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Current status and palaeostages of the Caspian Sea as a potential evaluation tool for climate model simulations

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ABSTRACT

Decadal-scale oscillations of the level of the Caspian Sea (CS) primarily stem from variations in runoff from the Volga River. Therefore, although the image of the CS within the climate models is very simplified, changes in the level of the CS can be used to assess the ability of climate models to reproduce the water budget over the East European Plain. The proxy dataset comprises a number of detailed maps of the CS for the main regression stages and transgression stages during the last 30 ka together with information about sea-level positions. We compare observed or reconstructed CS level positions during the last millennium and modern periods with the CS level positions calculated based on simulations in experiments using the CMIP5/PMIP3 protocol. The modelled data could be verified based on how well the models simulate: a) the observed decadal-scale CS level dynamics during the twentieth century; and b) the Derbentian regression, transition to New-Caspian (5th phase) highstand and slight lowering of the CS level at the end of the nineteenth century.

1. Introduction

Evaluating the models used for prediction is important for identifying uncertainties in prediction and guiding priorities for model development. Traditionally, a set of benchmark tests for climate models are used that are based on time series observed during the last ~150 y. These tests are not completely adequate because these data are used to verify all units of climate models. From this perspective, climate models are implicitly tuned to the current climatic conditions. Therefore, developing an additional set of benchmark tests (independent of the current climate conditions) is very important. These tests could be developed using either palaeodata or meteorological information from other planets. The latter data are not suitable to the necessary extent, but the great success of palaeoenvironmental reconstructions has established a foundation for the use of these data for model validation. At the present time, several climate-simulation projects belonging to Coupled Model Intercomparison Project, Phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/), and Palaeoclimate Modelling Intercomparison Project, Phase 3 (http://pmip3.lsce.ipsl.fr/) (CMIP5/PMIP3) have been focused on such time periods as the last millennium, Mid-Holocene, and the Last Glacial Maximum (LGM). Temperature and precipitation values are commonly used for comparison.

The aim of this paper is to assess whether palaeostages of the Caspian Sea could be used as a set of benchmark tests designed to quantify the performance of the simulated water budget (the balance between inflow and outflow components) of the East European Plain (EEP). The tests are designed to estimate the ability of models to reproduce the observed regional-scale changes of water fluxes on different time scales (interannual, decadal, and centenarian) under the different boundary conditions and parameters of the Late Pleistocene, Holocene, and the Last Millennium. Water-budget changes over the EEP are reflected by the fluctuations of level and its area of the Caspian Sea (CS), which collects precipitation from the majority of the EEP.

Such tests are important for assessing model quality because model data are more reliable over vast flat territories compared to complex land surfaces (mountains, archipelagos of islands, etc.). From this perspective, models must first be validated over such “idealized” areas. In terms of sufficient size and flat topography, there are several such areas in mid-latitudes. These areas are the EEP, the Great Plains, the Western Siberia Plain, and Australian deserts. The EEP is the most convenient area for detecting the water-budget changes induced by climate forcing because most of the EEP area drains into a closed lake (the CS). Hence, the CS level change is the integral indicator of the water-budget conditions of

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the EEP. The huge size of the water body allows more convenient quantification of the changes compared with other lakes, such as Lake Chad.

Precise reconstructions and dating have demonstrated that during the Late Pleistocene and postglacial periods, the CS fluctuated between regression and transgression stages. Sometimes, the CS overflowed into the Black Sea, and these water bodies periodically coalesced. These events occurred in response to the regional-scale water-budget change. Variations of these components can be calculated using climate models. Therefore, we were able to use a model-data comparison to test simulated variations of the river runoff against reconstructed time-series of the CS level changes. The focus of this study is the assessment of how well CMIP5/PMIP3 climate models simulate the CS level changes during different conditions of the past and how a system of benchmark datasets can be based on such simulations.

2. The Caspian Sea, changes in its level and the connections of such changes to river-runoff fluctuations

The CS is situated in a semi-arid area between southern Russia, Kazakhstan, Turkmenistan, Iran, and Azerbaijan (36–47 °N, 47–54 °E). The CS is a closed basin without any outlet. The mean CS sea level lies approximately 27 m below the mean sea level of the oceans (−25 to −29 m during the last 150 y). The main water source of the CS is the Volga River, whose catchment area reaches well into the humid mid-latitudes. The water inflow is compensated by evaporation over the CS. The CS lies in an area of strong tectonic activity (Allen et al., 2004). However, for the post-LGM time, tectonic impacts on sea-level changes do not have to be taken into account because there have been no tectonic deformations of the Holocene shorelines, and only low-degree deformations of the Khvalynian (the end of the Late Pleistocene) shorelines have been detected (Rychagov, 1997a, 1997b).

The CS level has experienced appreciable fluctuations during the period of instrumental observations, with a fast drop of 1.7 m during the 1930s, a further 1.2 m drop in 1977 and then a significant rise of 2.5 m between 1978 and 1995 (Kaplin and Selivanov, 1995). This study helps to understand the important processes that lead to these changes in the CS level. An inspection of the annual water-balance equation for the CS can provide some clues:

$$\frac{dV}{dt} = Q_{in} - Q_{out}. \quad (1)$$

This equation denotes how the annual CS volume (V) increment is determined by the balance between inflow and outflow components. The Q_{in} is practically fully determined by the total river inflow because the contribution of the subsurface runoff into the sea is less than 10% (practically, only 1% (Panin et al., 2005)). A total of 80% of the river discharge comes from the Volga River (Q). Hence, we can consider $Q \approx kQ_{in}$, where $k = (1 - 0.1)\cdot 0.8 = 0.7$. Additionally, $Q_{out} = f_0(E - P)$, where P and E are the precipitation and evaporation per unit of sea surface, respectively, and f_0 is the average area of the sea corresponding to the current range of the level positions. Observations of the single components are as follows (Golitsyn and Panin, 1989): $Q_{in} \approx 75$ cm y^{-1} and $(E - P) \approx 75$ cm y^{-1}.

Over the long term, we can describe the relationship between the sea level and status of climate, assuming that the closed lake (sea) is in hydrologic equilibrium with the climate conditions. A steady-state approach ($Q_{in} = Q_{out}$) allows calculations of the changes of the sea surface area (and level changes taking into account the lake size, bathymetry and surrounding topography) in each climate time period based on links between variations in sea level and water-budget components. Fig. 1 depicts the connection of the CS level with annual values of river runoff and $(P - E)$ over the sea surface. Such an approach was used to assess the Caspian Sea (and Black Sea) level response to the large climate perturbations of the late Pleistocene and the mid-Holocene (Kislov and Toropov, 2006, 2011).

We consider a simplified model demonstrating that the decadal variations of the CS level are primarily balanced by the Volga River runoff changes. Taking into account small changes of V, we consider $V \approx f_0 dh$, $dh \approx h - h_0$. The annual CS volume increment is the residual of mainly two large quantities, river runoff (practically, the Volga River runoff) and E, while the remainder is small compared to these two large quantities but is comparable to the increment itself.

An analysis of the time series of the observed data shows that the Q_{out} has changed randomly (Mikhailov and Povalishnikova, 1998). The standard deviation (std, in units of m y^{-1}) of the runoff fluctuations (0.16) is much greater than the std of the Q_{out} fluctuations (0.08) (Golitsyn et al., 1998). We can connect the average values of Q_{out} and the average runoff of the Volga River as follows: $Q_{out} = \mu Q_0$, where $\mu \approx 1/k$; otherwise, the Q has to be considerably different from the Q_0. Thus, the simplified form of the budget equation is as follows:

$$\frac{dh}{dt} = \frac{\mu Q_0}{f_0}\frac{(Q - Q_0)}{Q_0} \quad (2)$$

Hence,

$$\int_{h_0}^{h} dh \propto \int_{0}^{t} \frac{Q - Q_0}{Q_0} dt \quad (3)$$

Using interannual level changes and annually averaged values of the runoff, we calculate for modern conditions ($Q_0 \approx 274$ km^3/y and $f_0 = 0.366\cdot 10^6$ km^2) that proportionality factor $\mu Q_0 / f_0 \equiv \gamma \sim 1$ m/y. If the CS level changed, γ did not significantly change because the Volga River discharge and area of the CS are synchronously varying.

We calculate the following relation:

$$h_i - h_0 \propto \sum_i \frac{Q_i - Q_0}{Q_0}. \quad (4)$$

Therefore, the level change depends on the accumulated departures. This so-called "cumulative curve" depends on the period from which the mean value is calculated.

In Fig. 2, the cumulative curve of the Volga River runoff is shown together with the CS level changes. High correlations (unusually

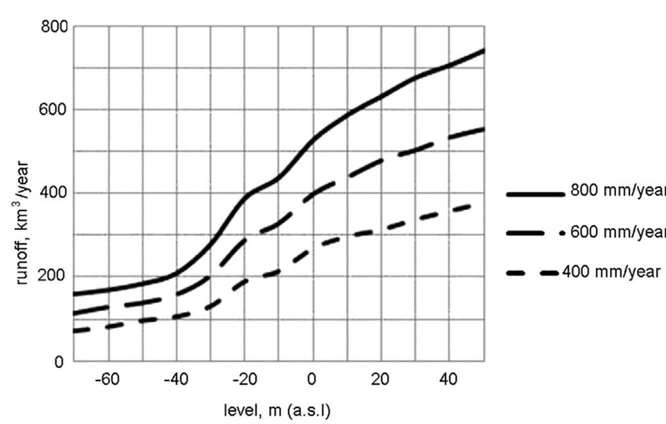

Fig. 1. The Caspian Sea level (steady-state condition) depending on the balance of "precipitation minus evaporation" over the sea surface (mm yr^{-1}) and runoff volume.