the interval 1923-1998, was 379 km³, equivalent to a layer of 90 cm /year. The trend of variation with time of

the mean annual evaporation is to decrease at a rate of 0.397 cm /year. Although small, the decrease in annual evaporation value causes a slow rise of the mean Black Sea level.

- The Black Sea freshwater budget was analysed as the sum of supplies of river water, rainfall and evaporation, estimated at 196 km³, and equal to a 46 cm thick layer of water. Calculations showed that the Black Sea freshwater budget is positive, with a tendency to increase with time by 0.544 cm /year. This feature leads to ample fluctuations in the exchange of water through the Bosphorus Strait, due to increased water outflow from the Black Sea.
- The results obtained regarding the spatial distribution on the Black Sea water surface of the supplies from rivers, from precipitations and evaporation, show that river inflow predominates in the north-west of the Black Sea; precipitation occurs mostly in the east and the evaporation concentrates in northern part of the Black Sea. In the southern part of the Black Sea, rainfall prevails over evaporation. The uneven distributions of the three factors that influence the Black Sea level generate various movements of water masses.
- As mentioned above, there is a continuous exchange of water through the Bosphorus and Kerch straits, which plays a significant role in the hydrological regime of the Black Sea. The following are the specific features of water exchange that distinguish the two straits:

- Bosphorus is a strait with a stable vertical stratification of water masses. Should the exchange of water stop in the Bosphorus strait, the Black Sea level would increase continuously due to the resultant of the freshwater budget components. Bosphorus is like a valve through which the water excess flows into the Marmara Sea as a surface current. On the other hand, due to the difference in density between the water masses of the two seas, the Marmara Sea water flows as a bottom current towards the Black Sea. The mean level difference between the two seas is of about 43.2 cm. The first hydrological survey on the Bosphorus strait was conducted, in the mid-nineteenth century, by the Russian admiral S.O. Makarov. It was followed by the measurements carried out by Mertz A. and later on, by the measurements carried out by Turkish researchers.

To assess the annual water exchange between the Black Sea and the Sea of Marmara, an indirect method was applied.

On a yearly average, the water outflow from the Black Sea generates a lowering of the sea-level by about 91 cm, while the Marmara Sea water inflow triggers a rise of the sea-level by 40 cm. The budget of the two currents of the Bosphorus strait induces a Black Sea level lowering of 51 cm.

The trend of change in time of water layer thickness resulted from the Black Sea water outflow is growing at an annual rate of 0.34 cm /year, while the trend of

change in time of the water inflow into the Black Sea is declining at an annual rate of 0.19 cm /year.

- The Kerch Strait, which is shallow, presents an unstratified water exchange between the Sea of Azov and the Black Sea. The winds in the area have a major influence on the direction of water-flow. Multi-annual mean water outflow through the Kerch Strait contributes to a rise of about 11.7 cm of the Black Sea level, while the penetration of water into the Sea of Azov induces a sea-level fall of 7.9 cm. The fluctuation trend of the resultant of water exchange through the Kerch Strait, is declining at a rate of 0.04 cm /year.
- The atmospheric pressure is also involved in the Black Sea level changes. An atmospheric pressure rise of 1 millibar triggers a 1 cm fall in sea level. In this way, the hourly fluctuations of atmospheric pressure reaching tens of mbar result in as many cm of water level changes. As the air pressure distribution across the Black Sea is un-homogeneous, the level changes are also un-homogeneous and this results into additional phenomena of level changes along the coasts (in bays and steep coasts).
- The steric effect in the sea water is a reaction to variations of temperature and of water density and it influences the sea level fluctuations. The variation in salinity has a contribution of about 70% in the Black Sea level change. The steric effect generates a decrease in the Black Sea level in the central area of the basin. The authors studied the long-term data on water temperature and salinity of the Black Sea and found diverging trends of variation of the two steric components as follows : while the sea water temperature increases with time, salinity decreases with time.
- The sediment discharge in the Black Sea evaluated at 68 million tonnes per year contributes to the rise of the mean sea level. About 80% of the sediment discharge belong to the Danube (51.2 mil.t /year), the Dniester (1.73 mil.t /year), the Dnieper (0.8 mil.t /year) and the Bug (0.2 mil.t /year). This alluvial discharge into the Black Sea - of about 0.025 km³/year - leads to a minor mean sea-level rise (of about 6 mm/100 years).
- The present-day tectonic movements influence the coastal geodynamics and the altitude of the sea-level monitoring stations. Geophysical research results show that the Crimean coast is sinking by about 0.2 cm /year, in Odessa, by about 0.51 cm /year and, in Poti, by about 0.65 cm /year. Average subsidence in the Black Sea basin is evaluated at about 0.1 cm /year, except for the Odessa and Poti sites. Based on long-term monitoring of the Black Sea level data, the subsidence is evaluated at 0.03 to 0.16 cm /year. In Odessa and Poti, the subsidence is of 0.52 and 0.66 cm /year, respectively.

Another assessment, resulting from the processing of long series of Black Sea level measurements in Poti, in Odessa and in Constanta, showed that the subsidence values are of 0.56, 0.43 and 0.35 cm, per year, respectively. In the other stations for sea-level

monitoring, there is an uplift of about 0.01-0.09 cm / year (in Sevastopol, the uplift is of 0.03 cm /year). Low-frequency filtering information through iterative processes allowed the separation of the regular seasonal level regime and the following conclusions were drawn:

- the north-western Black Sea coasts subside by about 0.1-0.16 cm /year;
- the Crimean and Caucasian mountainous coasts are uplifted by about 0.02-0.04 cm /year;
- the Western Crimea is not subject to any vertical movement.

The most significant Black Sea level change in time is located at Varna and at Burgaz, where, in the 1928-1980 interval, it reached 1.07 and 0.73 cm /year, respectively, which represents the highest value of crust subsidence.

2.2. Chapter 2, „Black Sea level change“, shows that there are temporal scales of sea-level fluctuation spectra with periods ranging between several minutes to thousands of years.

Thus, there are the long-term sea-level oscillations on the geological scale of thousands and millions of years, triggered by the World Ocean water mass variation, as well as the slow epeirogenic movements. These oscillations reach heights of tens of metres in amplitude.

The multi-annual sea-level oscillations reflect the atmospheric changes generated by the variation of ground water leakage. The vertical scale of these variations reach values of 30 cm.

The seasonal oscillations are caused by water mass variation in water budget, by the water density changes and by seasonal variations in atmospheric pressure and reach values of 20-30 cm.

Synoptic sea-level oscillations are caused by atmospheric processes that generate storms triggering sea-level change in coastal areas; the larger the depth in the coastal area, the lower the synoptic sea-level oscillations. These changes in the Black Sea reach up to 1 m. Also, the mesoscale sea-level oscillations which include seiches, tides and inertial oscillations, reach values from tens of centimetres (the seiches) up to 10 cm (the tides).

A particular class of sea-level oscillations are the tsunami waves produced by strong earthquakes in the Black Sea; they could reach up to 50 cm in height.

- the oscillations with long periods in the Quaternary, Upper Pleistocene and Holocene, in the Black Sea, are characterised by repeated transgressions and regressions. During the ice age, there was a lowering of the Black Sea level of about 110 m. The Black Sea basin was brought close to the current situation at the end of Pleistocene.

The results of large-scale geological research conducted along the coastal areas and on the continental shelf, using radiocarbon determinations, as well as the archaeological re-

search distinguish between the three main periods of evolution of the Black Sea level regime:

- a minimum regression between 20 and 16 thousand years ago, with the sea-level at - 60 m;
- an intermediate phase between 16 and 6 thousand years ago, related to the Holocene melting, characterised by a sea-level rise up to -3.5 - -4 m;
- a maximum in the last 6,000 years, characterised by a transgression, when the present-day sea-level is reached.

The authors conclude as follows:

- In the interval 18 to 8 thousand years BP, the Black Sea level rose steadily at a rate of ca 9-10 mm /year. During this time interval, the sea-level rose from - 85 to - 25 m.
- In the interval 8 to 5 thousand years BP, the sea-level continued to rise at a lower annual rate. At certain periods, the sea-level exceeded by about 2 m the present-day sea-level.

As for the historical period, the authors distinguish three phases of the sea-level change:

- The Black Sea new transgression which took place about 2-3 thousand years BC, when the sea-level reached the value of + (3-4) m above the present-day level.
- The Phanagorian regression, which took place between 2500 and 1000 BC, when the sea-level fell to - 3 m compared to the present one.
- The present-day transgression, which began in the twentieth century.

Considering the above, in the last 6000 years, the sea-level oscillations had a 3,000 year period, and the Black Sea level deviated from the present-day one, with - 5 to +2 m, at a 3-4 mm /year speed.

- As for Noah's Flood, it occurred 7600 thousand years ago, as a result of a catastrophic earthquake that allowed Marmara water to penetrate the Black Sea. Shortly, the Black Sea rose by more than 100 m, flooding large coastal areas.
- The multi-annual oscillations allow coastline change, coastal destruction or restoration. The mean multi-annual Black Sea level, between 1923-1993, calculated on the basis of measurements from 14 hydrometric stations on the northern coast, is 477 cm in the GVO altimetry system of the former USSR. Annual mean Black Sea levels depend upon the water volumes from tributary rivers. The spectral analysis showed oscillation periods of the mean annual sea-levels, of 2.4-2.6, 3.5-5 and 10-30 years. Based on the mean annual levels of the 1875-2005 time interval, two multi-annual cycles of variation were evidenced : the first, during the 1875-1915 time interval, with a weak trend of decrease in time and the second, starting from 1915 to present, with a growth trend of the sea-levels. During the 1946-1985 time interval, the average trend of the mean annual sea-level rise was found to be about 2.7 mm /year. By eliminating the vertical movement speed of Earth surface, a mean rate of sea-level increase of about 1.7 mm/year, due to eustatic factors, resulted.

- Seasonal sea-level oscillations are caused by seasonal components of water budget, with a maximum, during summer, when river discharge is at its peak and a minimum, in the cold autumn-winter period, when the river inflow reaches its minimum. Seasonal Black Sea level oscillations are shifted to about one month compared to the seasonal variations of water budget components.
- Synoptic sea level oscillations are related to wind frequencies and atmospheric pressure. These sea-level oscillations include wind-induced sea surface deformation. Also, winds parallel to the coastline form wind currents that, due to Coriolis acceleration, change the horizontality of water mass layers. Winds blowing from the left of the coastline push superficial water masses to the shore and blow away from the shore the deep-water masses. Conversely, winds blowing from the right side of the coastal line blow the shallow-water masses away from the shore towards the open sea and bring to the coast the deep-water masses with low temperatures and high salinities. Based on daily and hourly sea-level continuous measurements in the coastal stations of Batumi, Poti, Tuapse, Gelendzik, Kerch, Feodosiya, Yalta, Sevastopol and Odessa, in the 1980-1983 interval, the authors determined the sea-level oscillations spectra and evidenced 8 cycles of 16.7, 10.7, 6.1, 5.0, 3.1, 2.2, 1.7 and 1.3 days. The authors paid special attention to the interaction between coastal winds and their impact on sea-level oscillations in coastal waters. Based on this analysis, the authors evidenced the wind-triggered extreme limits and vertical deviations in a number of coastal stations.
- A large amount of monthly and individual sea-level means in terms of mean daily observations, gathered from coastal measurements, were processed to determine extreme Black Sea levels. Extreme values of the Black Sea levels are generated mainly by wind action during storms.
- Mesoscale sea-level oscillations occur due to seiches, tides and water masses inertia triggered by sudden variations in atmospheric pressure or sudden change in wind direction. Mesoscale dynamics is highly influenced by the coastal physical-geographical conditions.
- Based on hourly sea-level observations performed in the Poti, Tuapse and Feodosia stations, in the 1980-1983 interval, the density of the potential energy of Black Sea level changes was computed in order to evaluate the contribution of various categories of oscillations in the general energy changes. These calculations showed that the overall energy of the Black Sea level changes is made of seasonal variations, synoptic and mesoscale oscillations. The main long-term synoptic sea-level oscillations are those of 16.7 and 10.7 day-cycles.
- The authors have also described the tsunami waves produced by underwater earthquakes, as catastrophic. Tide gauge sea-level monitoring on the Crimean and the Caucasian coasts showed that the tsunami wave amplitude reached heights of about 50 cm with 8 to 107 minute periods and wavelengths ranging from 86 to 120 km. Tsunami propagation time varies widely, in the range of 5-8 minutes to 4.5 hours. On the Anatolian coast, the tsunami waves are caused also by continental earthquakes. Mathematical modelling of tsunami data show that, in the Black Sea, tsunami waves are rare and do not represent a potential danger to the coastal zones activities.
- Theoretical evaluations and measurements on the difference of levels between the Black Sea at the entrance of the Bosphorus Strait and Marmara Sea level at the exit of the strait show that, due to the difference between the specific weight of the two sea water masses, the sea-level difference would be about 43 cm. Level measurements performed regularly between 1966-1968 and 1985-1987, show that the difference in sea-levels would be of about 35 cm and 37 cm. Besides natural causes that generate the sea-level difference between the two seas due to the difference in density of the water masses, the winds and the atmospheric pressure play a significant role in the sea-level change at both ends of the strait and induce erratic sea-level changes in the strait, blocking sometimes the undercurrent.
- Measurements showed that there are delays (of approximately 2-3 months) in transmitting the mean seasonal Black Sea level oscillations to the Marmara and Aegean seas. Also, sea-level measurements made at coastal stations and by means of satellite altimetry offshore, show that there is certain synchronization in the sea-level change in the three seas. The altimetry measurements carried out, from 1993 to 2000, showed that the mean annual water levels of the three seas (the Black Sea, the Marmara and the Aegean seas) display growth trends in time with coefficients of 0.17 in the Black Sea, of 0.13 in the Sea of Marmara and of 0.12 in the Aegean.

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