Quaternary International xxx (2017) 1–9

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations

Valentina Yanko-Hombach [a, b, c], Alexander Kislov [d, *]

[a] Department of Physical and Marine Geology, Odessa I.I. Mechnikov National University, 2 Shampansky Per., Odessa 65052, Ukraine
[b] Interdisciplinary Scientific Centre of Geoarchaeology, Marine and Environmental Geology, Odessa I.I. Mechnikov National University, 2 Dvoryanskaya Str., Odessa 65082, Ukraine
[c] Avalon Institute of Applied Science, 976 Elgin Ave., Winnipeg, MB, R3E 1B4, Canada
[d] Faculty of Geography, Lomonosov Moscow State University, 1 Leninskie Gory, Moscow, 119991, Russia

A R T I C L E I N F O

Article history:
Received 7 September 2017
Received in revised form
2 November 2017
Accepted 17 November 2017
Available online xxx

Keywords:
Paradoxes
The Caspian Sea
The Black Sea
Climate simulation
The Langevin equation

A B S T R A C T

Different multidisciplinary data concerning the paleodynamics of sea-level variations in the Caspian and Black seas are controversial in some aspects. There are at least three paradoxes that are discussed in the paper. The Paradox No. 1 relates to the Early and Late Khvalynian transgressions that occurred in the CS during the second part of MIS 3 (~35–25 ka BP) and the Late Glacial epoch (~17–12 ka BP), respectively. It is unclear what the main source or sources of water were that caused them. Paradox No. 2 emerges from the comparison of climate events and transgressive-regressive cycles in the Caspian Sea and the Black Sea. It implies that large sea-level anomalies occurred in accordance with global climate changes (because they are influenced by climate variations). However, other (not so long-lived) sea-level fluctuations are poorly correlated with climate events. The question is why climatically-induced sea-level changes did not follow climatic variations. Paradox No. 3 concerns the contradiction between the massive water discharge from the Black Sea into the Sea of Marmara via the Bosphorus Strait and the Black Sea level fluctuations in the Latest Pleistocene-Holocene that could not exist simultaneously. It is shown that Paradox No. 2 has been solved, at least on conceptual level. Solutions to Paradoxes No. 1 and No. 3 are still lacking: further geological and geochronological evidence as well as climate simulation are required. Formulation of solutions for these paradoxes should make a major contribution not only to the problems of the Caspian and Black seas' paleogeography, but also provide help in explaining the reasons for inadequate simulation of regional climate changes. This is important in the context of the development of models for future climate prediction.

1. Introduction

The Caspian Sea (CS) and the Black Sea (BS) (Fig. 1) are relics of the Eastern Paratethys and the largest members of the Ponto-Caspian Corridor (Yanko-Hombach, 2007).

These basins were repeatedly connected (via the Manych outlet) and isolated from each other during the Quaternary. The BS was also periodically connected to the Mediterranean Sea (MS) via the Bosphorus Strait or alternative channel/s (Kerey et al., 2004; Yanko-Hombach, 2007), and then to the World Ocean via the MS and the Strait of Gibraltar. The BS is currently connected to the Sea of Azov via the Kerch Strait. The unique geographical location of these basins predetermined their environmental conditions and hydrologic regimes, and it imposed specific impacts on diverse biological populations (Yanko-Hombach, 2007). Therefore, they act as paleoenvironmental amplifiers and as sensitive recorders of climatic events, in particular for the glacial-interglacial cycles of the East European Plain and mountains that were responsible for main aspects of transgressive-regressive sea-level fluctuations. They also serve as stratotype regions for the development of the Northern Eurasian Quaternary stratigraphy (Yanko-Hombach et al., 2017). For these reasons, the study of their Quaternary geological history has attracted a lot of attention for more than two centuries (see Yanko-Hombach, 2007; Yanko-Hombach et al., 2014, 2017 for the references) and has made available abundant data for synthesis by the IGCP 521, INQUA 501, and IGCP 610 projects (http://www.avalon-

* Corresponding author.
E-mail addresses: valyan@onu.edu.ua, valyan@avalon-institute.org (V. Yanko-Hombach), avkislov@mail.ru (A. Kislov).

https://doi.org/10.1016/j.quaint.2017.11.030
1040-6182/© 2017 Published by Elsevier Ltd.

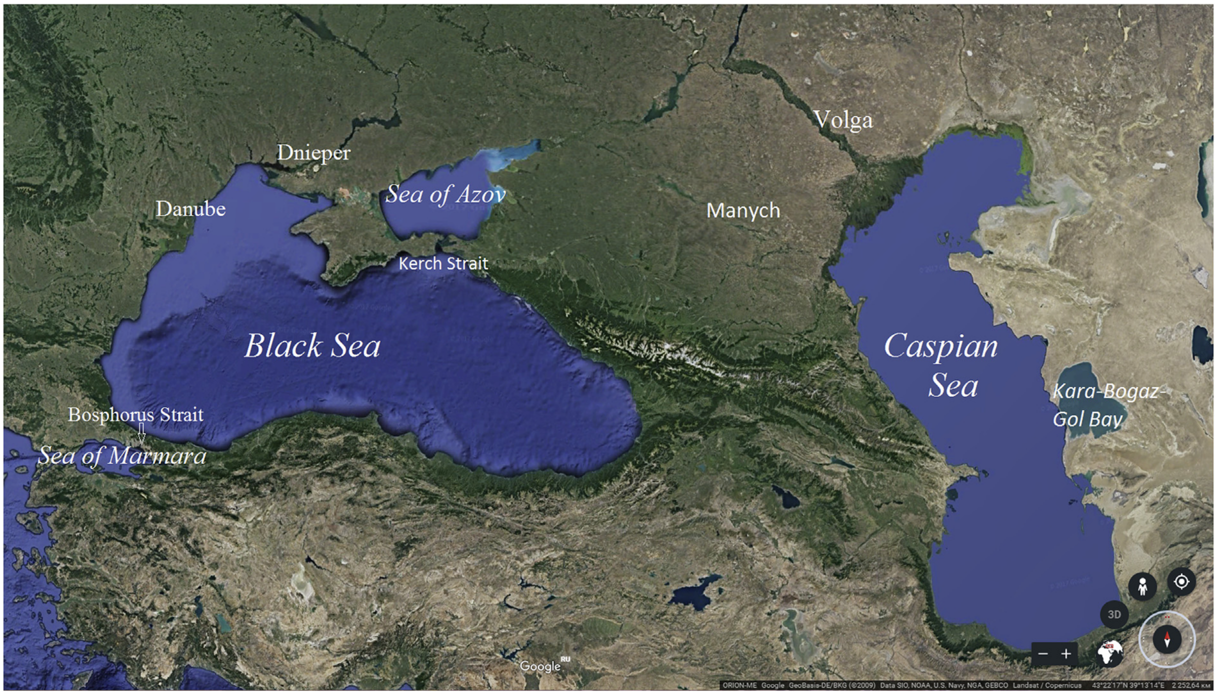

Fig. 1. Current map of Caspian Sea, Black Sea, connecting straits and main rivers (https://earth.google.com) demonstrating all geographical objects mentioned in this paper (Manych is fragments of spillway, which presumably connected the Caspian Sea and Black Sea).

institute.org/IGCP610/index.php).

This synthesis has enabled us to conclude that some data obtained through earth science investigations contradict other data that were obtained empirically. We call these contradictions paradoxes:

Paradox No. 1 relates to the Early and Late Khvalynian transgressions that occurred in the CS during the second part of MIS 3 (~35–25 ka BP) and the Late Glacial epoch (~17–12 ka BP), respectively (e.g., Yanina, 2012). It is unclear what the main source or sources of water were that caused them. As such, we face a paradox: "The event occurred, but it seems inexplicable because it cannot be described using reasonable arguments about its causation."

Paradox No. 2 emerges from the comparison of climate events and transgressive-regressive cycles in the CS (Yanina, 2012) and BS (Balabanov, 2007; Yanko-Hombach, 2007). It implies that large sea-level anomalies occurred in accordance with global climate changes (because they are influenced by climate variations). However, other (not so large and not such long) sea-level fluctuations are poorly correlated with climate events. The essence of Paradox 2 is why climatically-induced sea-level changes did not follow climatic variations.

Paradox No. 3 concerns the contradiction between the massive water discharge from the BS into the Sea of Marmara via the Bosphorus Strait (e.g., Aksu et al., 2002) and the BS level fluctuations in the Latest Pleistocene-Holocene (Balabanov, 2007; Konikov, 2007; Yanko-Hombach, 2007). Both scenarios could not exist simultaneously.

The main goal of this paper is to provide some ideas on possible reasons for these paradoxes using empirical methods with a hope to solve at least some of them and encourage a new round of research on the interrelation between climate and sea-level change.

2. Results and discussion

Paradox No. 1. The Early and Late Khvalynian transgressions increased water level in the CS to 50 m asl and 0 m asl, respectively (Yanina, 2012; Bezrodnykh et al., 2017). These transgressions were preceded by the Atelian and Enotaevian regressions. At their maximum, the former regression decreased the CS level to −140 m bsl and the latter to −110 m bsl (Maev, 1994). In total, the Early Khvalynian transgression rose from −140 m to +50 m (about 200 m), but Late Lhvalynian transgression rose from −110 m to 0 m (about 110 m). According to Chepalyga (2007), "In the process of flooding, the Khvalynian Sea expanded over an area of about one million km^2, up to 1.1 million km^2 if the Aral-Sarykamysh basin is included. The total area was three times that of the present Caspian Sea, and the accumulated water volume (which reached 48–50 m asl at peak flood stage) was twice that of today's Caspian (130,000 km^3)." These transgressions "… left distinct traces in the morphology of landforms, such as marine terraces, specific coastlines, flattened seafloor surface, as well as sculptured and constructional landforms within the former spillways: the Manych-Kerch Spillway, and the Bosphorus and Dardanelles Straits" Chepalyga (2007).

The question is from where could this water come? Several aspects of the problem were discussed earlier by Chepalyga (2007). Was meltwater from the decaying Scandinavian ice sheet a considerable contributor to the flood (Kvasov, 1979), or was it much higher precipitation in Eastern Europe (up to 600–800 mm per year) and increased river runoff into the CS (Sidorchuk et al., 2009), or decreased evaporation rate over the CS, etc.? Whatever it was, logic dictates that it should have been climatically induced, significantly contributing to river runoff into the CS.

As the first step, let's consider the main components of the water budget in the CS that could provide the long-lived inter-decadal water-level trends under climate change. The water budget consists of positive and negative components. The former include

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

river runoff into the basin and precipitation over the CS area. The latter include outflow from the CS into the Kara-Bogaz-Gol Bay (KBGB), and evaporation over the CS area.

The most prominent factors in this regard include changes in the Volga River runoff, followed by the varying discharge of other rivers, as well as the randomly fluctuating precipitation minus evaporation over the sea (Kislov et al., 2014). The fluctuations of the latter are very important for the realization of interannual anomalies, for example, the drop in sea level of the CS during the "hot 2010 summer event" (Arpe et al., 2012), however the long-lived trend-like level changes were determined by changes in the Volga River runoff. For example, PMIP1 simulation data show that river runoff changes are the biggest contributing factor to level fluctuations in the CS (Kislov and Toropov, 2011). They demonstrate that decrease in river runoff during the LGM was large enough to create a substantial drop in the level of the CS (~50 m lower compared to the present), and thereby causing the Enotaevkian regression.

If this was so, river runoff could equally increase the level of the CS to 0 m asl as can be evidenced by geomorphological data synchronous with the Late Glacial (18–13 ka BP) channels around the Volga River and macromeanders in the river valleys. Their width and meander wave length is 4–15 times larger compared to recent ones, and according to Borisova et al. (2006) and Sidorchuk et al. (2009), they could have been created by extremely high water discharge events. An increase in river runoff at that time is also supported by frequency analysis of absolute chronology data classified according to the magnitude of fluvial activity (Panin and Matlakhova, 2015).

Recently, the increase in CS water level to 50 m asl was dated 30–35 ka BP (Yanina, 2012, 2014). These data correspond to the epoch of valley deepening that occurred during the same time in the late MIS 3 (Panin et al., 2017).

In this way, it is more or less clear that the main source of additional water for both transgressions was located on the East European Plain.

The next question is: what was the main source of additional water over the East European Plain? Using the nomogram linking the sea level, water balance, and hypsographic curve of the CS (Sidorchuk et al., 2009), we calculated the runoff volume, which was required to provide figures for the Early and Late Khvalynian events. Using today's values of evaporation minus precipitation over the sea area, we obtained the following result. For the realization of both events, an increment in river runoff of ~650 and ~450 km^3/y, respectively, would have been needed. These amounts represent approximately 1.5 and over 2 times current Volga River runoff volumes, respectively.

Assessment of changes in Volga River runoff and quantitative estimation of mechanisms that influenced them during different climate epochs could be done using climate models; these enable us to compare the climate for the referenced and modern (control) epochs. We use results of the simulations focusing on the second part of MIS 3 that have been carried out with the help of the LMDZ.3.3 atmospheric general circulation model (Sima et al., 2013) as well as some other materials (not included in this paper) that were sent to us personally. It includes air temperature and specific humidity anomalies for different events (see below) for the CS drainage area. For the modern time simulation, the historical forcings are based as far as possible on observations.

In this numerical experiment, conditions of MIS 3 (corresponding to Early Khvalynian time) are represented in the simulation around the H4 event. The latter consists of a glacial stage (Greenland stadial, GS) and a warm (Dansgaard-Oeschger, or Greenland interstadial, GIS) perturbation. In the absence of reconstructions for MIS 3, sea surface temperatures (SSTs) and sea ice at the time was modeled on the GLAMAP2000 reconstruction for the LGM; this was used in the reference glacial climate simulation GS. The warm perturbations were obtained by altering only the North Atlantic surface conditions in the latitudinal band between 30°N and 63°N. All-year-long zonal SST anomalies of up to ±2 °C were applied in this band, and sea ice was imposed where the SST was lower than −1.8 °C.

The Earth orbital parameters needed for the calculation of insolation flux were set to 39 ka BP values (Berger, 1988), and the CO_2 concentration was set to 209 ppmv. Precise ice sheet configuration at 39 ka BP is absent; therefore, Sima et al. (2013) used the one for 14 ka BP. It was selected from the ICE-4G reconstruction (Peltier, 1994) as corresponding to a sea level similar to that at 39 ka BP, approximately 60 m lower than today with the land-sea mask adapted to this sea-level position. We stress that the mentioned set of data could be utilized to estimate not only the main features for the second part of MIS 3 but, in some aspects, for the Late Glacial period; this is very important because it allows us to use these simulations for assessment of both the Early and Late Khvalynian transgressions.

Based on the 20-year running mean (Sima et al., 2013), we conclude that climate changes under the above-mentioned orbital parameters, existence of the Scandinavian Ice Sheet, the CO_2 decrease, and decreased SST over the North Atlantic (experiment GS; see above) led to decrease in precipitation over the Volga catchment area (~15–20 mm, mean monthly and annually averaged). This promoted a drop in the level of the CS. The same reaction to the presence of the ice sheet, dropping of the SST, and the CO_2 decrease was depicted by Kislov and Toropov (2011). The transition to a warm stage, realized as a GIS experiment (see above), adds only ~4 mm (mean monthly and annually averaged) of precipitation over the Volga River catchment area. So, at least in the framework of the LMDZ.3.3 model, simulated precipitation would have had an insignificant reaction to the phase changes of the H4 event. Hence, the model experiment suggests that the stage of full-flowing rivers leading to the Khvalynian events **could not be a reaction to a strong increase in precipitation over the East European Plain.**

Therefore, we need to consider other factors. Moreover, we can search for such factors that exceed the negative (see above) effect of precipitation decrease over the catchment area during the periods in question.

Another way to explain the appearance of so much additional runoff was speculated by Kvasov (1979). He proposed that water concentrated in ice-dam lakes located along the southern boundary of the last Scandinavian Ice Sheet could penetrate to the Oka River, upper Volga River, the Pechora River, and the Kama River—all flowing into the Volga River basin. However, there are several contradictory facts that eliminate any possibility of such a mechanism. For example, the Pechora River seems always to have opened into the Arctic Ocean (Svendsen et al., 2004), and therefore, the flow of its meltwater was directed towards the northeast. Besides, the level of the ice-dam lakes was lower than previously assumed (Lunkka et al., 2001). All this does not support the hypothesis of a significant influence of meltwater flow on the Volga River water volume (Sidorchuk et al., 2009). The role of Scandinavian Ice Sheet melting during the second part of MIS 3 is not so certain, however. Based on our use of the ice-sheet reconstruction for 14 ka BP (see above) as a proxy for late MIS 3, we propose again that meltwater from the Scandinavian Ice Sheet played a minor role despite some earth science evidence provided, for example, by Tudryn et al. (2016).

The lack of a clear quantitative explanation has given rise to a series of much more speculative hypotheses. Some of them can be ignored based on theoretical calculations as will be demonstrated

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

later.

All other speculative hypotheses are characterized by a lack of geological or geomorphological evidence that could support the existence of the phenomena under discussion, such as the hypothesis of Grosswald (1998), who proposed that the ice complex formed during the late Pleistocene on the shelf along the Siberian arctic coastline could have covered and blocked the mouths of northern rivers such as the Ob', Enisey, and Lena, and thus the water from ice-dam lakes (that emerged within the river's catchment areas as well as meltwater) overflowed into the CS through different spillways.

Another hypothesis postulates that the source of the additional water may have been connected to an increase in precipitation over the Tian Shan Mountains due to penetration there of the South Asia monsoon (Kislov and Toropov, 2007). It was the development of an old idea that described how snow meltwater outflow could have been directed from the Amu Daria River toward the Uzboy Valley, eventually penetrating into the southeastern part of the CS throughout the intermediate Sarykamish Lake (Varushenko et al., 1987). However, there is no reliable evidence to support these hypotheses; at least, the quantitative estimations are impossible.

Sidorchuk et al. (2009) proposed a much more reliable hypothesis. They suggested that river runoff could have increased without any increase (or even decrease) in precipitation due to a decrease in water losses because of a lowering of evapotranspiration over the catchment area. This could have been caused by a decrease in the infiltration rate into the soil (e.g., a rise in the runoff coefficient) due to permafrost inherited from the LGM. In addition, the melting of permafrost could contribute to the runoff as well. The authors took into consideration that the Volga River basin during pre- and post-LGM existed under permafrost conditions, which began to disappear by ~14 ka BP (Velichko, 2009). Under modern conditions, the runoff coefficient over the Volga River basin varies from 0.3 to 0.5 (Sokolov, 1952). However, under permafrost conditions, it could presumably be about 0.6–0.8, as in the recent river basins under such conditions. For example, similar changes in the runoff coefficient of the Moskva River basin during Late Glacial time were reconstructed by Sidorchuk et al. (2009). It was shown that annual surface runoff concentrating into intensive spring flooding was 2–3 times greater than current runoff.

It should be noted that during the interval 14–18 ka BP (the time of the Late Khvalynian event), the pattern of insolation anomalies at the top of the atmosphere would have been especially high in the spring months. In turn, an increase in insolation would have caused a quick increase in temperature and rapid snow melting, leading to further intensification of the spring effect and development of intense flooding. During MIS 3, the pattern of insolation anomaly during the spring and summer time was approximately the same (Berger, 1988).

The “permafrost” hypothesis provides the required water volume for the Volga River runoff, however, its shortcoming is the absence of quantitative estimation and lack of detailed data about the permafrost configuration before and after the LGM. So far, it is unclear whether this source was sufficiently strong to ensure both the Early and Late Khvalynian transgression.

So, we face a paradox: The event took place, but the reason is still unexplained because a likely source of “additional water” is still unknown.

Paradox No. 2. This problem emerges from the comparison of climate event scheduling and that of transgressive-regressive sea-level changes of the CS (and the BS as well). On a large scale, a good correlation can be observed between CS level changes and the calendar of global climate events during the Quaternary, and determining reasons for this can be evidenced. For example, simulation data validate the theory of connection between deep regressive stages of the CS (and BS) and mature stages of the late Quaternary glacial events (Kislov and Toropov, 2011). Another example is the correlation between CS level variations and changes in river runoff during the last 2 ka (Panin and Matlakhova, 2015). But on a smaller or secular-scale, the interrelation between climatic events and transgressive-regressive cycles of CS level, which are definitely caused by climate variations, is difficult to assess. For this reason, the essence of Paradox No. 2 is: Why do secular-scale climatically-induced sea-level changes reflected by transgressive and regressive dynamics of the Caspian and Black seas not follow climate variations? Is this because the CS is not connected with the World Ocean? Could the system responding to climate changes have developed chaotic level fluctuations in the CS, and can such behavior be described analytically?

Using the CS level data set (20 years time-resolved, during the last 2000 years), we calculated the probability distribution function (PDF). It describes statistical conditions during the relatively stable climatic conditions of the Sub-Atlantic phase of the Holocene. It is very important to stress that such temporal resolution provides an independence of random variables, because the statistical connection between sea-level anomalies is revealed over ~20 years (as will be demonstrated later). Using the Kolmogorov-Smirnov test, or using the chi-squared test statistic, we assess that the null hypothesis, which asserts that the sample comes from a population with a Gaussian distribution, cannot be rejected. A normal distribution is characterized by the mean CS level at −28 m and the standard deviation at 1.4 m. Note that using the observational data set (~100 years of records) for the PDF calculation leads to an incorrect estimation of the PDF; this happens because this time-series consists of only ~5 independent random variables due to dependence of annual data.

To explore the mechanism of CS variability, we used a deterministic equation suitable for describing the water budget of any lake:

$$\frac{dW(t)}{dt} = V_{+}(t) - f(t)e(t) - V_{-}(t) \quad (1)$$

The right-hand side of Eq. (1) consists of the total river inflow and outflow of CS waters into the KBGB: the $f(t)e(t)$ term includes $e(t)$, which is the evaporation minus precipitation over the sea area per unit of sea surface, and $f(t)$, which is the area of the sea corresponding to the current level position.

The outflow discharge is determined by the level anomaly. In a situation where ancient morphological parameters are poorly known, it makes sense to use the simplest expression.

$$V_{-}(t) = V_{-,0} + \alpha h(t) \quad (2)$$

where $\alpha = \frac{glH_0^2 sin\gamma}{\nu}$ (Esin, 2014; Esin and Esin, 2014; Kislov, 2016b), $g = 9.81$ m/s^2, ν is the kinematic viscosity coefficient, l is the width of the stream and H is its depth, and γ is the incline.

We utilize the relation between the area and level in the form (justification of this approach appears below):

$$f(t) = a + bh(t) \quad (3)$$

Traditionally, for a reference CS level of −28.5 m, $a = 3.7 \cdot 10^5$ km^2 and $b = 1.4 \cdot 10^4$ km^2/m (Kislov, 2016a). For the BS, $a = 4.2 \cdot 10^5$ km^2 and $b = 1.0 \cdot 10^3$ km^2/m (Ivanov and Belokopytov, 2011).

A bit of algebra yields Eq. (1) in the following form, which describes interannual oscillations:

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

$$\frac{dh(t)}{dt} = -\left(\frac{\alpha}{a} - \frac{bV_{-,0}}{a^2}\right)h(t) - \frac{bV_{+,0}}{a^2}h(t) + \frac{V_+(t) - V_{-,0}}{a} - e(t) \quad (4)$$

or in a shortened form:

$$\frac{dh}{dt} = -\lambda_1 h - \lambda_2 h + q \quad (5)$$

The equation demonstrates that the positive and negative anomalies of river runoff and evaporation minus precipitation (concentrating in q) form a deviation of h from the equilibrium state. Negative feedback expressed by the two first terms of the right-hand side of Eq. (4) or (5) prohibit the development of large deviations. There, $\lambda_1 \equiv \tau_1^{-1}$ and $\lambda_2 \equiv \tau_2^{-1}$ represent the inverse of the spin-down times. For the CS, $\lambda_1 + \lambda_2 = \lambda$~0.05 yr^{-1}, corresponding to a full spin-down time equal to ~20 years (as was mentioned above).

During the Holocene, fluctuations in Volga River runoff and variations in evaporation vs. precipitation were influenced by the same processes as today. Indeed, simulated Holocene climate changes over the CS, and its adjacent basin of tributaries does not vary much from simulated ones for the current climate (Kislov and Toropov, 2007). Detailed analysis shows little change in the winter mean-state atmospheric circulation as well as in the inter-annual and decadal North Atlantic Oscillation (NAO) variability (Lu et al., 2010). Indeed, based on a new pollen-based reconstruction of European climate, it has been shown that the fingerprints of the mid-Holocene climate anomalies are entirely consistent with those from modern analogue atmospheric circulation patterns. The latter are associated with a strong westerly circulation in winter (positive NAO) and a weak westerly circulation in the summer associated with anti-cyclonic blocking (Mauri et al., 2014). The same conclusion was made by Rimbu et al. (2004a,b) regarding the prevailing of the NAO positive phase in the early Holocene. However, as for today, the prevailing of the positive NAO index does not provide the uniqueness in the behavior of the CS level anomalies. It looks as if Holocene flood patterns reveal a similar complexity. Spatially interconnected climate-flood relationships result in multidecadal to secular variability in flood frequency with strong in-phase or out-of-phase relations between regions (Benito et al., 2015; Panin and Matlakhova, 2015).

Such information allows us to conclude that $q(t)$ in Eq. (5) can practically be characterized by the stochastic interannual oscillations with typical time changes of q that are no more than 1–2 years (see the definition below). In such a frame, we propose that q represents asynchronous uncorrelated processes whose autocorrelation function is approximated by:

$$\langle q(\xi)q(\zeta)\rangle = \sigma_q^2 exp\left(-\frac{|\xi - \zeta|}{\tau_q}\right) \quad (6)$$

where ξ and ζ are different moments and $\langle\ldots\rangle$ denotes ensemble average value. A time-series of river runoff and precipitation minus evaporation allowed us to calculate the autocorrelation coefficient $r(\tau_q)$, which is needed to establish a deadtime between consequent fluctuations (estimation of the τ_q that follows from the expression describing the loss of correlation $r(\tau_q)$~0). This was shown to be less than 2 years. Therefore, we use τ_q~2 years. The form of the autocorrelation curve is assumed to be sufficiently acute and is approximated by the δ-function curve.

Because $\tau_q \ll \lambda^{-1}$, we can consider Eq. (5) as a stochastic one, proposing that slow changes in h are balanced by the statistically averaged result of the fast fluctuations generated by q. The CS water volume (like a massive inertial object) integrates these fast signals of forcing over a vast area, making the CS level changes quite stochastic. How does such an adjustment work? Consecutive positive and negative (stochastic) anomalies of water budget do not completely cancel each other out, and their residual effects accumulate. This process forms (step by step) a deviation that is controlled by the spin-down processes. From this approach, Eq. (5) is represented as a stochastic Langevin equation (the foundation of the Brownian concept).

Another approach was used to calculate sea-level variations in the basin based on the water balance equation, Eq. (1), but here changes in precipitation and evaporation over the river catchment and variations in river runoff were directly a priory tied to the global paleoclimate calendar using simple considerations about the hydrometeorological conditions of watersheds (Georgievski and Stanev, 2006; Thom, 2010). Taking into account some available geological observations, authors have developed a simple theory relating the runoff ratio to climatic characteristics.

Returning to the stochastic interpretation of Eq. (5), note that the probabilistic interpretation is based on the deterministically constructed model (4), which is based on the physical law of conservation of water mass. It is well-known that the solution of Eq. (5) should be set for the variance (standard deviation). When $t \ll \lambda^{-1}$, the standard deviation of level variations, is proportional to the square root of time. Such a feature of a stochastic process is denoted as red noise behavior. When $t \ll \lambda^{-1}$, the standard deviation does not depend on time, as defined by Kislov (2016a):

$$\sigma_{h,st}^2 = \frac{\tau_q \sigma_q^2}{\lambda} \quad (7)$$

We apply an expression (7) that estimates the upper limit of the CS variance. Parameters λ and τ_q were estimated above. The variance, σ_q^2, is determined by taking into account the variance of river runoff volume and e, which were estimated (only modern observation data can be used) as 0.026 and 0.007 (m/y)^2 (Golitsyn et al., 1998), correspondingly. Due to their practical independence (Frolov, 2011), $\sigma_q^2 = 0.033$ (m/y)^2. Using these values, we obtain using (7) $\sigma_{h,st} = 1.15$ m, a result that is only slightly smaller than the empirical estimation (1.4 m). The closeness of the calculated theoretical $\sigma_{h,st}$ to the empirical value could indicate that the Brownian concept does not contradict the recorded time-series. Under these conditions, the CS level dynamics is represented by a system undergoing random walk.

As was mentioned above, the observed time variations are the Gaussian random noise. Taking into account the properties of the Gaussian process, the probability of the time (t_*) required to achieve a prescribed level (h=a) is given by the formula (Feller, 1968):

$$p\{t_*\} = \sqrt{\frac{2}{\pi}}\frac{a}{\varepsilon t_*^{-\frac{3}{2}}} exp\left(-\frac{a^2}{2\varepsilon^2 t_*}\right) \quad (8)$$

where $\varepsilon^2 \equiv \tau_q \sigma_q^2$ =0.132 m^2/y. The most probable transition time is distinctly expressed only in the case of small deviations when anomaly a can be achieved in a small number of time-steps. Increase in the prescribed deviation leads to a transformation of the histogram: the peak of the probability function is stretched, and the uni-modal curve is drastically flattened. This theory manifests that a large anomaly is a rare and irregular event, and the concepts of most-probable transition time or average transition time needed to transit from one state to another lose their meaning.

The adaptation of the hydrological regime of the sea to climate change is not a response to each perturbation. The CS responded to

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

the statistical effect of climatic anomalies at different scales. In many aspects, the same mechanism should be realized in the BS system during Early Neoeuxinian (24–17 ka BP) time, when the Black Sea was a brackish lake (Yanko-Hombach, 2007; Yanko-Hombach et al., 2017) governed by river runoff changes and evaporation minus precipitation like the CS.

Keep in mind that this conclusion is based on simplified physics. But we are sure that detailed calculations (which hopefully will be realized in the future) will not change things much.

We now investigate the dynamic regime of the variability in CS level consistent with its dependence on parameters. For this goal, we note that the hypsographic curve of the CS (courtesy of A. Panin) can be divided into three intervals (Fig. 2).

In all, the relationship between area and level can be presented as linear relations—see Eq. (3) —and within each interval, the variance is described by Eq. (7) (with different λ) and the PDF is presented by Gauss distributions. But, there are two inflection points, where parameters of the hypsographic curve denote sharp changes, determining that the variance and consequently the form of the PDF as well as typical timing of the level fluctuations will be changed manifesting the transition into another state.

Near the current state of the CS (central range on Fig. 2), the typical timing of the level fluctuations is calculated as λ^{-1}~20 years. It is important to note that runoff to the KBGB is regulated by anomalies of the CS level and runoff to the KBGB itself regulates the amplitude and duration of the CS level anomalies. This spin-down role of the KBGB, "eating" the water-level anomalies, takes place only near the current position of the CS level. When the CS level rises significantly, the KBGB transforms into an ordinary bay, thereby stopping the runoff of water. Under such conditions (blue branch on Fig. 2), λ^{-1}~50 years, and the variance increases 2.5 times. On the other hand, if the level goes lower, the KBGB would soon transform into land area. It again stops the water discharge, and λ^{-1}~100 years and the variance increases 5 times (green branch on Fig. 2).

In all three cases, we have Gaussian curves with different widths, however, the differences are not so strong. So we can conclude that "super large" anomalies (like the Khvalynian transgressions) are practically impossible. Such an event could not occur as a burgeoning stochastic anomaly.

The observed transgressive-regressive cycles of the CS level under the Holocene quasi-steady climate state could result from the accumulation of small anomalies in the water regime. They could have occurred without significant changes in external forces. Thus, Paradox No. 2 has been solved, at least on a conceptual level.

Paradox No. 3. Today, the two-layer (outflow and inflow) hydraulic transport of water via the Bosphorus Strait controls water exchange with the World Ocean, linking the BS with the Sea of Marmara. Presently, the mass balance through the Bosphorus is on average ~420 km^3/y (outflow) and 200 km^3/y (inflow) (Ivanov and Belokopytov, 2011). However, according to Ozsoy and Unluata (1998), it is ~600 km^3/y and 300 km^3/y, respectively. In these assessments, only water budget is the same. The current mass balance through the Kerch Strait yields on average ~40 km^3/y (outflow) and ~55 km^3/y (inflow) (Ivanov and Belokopytov, 2011). During the first quarter of the Holocene, the water exchange via the Kerch Strait was replaced by runoff from the Don and Kuban Rivers into the BS, considering that the BS level lay below the shallow bottom of the Sea of Azov at the time (~10 m).

The asymmetric transports, mainly via the Bosphorus, are maintained by the excess of river runoff (~355 km^3/y) and evaporation against precipitation $(E-P)$ ~115 km^3/y over the BS area. The water balance is not comparable to the residual of approximately 30 km^3/y, and such conditions provide that the surface of the BS is ~30 cm above the level of the Sea of Marmara.

The BS is infilled largely by the discharge of the European rivers, which provide more than 70% of the water runoff. These rivers include the Danube River with a mean water discharge of approximately 210 km^3/y and other rivers belonging the northwestern

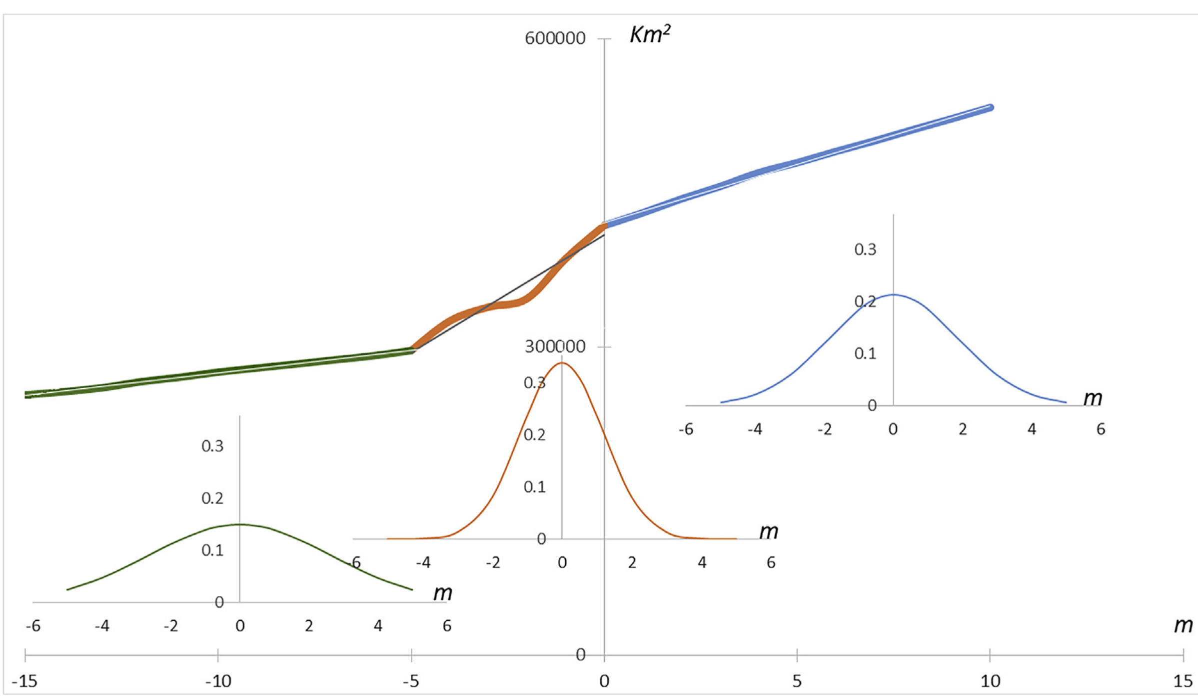

Fig. 2. Hypsographic curve (HC) of the Caspian Sea (km^2) vs. position of its water level (m). Zero at the x-axis corresponds to −28 m. Three various intervals are depicted by curves of different colors. Thin white and grey lines in interior (or in vicinity) of these curves are the linear regression lines. Graphs located below the curve are the pdfs (Gauss distributions) corresponding to different ranges of the HC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

shore of the BS (the Dnieper, Dniester, and Southern Bug), which contribute approximately 54 km^3/y. The rivers of the Caucasian and Anatolian coasts contribute approximately 13 and 10%, respectively. Snow cover, accumulating during the cold period, mainly forms the annual discharge of the major rivers.

At the LGM, during the period of lowstand for the World Ocean, the BS evolved independently. Several quantitative estimations of the sea-level regime and mass-balance changes were summarized by Chepalyga (2002), Yanko-Hombach (2007), and Kislov and Toropov (2011). The next phase (after the LGM) of the large-scale transgressive cycle was linked to postglacial global warming. Low-salinity outflows from the Black Sea into the Marmara Sea were recorded in the early Holocene (Aksu et al., 2002; Buyukmeriç, 2016). The Marmara Sea inflow to the BS began as occasional spilling over the Bosphorus (~9–7 ka BP) based on multidisciplinary data from the BS sediments (e.g., Algan et al., 2007). The two-way flow regime was established due to the confluence of both Mediterranean and Black Sea overflows. It was slow at the beginning, becoming prominent after 7.2 ka BP (Yanko-Hombach et al., 2011).

Reconstructed sea-level changes in the BS basin for the Late Glacial and first quarter of the Holocene (11–7 ka BP) have been discussed in many publications, and they are quite different from each other (Kislov, 2016b). Half of the curves demonstrate continuous rise without cyclic fluctuations (Aksu et al., 2002; Filipova-Marinova, 2007; Brückner et al., 2010; Starkel et al., 2015) while the other half include transgressive-regressive fluctuations of the Black Sea and differing opinions exist over their occurrence and magnitudes (Balabanov, 2007; Chepalyga, 2002; Hiscott et al., 2007; Izmailov, 2005; Konikov, 2007; Konikov et al., 2010; Ryan, 2007; Yanko, 1990; Yanko-Hombach, 2007; Yanko-Hombach et al., 2011, 2017). There are also long-lasting debates regarding the role of local tectonics in sea-level changes (Glebov and Shel'ting, 2007; Brückner et al., 2010; Esin, 2014; Esin and Esin, 2014) as well as correspondence of the BS level changes and paleohydrological phases to the calendar of climatic anomalies after the Younger Dryas event (Lericolais et al., 2010; Starkel et al., 2015).

These level variations (lasting a few centuries to a few thousand years) must correspond to inflow-outflow water mass fluxes because changes in salinity cannot generate BS level fluctuations of more than 2.5 cm per 1000 years (Esin, 2014; Esin and Esin, 2014).

We calculated the standard deviation of the curves presented by Balabanov (2007), Izmailov (2005), Chepalyga (2002), and Konikov et al. (2010) considering a formal connection between the amplitude of harmonic function and the variance. They are ~5–10 m; ~7 m; ~7 m and ~4 m, respectively.

As such, the question of the existence, origin, and magnitude of the BS fluctuations in the Holocene remains open, despite the widely accepted theory that the changes were climatically induced. Furthermore, the climate models do not simulate the required large secular-scale changes of precipitation and river runoff volume (Kislov and Toropov, 2007, 2011; Kislov et al., 2014).

It is very important to note that, as mentioned above, there is a fundamental contradiction between a large water volume discharged from the BS into the Sea of Marmara via the Bosphorus (Aksu et al., 2002, 2016) and a fluctuating character of sea level in the Black Sea during the Holocene (Balabanov, 2007; Yanko-Hombach, 2007; Martin and Yanko-Hombach, 2011; Yanko-Hombach et al., 2011); this forms the essence of Paradox No. 3. Indeed, if water discharge via the Bosphorus Strait is quite significant, the large long-term BS level fluctuations cannot occur because the excess of outflowing water volume largely depends on the difference between the BS and the Sea of Marmara levels. It can be most simply visualized in the context of the mathematical approach developed above.

We again use for analysis Eq. (5). First, we estimate the typical time characterizing the variation of $q = q(t)$. Taking a time-series of river runoff and precipitation minus evaporation (Stanev and Peneva, 2002), we calculate the autocorrelation coefficient to establish a deadtime between consequent fluctuations. Its value is estimated as τ_q~2 years.

Taking the typical parameters, we can estimate the efficiency of spin-down processes characterized by the first and second terms of the right-hand side of Eq. (4) or (5). Using parameters of the Bosphorus (Esin, 2014; Esin and Esin, 2014), it was found that $\tau_1 \sim 5$ years (Kislov, 2016b). Taking typical values of the water inflow flux into the BS and parameters of the hypsometric curve of the BS basin, we found that $\tau_2 \sim 500$ years. Thus, the first spin-down process (as was hypothesized above) is a much more effective mechanism for destroying BS level anomalies due to the levelling effect of free water exchange between the BS and Sea of Marmara. It has prohibited the development of large-scale and long-lived anomalies since ~11 ka BP, when the BS has been flowing into the world ocean (Hiscott et al., 2007). After that, due to water exchange between the BS and Sea of Marmara, the BS level increased. Such continuous level rise without cyclic fluctuations provided the empirical grounds for this conclusion.

However, if the BS level variations during Holocene had really existed as shown by the geological and paleontological records (see above), it would mean that water exchange via the Bosphorus did not play an important role as a spin-down process. Now, assume that the water exchange between the BS and the Sea of Marmara was not significant. Neglecting the effects of water outflow, the basic equation for the dynamics of a closed reservoir level may be written as Eq. (5), where $\lambda_1 = 0$, and the last term depicts the variation of both river runoff and evaporation minus precipitation. So, the theory, developed for CS level dynamics, could be used also for the BS: the variance of BS level variations in the steady state is described by Eq. (7) but for a different set of parameters. The variance σ_q^2 was roughly calculated as 0.057 $(m/y)^2$ (Kislov, 2016b). Using these values, we obtain $\sigma_{h,st}$~7 m. This value is close to the empirical estimate (see above). This similarity could indicate the reality of observed paleochanges in BS level, the existence of which was questioned above. If the outflow had been small, the reconstructions of Algan et al. (2007) should be corrected.

However, we can now return to a large water discharge value via the Bosphorus: intensive water exchange between the BS and the Sea of Marmara is/was a very effective spin-down process, destroying BS level anomalies and prohibiting the development of large-scale anomalies lasting a few centuries or, furthermore, a few thousand years.

Therefore, the theoretical analysis has shown that the empirical data are controversial; observed BS level fluctuations during the first quarter of the Holocene and a large water discharge value via the Bosphorus could not co-exist simultaneously.

3. Conclusions

Solutions to Paradox No. 1 are still lacking. It is more or less clear that the main source of additional water for both the Early and Late Khvalynian transgressions was located on the East European Plain. But the main source of additional water is still unclear. The model experiment suggests that the stage of full-flowing rivers leading to the Khvalynian events could not be a reaction to a strong increase in precipitation over the East European Plain. Other hypotheses about sources of additional water seam to be even less reliable due to impossibility of making the quantitative estimations.

Paradox No. 2 has been solved, at least on conceptual level. The

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030

observed transgressive-regressive cycles of the CS level under the Holocene quasi-steady climate state could result from the accumulation of relatively small anomalies in the water regime. They could have occurred without significant changes in external forces. It should be considered as one of the possible mechanisms responsible for the generation of a wide range (decadal to secular-scales) of the CS level stochastic anomalies. Their typical amplitudes can be estimated taking into account the properties of the Gaussian random noise. As is well-known, the so-called three (two or one)-sigma rule of thumb expresses a conventional heuristic that values are taken to lie within three (two or one) standard deviations of the mean. It corresponds (using again mentioned connection between the amplitude of harmonic function and the variance) to ~6 m (4 or 2 m) anomalies of the CS level.

Solutions to Paradox No. 3 are also still lacking. According to empirical data, observed BS level fluctuations during the first quarter of the Holocene and a large water discharge value via the Bosphorus could not co-exist simultaneously.

Formulation and solutions for these Paradoxes should make a major contribution not only to the problems of the paleogeography of the CS and BS, but also to explanations of the reasons for inadequate simulation of regional climate changes. This is important in the context of the development of models for future climate prediction. All this requires further geological and geochronological evidences as well as climate simulations.

Acknowledgments

Funding for this research was provided by grants from the Russian Foundation for Basic Research (Grant No. 16-05-00509) and the Ministry of Education and Science of Ukraine (State Budget Themes No 539 and 557). This study is a contribution to the UNESCO-IUGS-IGCP 610 project: “From the Caspian to Mediterranean: Environmental Change and Human Response during the Quaternary” and INQUA Focus Group POCAS (SACCOM 1709F) “Ponto-Caspian stratigraphy and geochronology”.

We are much obliged to A. Panin, T. Yanina, V. Archipkin, and N. Frolova, Lomonosov Moscow State University, for providing us with new materials and discussions. We are much obliged to A. Sima, Laboratoire de Météorologie Dynamique, INSU-CNRS&CERES-ERTI – UMR8539, Ecole Normale Supérieure, who provided the materials on climate modeling.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quaint.2017.11.030.

References

Aksu, A.E., Hiscott, R.N., Yaltirak, C., 2016. Early Holocene age and provenance of a mid-shelf delta lobe south of the Strait of Bosphorus, Turkey, and its link to vigorous Black Sea outflow. Mar. Geol. 380, 113–137.

Aksu, A.E., Hiscott, R.N., Yaşar, D., Işler, F.I., Marsh, S., 2002. Seismic stratigraphy of Late Quaternary deposits from the southwestern Black Sea shelf: evidence for noncatastrophic variations in sea-level during the last 10,000 years. Mar. Geol. 190, 61–94.

Algan, O., Ergin, M., Keskin, S., Gokasan, E., Alpar, B., Ongan, D., Kirci-Elmas, E., 2007. Sea-level changes during the late Pleistocene e Holocene on the southern shelves of the Black Sea. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 603–631.

Arpe, K., Leroy, S.A.G., Lahijani, H., Khan, V., 2012. Impact of the European Russia drought in 2010 on the Caspian sea level. Hydrol. Earth Syst. Sci. 16, 19–27. https://doi.org/10.5194/hess-16-19-2012.

Balabanov, I.P., 2007. Holocene sea-level changes of the Black sea. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 711–730.

Benito, G., Macklin, M.G., Panin, A., Rossato, S., Fontana, A., Jones, A.F., Machado, M.J., Matlakhova, E., Mozzi, P., Zielhofer, C., 2015. Recurring flood distribution patterns related to short-term Holocene climatic variability. Sci. Rep. 5, 16398. https://doi.org/10.1038/srep16398.

Berger, A., 1988. Milankovitch theory and climate. Rev. Geophys. 26, 624–657.

Bezrodnykh, Yu P., Romanyuk, B.F., Sorokin, V.M., Yanina, T.A., 2017. First data on the radiocarbon age of the atelian deposits in the north Caspian region. Dokl. Earth Sci. 473 (1), 278–281. https://doi.org/10.1134/S1028334X17030217.

Borisova, O., Sidorchuk, A., Panin, A., 2006. Palaeohydrology of the Seim River basin, Mid-Russian Upland, based on palaeochannel morphology and palynological data. Catena 66 (1–2), 53–73.

Brückner, H., Kelterbaum, D., Marunchak, O., Porotov, A., Vött, A., 2010. The Holocene sea level story since 7500 calBP e lessons from the Eastern Mediterranean, the Black and the Azov Seas. Quat. Int. 225 (2), 160–179.

Buyukmeriç, Y., 2016. Postglacial floodings of the Marmara Sea: molluscs and sediments tell the story. Geo-Marine Lett. 36, 307–321. https://doi.org/10.1007/s00367-016-0446-6.

Chepalyga, A.L., 2007. The late glacial great flood in the ponto-Caspian basin. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, N.P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 119–148.

Chepalyga, A.L., 2002. The Black sea. In: Velichko, A.A. (Ed.), Dynamics of Terrestrial Landscape Components and Inner Marine Basins of Northern Eurasia during the Last 130,000 Years. GEOS, Moscow, pp. 453–481 (in Russian).

Esin, N.I., 2014. The Black Sea Level Dynamics during Last 20 ka cal BP. PhD thesis. P.P. Shirshov Institute of Oceanology (Southern Branch), Gelendgik (in Russian).

Esin, N.V., Esin, N.I., 2014. Mathematical modeling of Black Sea level change for the last 20000 years. Quat. Int. 345, 32–47.

Feller, W., 1968. An Introduction to Probability Theory and its Applications. Wiley, Boston.

Filipova-Marinova, M., 2007. Archaeological and Palaeontological evidence of climate dynamics, sea-level change, and coastline migration in the Bulgarian sector of the Circum-Pontic region. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 453–481.

Frolov, A.V., 2011. Discrete dynamic-stochastic model of long-term river runoff variations. Water Resour. 38, 583–592.

Glebov, A.Yu, Shel'ting, S.K., 2007. Sea-level changes and coastline migrations in the Russian sector of the Black Sea: application to the Noah's Flood hypothesis. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 731–773.

Georgievski, G., Stanev, E.V., 2006. Paleoevolution of the Black Sea watershed: sea level and water transport through the Bosporus Straits as an indicator of the Lateglacial–Holocene transition. Clim. Dyn. 26, 631–644.

Golitsyn, G.S., Ratkovich, D., Fortus, M., Frolov, A.V., 1998. Current rise of the Caspian sea level. Water Resour. 25, 133–139.

Grosswald, M.G., 1998. New approach to the ice age paleohydrology of northern Eurasia. In: Benito, G., Baker, V.R., Gregory, K.J. (Eds.), Paleohydrology and Environmental Change. John Wiley & Sons, Chichester and New York, pp. 199–214.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Kaminski, M., Abrajano, T., Yaşar, D., Rochon, A., 2007. The Marmara sea gateway since ~16 ky BP: non-catastrophic causes of paleoceanographic events in the Black sea at 8.4 and 7.15 ky BP. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 89–117.

Ivanov, V.A., Belokopytov, V.N., 2011. Oceanography of the Black Sea. Marine Hydrophysical Institute, Sevastopol (in Russian).

Izmailov, Y.A., 2005. Evolutionary Geography of the Coastal Area of the Black Sea and the Sea of Azov. Lazarevskaya Polygraph, Sochi (in Russian).

Kerey, I.E., Meriç, E., Tunoğlu, C., Kelling, G., Brenner, R.L., Doğan, A.U., 2004. Black sea–marmara sea quaternary connections: new data from the Bosphorus, Istanbul, Turkey. Palaeogeogr. Palaeoclimatol. Palaeoecol. 204, 277–295.

Kislov, A., 2016a. The interpretation of secular Caspian Sea level records during the Holocene. Quat. Int. 409 (Part A), 39–43.

Kislov, A., 2016b. On the interpretation of century-millennium-scale variations of the Black Sea level during the first quarter of the Holocene. Quat. Int. https://doi.org/10.1016/j.quaint.2016.09.008.

Kislov, A., Toropov, P., 2007. Climate modeling results for the Circum-Pontic region from the late Pleistocene to the mid-Holocene. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 47–62.

Kislov, A., Toropov, P., 2011. Modeling extreme Black Sea and Caspian Sea levels of the past 21,000 years with general circulation models. In: Buynevich, I.V., Yanko-Hombach, V., Gilbert, A.S., Martin, R.E. (Eds.), Geology and Geoarchaeology of the Black Sea Region: beyond the Flood Hypothesis, vol. 473. Geological Society of America Special Paper, pp. 27–32.

Kislov, A.V., Panin, A., Toropov, P., 2014. Current status and palaeostages of the Caspian Sea as a potential evaluation tool for climate model simulations. Quat. Int. 345, 48–55.

Konikov, E., 2007. Sea-level fluctuations and coastline migration in the northwestern Black Sea area over the last 18 ky based on high resolution lithological-genetic analysis of sediment architecture. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 405–435.

Konikov, E., Ivanova, S., Vinogradova, E., Kiosak, D., Govedarica, B., 2010. The role of the liman-baymouth complexes in human settlement in the Eneolithic to Bronze Age. In: Gilbert, A., Yanko-Hombach, V. (Eds.), Extended Abstracts of IGCP 521-INQUA 501 Sixth Plenary Meeting and Field Trip, «Black Sea -Mediterranean Corridor during the Last 30 Ky: Sea Level Change and Human Adaptation», pp. 101–103. Rhodes, Greece.

Kvasov, D.D., 1979. The Late Quaternary history of large lakes and inland seas of Eastern Europe. Ann. Acad. Sci. Fenn. Ser. A III, 127. Helsinki.

Lericolais, G., Guichard, F., Morigi, C., Minereau, A., Popescu, I., Radan, S., 2010. A post Younger Dryas Black Sea regression identified from sequence stratigraphy correlated to core analysis and dating. Quat. Int. 225, 199–209.

Lu, J.M., Kim, S.J., Abe-Ouchi, A., Yu, Y.Q., Ohgaito, R., 2010. Arctic oscillation during the mid-Holocene and last glacial maximum from PMIP2 coupled model simulations. J. Clim. 23, 3792–3813.

Lunkka, J.P., Saarnisto, M., Gey, V., Demidov, I., Kiseleva, V., 2001. Extent and age of the last glacial maximum in the southeastern sector of the Scandinavian ice sheet. Glob. Planet. Change 31 (1–4), 407–425.

Maev, E.G., 1994. Regressions of the Caspian Sea (there position in the Caspian Quaternary and role in the bottom relief formation). Geomorphology 4, 94–101 (in Russian).

Martin, R.E., Yanko-Hombach, V., 2011. Repeated freshwater discharge events stimulated rapid sea-level change in the Black Sea during the Holocene. GSA Special Paper 473. In: Buynevich, I., Yanko-Hombach, V., Gilbert, A., Martin, R. (Eds.), Geology and Geoarchaeology of the Black Sea Region: beyond the Flood Hypothesis, pp. 51–58. Colorado, USA.

Mauri, A., Davis, B.A.S., Collins, P.M., Kaplan, J.O., 2014. The influence of atmospheric circulation on the mid-Holocene climate of Europe: a data-model comparison. Clim. Past 10 (5), 1925–1938.

Ozsoy, E., Unluata, U., 1998. The Black Sea. In: Robinson, A., Brink, K. (Eds.), The Sea, vol. 11. Wiley, New York, pp. 889–914.

Panin, A., Adamiec, G., Buylaert, Jan-Pieter, Matlakhova, E., Moska, P., Novenko, E., 2017. Two Late Pleistocene climate-driven incision/aggradation rhythms in the middle Dnieper River basin, west-central Russian Plain. Quat. Sci. Rev. 166, 266–288.

Panin, A., Matlakhova, E., 2015. Fluvial chronology in the East European plain over the last 20 ka and its palaeohydrological implications. Catena 130, 46–61.

Peltier, W.R., 1994. Ice age paleotopography. Science 265, 195–201.

Rimbu, N., Dima, M., Lohmann, G., Stefan, S., 2004a. Impacts of the North Atlantic oscillation and the el nino-southern oscillation on Danube River flow variability. Geophys. Res. Lett. 31 (23), L23203.

Rimbu, N., Lohmann, G., Lorenz, S.J., Kim, J.H., Schneider, R.R., 2004b. Holocene climate variability as derived from alkenone sea surface temperature and coupled ocean-atmosphere model experiments. Clim. Dyn. 23, 215–227.

Ryan, W.B.F., 2007. Status of the Black sea flood hypothesis. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, P.M. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate and Human Settlement. Springer, Dordrecht, pp. 63–88.

Sidorchuk, A., Panin, A.V., Borisova, O., 2009. Morphology of river channels and surface runoff in the Volga River basin (East European plain) during the late glacial period. Geomorphology 113, 137–157.

Sima, A., Kageyama, M., Rousseau, D.-D., Ramstein, G., Balkanski, Y., Antoine, P., Hatt, C., 2013. Modeling dust emission response to North Atlantic millennial-scale climate variations from the perspective of East European MIS 3 loess deposits. Clim. Past 9, 1385–1402.

Sokolov, A.A., 1952. Hydrography of the USSR. Hydrometeoizdat, Leningrad (In Russian).

Stanev, E.V., Peneva, E.L., 2002. Regional sea level response to global climatic change: Black Sea examples. Glob. Planet. Changes 32, 33–47.

Starkel, L., Michczynska, D.J., Gebica, P., Kiss, T., Panin, A., Persoiu, I., 2015. Climatic fluctuations reflected in the evolution of fluvial systems of Central-Eastern Europe (60-8 ka cal BP). Quat. Int. 388, 97–118.

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F., Stein, R., 2004. Late Quaternary ice sheet history of Northern Eurasia. Quat. Sci. Rev. 23 (11–13), 1229–1271.

Thom, N., 2010. A hydrological model of the Black and Caspian seas in the late Pleistocene and early-middle Holocene. Quat. Sci. Rev. 29, 2989–2995.

Tudryn, A., Leroy, S.A.G., Toucanne, S., Gibert-Brunet, G., Tucholka, P., Lavrushin, Y.A., Dufaure, O., Miska, S., Bayon, G., 2016. The Ponto-Caspian basin as a final trap for southeastern Scandinavian ice-Sheet meltwater. Quat. Sci. Rev. 148, 29–43.

Varushenko, S.I., Varushenko, A.N., Klige, R.K., Leont'ev, O.K., 1987. Changes in the Regime of the Caspian Sea and Closed Basins in Paleotime. Nauka, Moscow, p. 239 (in Russian).

Velichko, A.A., 2009. Paleoclimates and Paleoenvironments of Extra-tropical Area of the Northern Hemisphere. Late Pleistocene – Holocene. Atlas-monograph. GEOS, Moscow, p. 120, 24 maps.

Yanina, T.A., 2012. Correlation of the late Pleistocene paleogeographical events of the Caspian sea and Russian plain. Quat. Int. 271, 120–129.

Yanina, T.A., 2014. The Ponto-Caspian region: environmental consequences of climate change during the late Pleistocene. Quat. Int. 345, 88–99.

Yanko, V.V., 1990. Stratigraphy and paleogeography of marine Pleistocene and Holocene deposits of the southern seas of the USSR. Mem. Della Soc. Geol. Ital. 44, 167–187.

Yanko-Hombach, V., 2007. Controversy over Noah's Flood in the Black Sea: geological and foraminiferal evidence from the shelf. In: Yanko-Hombach, V., Gilbert, A.S., Panin, N., Dolukhanov, N.P. (Eds.), The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Springer, Dordrecht, pp. 149–204.

Yanko-Hombach, V., Mudie, P.J., Kadurin, S., Larchenkov, E., 2014. Holocene marine transgression in the Black sea: new evidence from the northwestern Black sea shelf. Quat. Int. 345, 100–118.

Yanko-Hombach, V., Mudie, P., Gilbert, A.S., 2011. Was the Black Sea catastrophically flooded during the post-glacial? Geological evidence and archaeological impacts. In: Benjamin, J., Bonsall, C., Pickard, C., Fischer, A. (Eds.), Underwater Archaeology and the Submerged Prehistory of Europe. Oxbow Books, pp. 245–262.

Yanko-Hombach, V., Schnyukov, E., Pasynkov, A., Sorokin, V., Kuprin, P., Maslakov, N., Motnenko, I., Smyntyna, O., 2017. Late pleistocene-Holocene environmental factors defining the azov-Black sea basin, and the identification of potential sample areas for seabed prehistoric site prospecting and landscape exploration on the Black Sea Continental shelf. In: Flemming, N., Harff, J., Moura, D. (Eds.), Quaternary Palaeoenvironments of the European Continental Shelf: Environments for Occupation and Conditions for Survival or Destruction of Submerged Prehistoric Deposits. Wiley-Blackwell, Chichester, UK, pp. 431–478.

Please cite this article in press as: Yanko-Hombach, V., Kislov, A., Late Pleistocene – Holocene sea-level dynamics in the Caspian and Black Seas: Data synthesis and Paradoxical interpretations, Quaternary International (2017), https://doi.org/10.1016/j.quaint.2017.11.030