Paleo sea-level changes in the Black Caspian Seas: Links to river runoff and global climate change

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Introduction

To assess the link between climate variability and hydrological regime, we focused our study on the mid-Holocene (6 ka years BP) and the last cold period of the Late Quaternary (21 ka BP). We discuss how well current general circulation models (GCMs) can reproduce river runoff changes and, consequently, variations in closed lake level under contrasting climate conditions. The Paleoclimate Modeling Intercomparison Project (PMIP) (Joussaume and Taylor, 1995) has run simulations that are used in this study. The rivers of the East European Plane (EEP) were selected for analysis. Feed of rivers is determined by the balance of precipitation and evaporation in the catchment, hence river runoff change responds immediately to climate changes. It is important that both precipitation and evaporation are calculated by a GCM. Moreover, on large planes, such as the EEP, GCM data much better reflect the state of climate compared to areas with complex mosaic surface conditions. Additionally, large amounts of paleoclimate data exist on the EEP for selected periods of the past.

Modern GCM runs

Prior to investigating river runoff changes in the past, it is necessary to be convinced that GCMs are capable of simulating the modern climate state. It was shown that only large river catchments (covered by about 15 GCM cells with typical GCM horizontal resolution 2.5 x 2.5°) can be correctly analyzed and analyzing the smaller river basins is not meaningful. The runoff value is estimated in the framework of a GCM as the annual value P-E (precipitation minus evaporation). If the error of modeled runoff is ±20%, the result was considered to be "successful" because in this case deviation does not exceed observed natural variability. The data of these "successful" models were examined more closely by running simulations of other climate regimes. Validation can be done on the basis of comparison of modeled P-E with data of standard hydrological observation in river estuaries. The majority of models simulate runoff to the Baltic Sea well (Table 1), but only a few models are capable of reproducing runoff to the Black Sea and the Caspian Sea with good accuracy.

Fig. 1: Area of the Caspian Sea during the mid-Holocene/modern (blue color) and regression stage of the LGM evaluated based on the PMIP1 data (purple color).

The mid-Holocene

The mid-Holocene study within PMIP 1 focussed on the 6 ka BP climate. As a first approximation, SSTs were prescribed to be the same as today, the CO_2 concentration was similar to its pre-industrial value of 280 ppm, and vegetation and land-surface characteristics were held constant. Climate change is only influenced by the change of insolation forcing.

Calculations indicate that at 6 ka BP there is no significant change of the EEP river runoff (see Table 2). The Volga River contribution to the total volume of water running to the Caspian Sea slightly increases (93%) compared to today's climate (88% according to PMIP 1 model simulations and 84% based on observation). In spite of the slight reaction of river runoff to external orbital forcing, it is unexpected that the Caspian Sea level was not stable during the Holocene. The amplitude of sea-level perturbations was several meters (Varushenko et al, 1987).

The LGM

The time slice at 21 ka BP, as an example of the last glacial maximum (LGM), involves large changes in the surface boundary conditions: ice sheet extent and height, changes in SSTs, albedo, sea level and concentration of greenhouse gases and aerosols, but only minor changes in solar radiation at the top of the atmosphere. Here we look at the results of calculation of annual river runoff volumes for the Caspian and Black Seas. The regions of the modern Baltic Sea and Arctic seas were strongly perturbed during the LGM, and are therefore not included in this study.

At 21 ka BP, the total river runoff to the Caspian Sea (calculated by "successful" models) was substantially decreased (~50%) compared to today's climate (see Table 3). The relative contribution of Volga River runoff is 72%. These facts are in accordance with the observational data (Varushenko et al, 1987).

Implications for sea level

Information about river runoff change also provides a useful guide for conclusions about the status of the Caspian Black Seas. According to the definition of the water budget for closed lakes, the steady-state equation of the annual water budget is:

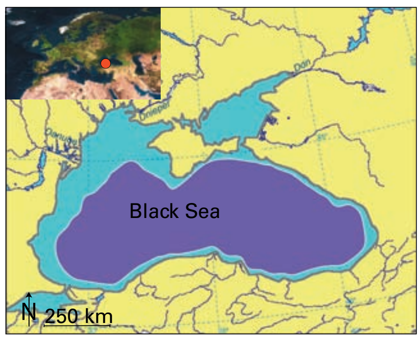

Fig. 2: Area of the Black Sea during the mid-Holocene/modern (blue color) and regression stage of the LGM evaluated based on the PMIP1 data (purple color).

Table 1: Today's annual volume of the EEP river runoff (km³) into different ocean basins, simulated by the PMIP1 GCMs.

GCM	BASINS							
	Black Sea		Caspian Sea		European Arctic seas		Baltic Sea	
	runoff, km^3	error[1]	runoff, km^3	error	runoff, km^3	error	runoff, km^3	error
BM RC	6,0	-98	68,0	-75	174,2	-62	377,0	-20
CCC2	182,7	-41	242,6	-11	440,6	-3	518,9	10
CCM3	358,2	9	308,7	13	422,5	-7	535,6	14
CCSR	341,7	15	195,5	-29	307,2	-32	491,1	4
CNRM1	262,1	-16	191,8	-30	407,4	-10	568,6	21
CSIRO	251,2	-20	209,5	-24	272,8	-40	372,7	-21
ECHAM3	161,1	-48	173,6	-37	462,7	2	488,7	4
GEN2	225,2	-27	94,5	-66	222,4	-51	402,9	-14
GFDL	238,8	-23	44,3	-84	250,6	-45	416,4	-12
GISS	41,3	-87	94,5	-66	277,2	-39	308,1	-35
LMD5	653,3	109	187,9	-31	201,6	-55	330,2	-30
MRI2	233, 1	-25	132,8	-52	308	-32	425,4	-10
UGAMP	335,1	7	229,3	-16	407,5	-10	450,1	-4
UKMO	303,8	-3	138,1	-50	339,6	-25	496,3	5
UIUC	515,9	65	141,6	-48	251,8	-44	434,0	-8
YONU	566,5	82	211,8	-23	262,3	-42	414,8	-12
ENS[2]	292,3	-6	166,5	-39	313	-31	439,4	-7
SUCS[3]	308,7	-1	260,2	-5	428,1	-5	454,3	-3
Obs[4]	312	-	274	-	453	-	470,6	-

[1]Relative error (%); [2]ENS: Ensemble mean of GCMs data; [3]SUCS: Ensemble mean of successful GCM data (selected in Table 1); [4]Obs: Mean of observational data

$$ef = YF \quad (1)$$

where F, f, e, and Y stand for the catchment area, lake area, difference (E-P) over the lake area, and the river runoff from the catchment into the lake, respectively. Variation of the lake area relative to the present status (denoted by index '0') may be expressed by:

$$\frac{\Delta f}{f_0} = \frac{\Delta Y}{Y_0} + \frac{\Delta F}{F_0} - \frac{\Delta e}{e_0} \quad (2)$$

It allows us to evaluate the contribution of different factors to change of the level (h) as:

$$\Delta h = (\Delta h)_Y + (\Delta h)_F + (\Delta h)_e \quad (3)$$

It is supposed (based on geomorphological evidences) that the configuration of the catchment area of the rivers was principally unchanged at 21 ka BP, therefore the second term in the Eq. (3) is equal to zero. Value over the Caspian Sea was estimated (based on regional climate modeling (Kislov and Surkova, 1997)) to be small relative to the first term in Eq. (2). Calculations indicate that a decrease of the river runoff causes a substantial drop in the Caspian Sea level (~50 m) (see Fig. 1). The calculated river runoff for the Black Sea is also substantially decreased (~50%) (see Table 3). This fact, coupled with the assumption that due to decreasing sea level the Black Sea was a closed lake at 21 ka BP, allows us to estimate that the drop in level was approx. 200 m (Fig. 2).

Conclusions

GCMs are able to correctly reproduce elements of the hydrological cycle (precipitation, evaporation and runoff) for large rivers under different climatic situations. The differences in hydrological mode of the rivers of the EEP between 6000 years BP and today are small. This fact corresponds to results of paleohydrological reconstructions and is particularly interesting from the point of view that the warm mid-Holocene is often considered to be an analog of expected future climate warming conditions.

The results of modeling have shown that during the LGM, the runoff of the EEP rivers was considerably decreased (~50 %) and provided strong regression of the Caspian and Black Seas. Comparing our modeling results with geological evidence, we suppose that simulated conditions reflect the so-called Atelskay regression stage of the Caspian Sea and the so-called Postkarangatskay regression stage of the Black Sea (Varushenko et al, 1987; Svitoch, 2003). This lends credit to the idea of the connection between Late Quaternary glacial/cooling/drying planetary events and deep regression states of the Caspian Sea and the Black Sea.

Table 3: Annual volume at 21 ka BP of the EEP river runoff (km³) into different ocean basins, simulated by the ensemble and the "successful" PMIP1 models

basins / GCMs	Black Sea		Caspian Sea	
	runoff, km^3	deviation[1]	runoff, km^3	deviation[1]
ENS	232	-22	115	-39
SUCS	171	-45	83	-56

For definitions, see Table 1; [1]Relative deviation from today's value (%)

Table 2: Annual volume at 6 ka BP of the EEP river runoff (km³) into the different basins

basins / GCMs	Black Sea		Caspian Sea		European Arctic seas		Baltic Sea	
	runoff, km^3	deviation[1]	runoff, km^3	deviation	runoff, km^3	deviation	runoff, km^3	deviation
BMRC	337	>1000	385,2	466	564,5	224	695,1	>l000
CCC2	181,7	-1	260,9	8	425,7	-3	494,1	-5
CCM3	375,2	5	356,1	15	419,1	-1	517,5	-3
CCSR	304,2	-11	166	-15	311,7	1	442,2	-10
CNRM1	185,8	-29	153,9	-20	404,9	-1	580,4	2
CSIRO	30,5	-88	60,8	-71	217,5	-20	303,3	-19
ECHAM 3	101,3	-37	138,3	-20	445,8	-4	501,0	3
GEN2	250,2	11	88,4	-6	193,9	-13	365,6	-9
GFDL	236,2	-1	46,6	5	249,8	0	446,7	7
GISS	14,5	-65	115,5	22	315,3	14	279,9	-9
LMD5	1088,4	67	414,8	121	315,3	56	652,4	98
MRI2	239,2	3	112,7	-15	238,5	-23	408,7	-4
UGAMP	327,5	-2	221,8	-3	322,8	-21	371,5	-17
UKMO	335,7	11	146,5	6	293,7	-14	405,8	-18
UIUC	521,2	1	156,4	10	232,8	-8	390,1	-10
YONU	575,7	2	209,1	-1	258	-2	412,4	-1
ENS	319	9	189,6	14	326	4	454,2	3
SUCS	305,7	-5	262	5	403,7	-6	432,3	-7

For definitions, see Table 1. [1]Relative deviation from today's value (%)

Acknowledgments

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