Quaternary International 409 (2016) 39–43

Contents lists available at ScienceDirect

Quaternary International

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

The interpretation of secular Caspian Sea level records during the Holocene

A.V. Kislov

Lomonosov Moscow State University, Faculty of Geography, Department of Meteorology and Climatology, Lenin Gory 1, 119991 Moscow, Russia

ARTICLE INFO

Article history:
Available online 30 July 2015

Keywords:
Caspian Sea
Regional climate change
Paleodata
Model of random walk

ABSTRACT

The Caspian Sea (CS) experienced significant changes during the Holocene. The standard deviation for Caspian Sea level (CSL) variations over that interval is estimated as $\sigma = 1.4$ m. Based on well-established views, they were climate-induced variations. There are no clear links with the calendar of climatic anomalies, and climate models do not reproduce the changes. Therefore, the question about the origin of "secular" CSL fluctuations remains open. Based on general ideas about the laws of temporal dynamics relating to massive inertial objects, the observed slow changes of the CSL under the semi-steady climate state of the Holocene can be represented as resulting from the accumulation of small anomalies in the water regime, as a kind of "self-developing" system. To test this hypothesis, the model of the water balance of the CS was used. Time scale for the sea fluctuations was estimated as ~20 years. This model is interpreted as stochastic, and from this perspective, it is a Langevin equation that incorporates the action of precipitation and evaporation as random white noise, so that the whole can be thought of as an analogue of Brownian motion. Under these conditions, the CS is represented by a system undergoing random walk. Modeling results are interpreted from the probabilistic point of view, although the model is deterministically based on the physical law of conservation of water mass. The results showed that the CSL fluctuations under steady state conditions are characterized by $\sigma = 1.1$ m, close to the empirical value. "Super-large" anomalies in CSL are not prohibited by the theory, but their development requires a correspondingly long time. However, during long periods of time, background conditions change, and uniformity of the Brownian process becomes disrupted. The origin of large transgressive/regressive stages can be different. For example, the low stand of the Enotaevkian Regression during the LGM was determined by a significant reduction in precipitation over the Volga River catchment and by a corresponding reduction in the volume of river runoff. Hence, based on modeling results, the possibility of "self-development" effects is not prohibited by the theory: there need not be any cause for specific level changes or shifts, merely the expected behavior of red noise processes.

1. Introduction

The Caspian Sea (CS) (36–47° N, 47–54° E) is a closed basin. Its sea level lies below the mean sea level of the ocean and has varied between −25 and −29 m in the last ~100 years of recorded history. Water level fluctuations have occurred 100 times faster in comparison to global sea level changes over the last century.

The main water source is the Volga River (a total of 80% of river inflow to the CS comes from the Volga River), whose catchment area covers a large part of the Eastern European Plain (EEP). The water inflow is offset by evaporation over the CS. Other rivers, such as the Ural, Kura, Terek, and Sefidrud, and the subsurface runoff into the sea have to be considered as well, but their contributions are significantly less, uncoordinated and irregular. The water budget of the CS and the current Caspian Sea Level (CSL) variability have been investigated in many studies, e.g., Golitsyn and Panin (1989), Rodionov (1994), Golitsyn et al. (1998), Arpe et al. (2000, 2012) and Arpe and Leroy (2007).

Precise reconstructions and dating have demonstrated that during the Holocene, the CS fluctuated between regressive and transgressive stages (Rychagov, 1997). The variations were climate-induced. These significant secular-scale changes took place although only subtle changes were observed in external climate forcings (solar insolation change has been slow and gradual, and the amplitude of CO_2 variation was small). Although the CS lies in

---

E-mail address: avkislov@mail.ru.

http://dx.doi.org/10.1016/j.quaint.2015.07.026
1040-6182/

an area of tectonic activity (Allen et al., 2004), tectonic impacts on sea-level changes do not have to be taken into account for the post-Last Glacial Maximum (LGM) timeframe. No tectonic deformations of the Holocene shorelines have been detected, and only low-degree deformations of the Khvalynian (the end of the Late Pleistocene) shorelines have been detected (Rychagov, 1997).

The question of the origin of the fluctuations remains open because there are no clear stable links of the CSL anomalies and palaeohydrological phases with the calendar of climatic anomalies. Correspondence of river runoff changes (on the bases of fluvial activity) to the Caspian Sea level changes was unstable during the Holocene: it was rather high in the second part of the Holocene and was poor before 4–5 ka BP (Panin and Matlakhova, 2015). Climate models (CMIP3 and CMIP5) do not reproduce the needed changes of precipitation, evaporation, and river runoff (Kislov et al., 2014).

It is hypothesized that observed anomalies of the CSL, under assumption of a quasi-steady state Holocene climate, are derived from accumulation of small water budget anomalies of opposite signs. Their residual effect forms the CSL response, much like a random walk. Although this assumption cannot be precisely proven, it is possible to determine whether it contradicts the results of observations.

2. Caspian Sea level changes: probability distribution function and Langevin equation

The Holocene (11.7 ka) was a stage of Earth history in which the global climate and the environment were characterized by a quasi-steady state (compared with the post-LGM timeframe) with gradual long-term trends. Despite this relative stability, the CSL has experienced significant secular-scale and decadal-scale changes during the Holocene (Fig. 1). At each hierarchical level, the dynamic of the CS is characterized by complex oscillations, and its amplitude increases with decreasing frequency.

The probability distribution function (pdf) of the CSL variations, calculated on the basis of instrumental records (~100 years), is a bimodal curve (Naidenov, 1992). However, it is reasonable that this assessment is incorrect because there is strong correlation seen in annually averaged data of the CSL. At 1 year time lag, the autocorrelation coefficient r_1 ~0.95, and autocorrelation disappears only after ~20 years, i.e., r_{20} ~0 (Nikolaenko, 1997). This means that the 100-year series is equivalent to approximately five independent values (see Fortus (1998) for strong statistical conclusion). Hence, this amount of data is too small for statistical calculation (e.g., for accurate calculation of the pdf).

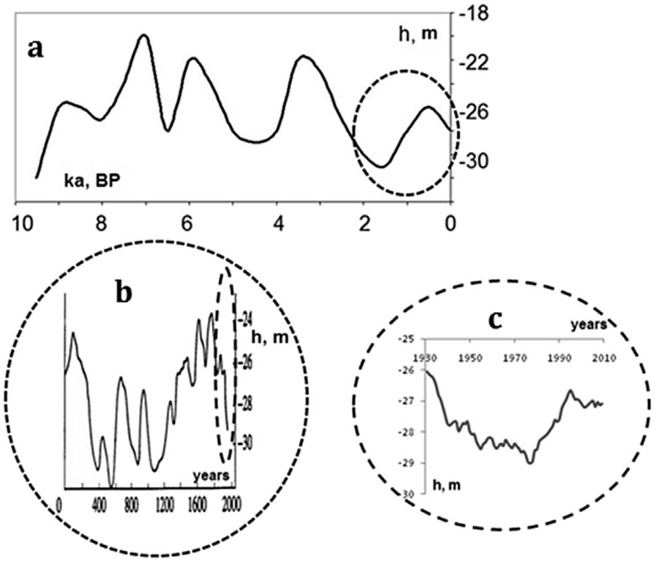

Fig. 1. The Caspian Sea level changes during the Holocene (Based on: a – (Rychagov, 1997); b – (Hydrometeorology and Hydrochemistry of the Seas, 1992); c – http://www.oceanography.ru/index.php/ru/2010-03-15-15-57-22/2010-03-15-15-59-06).

Taking this fact into account, the last 2000-year series, consisting of a sequence of 20-year averaged quantities of reconstructed CSL data (Fig. 1b), was used to calculate the pdf. Of course, these data are not as accurate as measurements, but they are statistically independent variables. They characterize the climate of the Sub-Atlantic stage, during which the environmental–climatic regime did not experience significant changes. As for long-term changes taking place in the Holocene, this stage logically is named as “current climate”. It was shown (Kislov, 2011) that the pdf of the CSL can be represented by a Gaussian curve (statistical significance is 0.02 using the chi-squared test statistic); the mean CSL is −28 m, the standard deviation is 1.4 m.

Using a smooth curve (Fig. 1a) for the same time interval, we can calculate (using connection between amplitude of harmonic function and its variance) that the standard deviation is 1.6 m. However, Kroonenberg et al. (2008) reconstructed the drop of CSL to −42 m a.s.l. during the Derbentian Lowstand (~1000 years ago). Use of such data leads to standard deviation increases up to 5 m.

The main components of the CS water budget are the Volga River runoff and the evaporation minus precipitation (e) over the CS water surface. Analysis of time behaviour has shown that the variance of the Volga River runoff is substantially larger than the variance of e. Additionally, e fluctuates irregularly, whereas the Volga River runoff changes are characterized by long-term trends (Golitsyn and Panin, 1989). Decadal-scale Volga River runoff oscillations (reflecting the influence of precipitation and evaporation over the catchment, and soil water storage) are governed by atmospheric circulation changes. This has been demonstrated from data showing a well-established connection between the CSL changes and variations of circulation indices (dry-wet variations), as well as variations of the North Atlantic Oscillation index, the Wangenheim index, and the Southern Oscillation Index (Isaev et al., 1995; Arpe et al., 2000; Nesterov, 2001; Tugilkin et al., 2011).

Explanation of the origin of the secular-scale oscillations is difficult because there is no clear link between CSL changes and the calendar of climate anomalies despite the widely accepted theory that the changes were climatically induced (Kislov, 2001; Bolichovskaya, 2011; Svitoch, 2011; Sidorchuk et al., 2012; Panin and Matlakhova, 2015). Furthermore, climate models (in the framework of CMIP3 and CMIP5) do not simulate the required secular-scale changes of precipitation and river runoff volume (Kislov et al., 2014).

However, the origin of long-lasting CSL anomalies can be interpreted another way. The theory of Brownian motion argues that the multi-scale stochastic dynamic of a system is formed through interaction of its fast and slow components. Positive and negative fast anomalies do not cancel each other out and their residual effects accumulate slowly to form a large deviation from the initial state. However, negative feedbacks, which usually exist in the system, prohibit large deviations, and the steady state regime of slow chaotic oscillations is eventually realized. Hasselmann (1976) used this mechanism to describe and reproduce the stochastic behaviour of several geophysical processes.

The random time evolution of a Brownian particle position (one-dimensional) $h = h(t)$ approximately satisfies the Langevin equation:

$$\frac{dh}{dt} = -\lambda h(t) + \eta(t) \quad (1)$$