THE CASPIAN SEA LEVEL FORCED BY THE ATMOSPHERIC CIRCULATION, AS OBSERVED AND MODELLED

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Abstract

The Caspian Sea Level (CSL) has experienced large fluctuations with wide reaching impacts on the population on the coastal regions and on the economy. The CSL variability is dominated by the variability of precipitation over the Volga River basin. The precipitation during summer plays a dominant role and can explain the two major events that happened in the 1930s (drop) and after 1977 (rise). Impacts are expected from global warming due to enhanced greenhouse gas concentrations; especially the precipitation over the Volga River basin is expected to increase. It is, however, compensated more or less by increased evaporation over the Caspian Sea itself. It is shown that the Max-Planck Institute for Meteorology (Hamburg) models are able to simulate most processes relevant for the CSL variability quite realistically, i.e. within the uncertainty of observational data. The simulations suggest a slight increase of the CSL in the 21st century; but due to a large variability of precipitation over the Volga River basin a statement concerning the future development of the CSL cannot be made with confidence at the moment.

Keywords: Caspian Sea Level, Sea Level variability, model simulations, global warming

1. Introduction

The Caspian Sea (CS) is situated in a semi-arid area between southern Russia, Kazakhstan, Turkmenistan, Iran and Azerbaijan (36°-47°N, 47°-54°E). It is a closed basin without any outlet. Its sea level lies about 26 m below the mean sea level of the oceans (-25 to -29 m during the last 150 years). Its main water source is the Volga River whose catchment area reaches well into the humid mid-latitudes. The water inflow is compensated by evaporation over the CS itself. At the eastern coast there is a shallow gulf, the Kara-Bogaz Gol, that covers only 3 % of the total area of the CS but evaporates about 5 % of its total.

The CS lies in an area of strong tectonic activity mostly a strike slip movement, but with a rise of land on its southern coast and a subsidence in the south basin (Allen et al., 2004). Such impacts can, however, be neglected for the investigated period of 200 years.

The Caspian Sea Level (CSL) has experienced wide fluctuations during geological and historical times (Kazanci et al., 2004, Leroy et al., 2006). These changes may be very rapid (13 cm per year between 1977 and 1995), and have a drastic impact on the economies of the 5 countries surrounding the CS. The impact may reach even much wider areas as oil and gas exploitation is directly affected by both the rise and the drop of sea level. Scientists have tried to find out how much of such fluctuations are initiated locally, i.e. within the catchment area of the CS, and what are the possible forcings outside this area. Recently the impact of increased concentrations of greenhouse gases on temperature and precipitation has been added to the possible sources for the fluctuation of the CSL. Investigating the external forcings is the topic of the present study. In case of significant external forcings there is some hope that the variability of the CSL can be predicted. Section 2 gives an overview about observational findings, including a connection between the CSL variability and ENSO (El Niño/Southern Oscillation) shown by Arpe et al. (2000).

The focus of this study is the search for an impact of global warming on the CSL. Recently scenario simulations have been carried out at the Max Planck Institute for Meteorology (MPI) with the ECHAM5 atmospheric model coupled with ocean, lake, ice and soil models which are used for this study. Roeckner et al. (2003, 2006) give a comprehensive description of these models that are shortly introduced in section 3. In section 4, the global aspect of global warming is shown on precipitation and heat flux. Its impact on the CSL is investigated in section 5. Further discussion on these topics in sections 6 and 7 deal with the validation of the simulations for the 20th century. This provides some ideas about their realism. Important for the evaporation over the sea is the Sea Surface Temperature (SST), generated by a coupled atmosphere-lake model, which is evaluated in section 7. By integrating the precipitation minus evaporation (P-E) in time one gets the CSL variability during the centuries (section 8). This leads to the conclusions in section 9.

2. Caspian Sea Level variability in the 20th century

The CSL has undergone during the 20th century an enormous variability with a fast drop of 1.7 m during the 1930s, a further drop until AD 1977 by another 1.2 m and then a significant rise of 2.5 m from 1978 to 1995 (Fig. 1). Between 1995 and 2001, a drop of the CSL can also be seen. This study helps to understand the important processes which lead to these changes in the CSL. An inspection of the annual water balance equation for the CS can give some clues:

CSLinc=R+P+S-E-KBG

CSLinc is the annual CSL increment, R the total river inflow, P the precipitation over the sea, S the subsurface runoff into the sea, E the evaporation, and KBG the water discharge into the Kara-Bogaz Gol where the water is eventually evaporated. The CSLinc is the residual of mainly two large quantities, R and E, while the remainder is small compared to these two large quantities but comparable to the CSLinc itself. Estimates of the single components (units: cm/year change of CSL) are as follows (Golitsyn and Panin, 1989):

R= 77, E-P=76, S=1, KBG=4, and under stationary conditions the CSLinc needs to be small when averaged over a longer period. However the CSL is never stationary and therefore the balance is not complete in this equation with the given data. 80% of the river discharge (R) is coming from the Volga River. This river and the precipitation over its catchment will be one of the main points for the following investigations.

By comparing the time variability of CSLinc and the Volga River discharge one can see that the CSL variability can mainly be assigned to a variability of the Volga River discharge, which results from the variability of the precipitation over its catchment area (e.g. Arpe et al., 2000). Rodionov (1994) gives a detailed overview. In Figure 1, the effect of precipitation over the Volga River basin, and thus of the Volga discharge, is shown by integrating the precipitation anomalies over its catchment area from AD 1900 onward, using an initial value of

-26 m and applying a factor which is the ratio between the Volga catchment area and the area of the CS.

Anomalies are used here to compensate for the evaporation that is an unknown quantity. Because anomalies are integrated, the calculated CSL is forced to return to its initial values at the end of the integration. This depends of course also on the period, on which the mean is calculated. The period 1935-1995, i.e. a period when the CSL had the same level at the beginning and the end, has been tried as well but the difference was very small to the one shown. Therefore the whole period for performing the calculation for the anomalies was used.

The CSL calculated from the annual mean precipitation is following the observed CSL, especially it reproduces the strong drop in the 1930s and the increase after 1977. However, there is a shift from 1950 onward, which can be assigned to the filling of water reserves along the newly built dams along the Volga as already shown by Rodionov (1994); it leads to a loss of water for the CS due to filling of the reservoirs, irrigation and enhanced evaporation over larger open water. It is interesting to note that the ~~small~~ drop of the CSL after 1995 cannot be explained by the precipitation over the Volga river catchment.

The variability of evaporation (LHFX - latent heat flux) was not needed above to explain most of the CSL variability and is therefore less important for this. Correlating the summer precipitation over the Volga River with the MSLP or upper air height field at each grid point shows that precipitation maxima are connected with large-scale low pressure over the same area which reaches south to the CS. Low pressure normally goes hand in hand not only with enhanced precipitation but also with enhanced cloudiness which would suggest also less solar radiation reaching the ground leading to less evaporation not only over the Volga river but also over the CS. This agrees with investigations by Sidorenkov and Shveikina (2006) who assigned CSL changes to synoptic features. The data to our disposal are not accurate enough to show this but it is assumed that decreased evaporation contributed to the rise after 1977 though the increase of precipitation is sufficient to explain the increase, as shown in Figure 1.

Figure 1 further shows the individual contributions from the four seasons. Here it is the summer precipitation, which has the closest similarity with the annual mean curve, not only because of the decrease in the 1930s and increase after 1977 but also in the year-by-year variability. The DJF (December-January-February) variability has still some similarities while the spring variability is even negatively correlated.

Already Arpe et al. (2000) looked for global phenomena that might have affected the precipitation over the Volga River basin using several widely used indices, e.g. the North Atlantic Oscillation and ENSO. The only stable connections that have been found are with ENSO that, for most of the world, has its peak impact in northern winter and spring and less in summer. Perhaps the largest global-scale variability in summer is that connected to the Indian summer monsoon but a connection with the CSL variability could not be found.

3. Methods

It has been an important task to combine observational data to create a consistent gridded data set, and here it is the precipitation which is of special interest. The impact of different use and interpretation of observational precipitation data can be investigated by comparing CRU analyses (Climate Research Unit in East Anglia, UK) (Mitchell et al., 2004) with those by the Global Precipitation Climate Project (GPCP) (Huffman et al., 1996). GPCP corrects the observations for the blowing off of precipitation out of the gauge by wind, which is especially effective with snow and can result in differences of 50 % (Sevruk, 1982). Another difference is that the GPCP uses on top of the conventional gauge observations also estimates made from satellite observations. This is restricting the latter data set to the more recent period but provides also estimates over oceans and lakes. These differences lead to a 20% higher annual mean precipitation in the GPCP analysis over the Volga. Because of the longer time series the CRU data set is used but its possibly too low values have to be kept in mind.

The present study is using recent scenario simulations with the ECHAM5 atmospheric model coupled with ocean, lake, ice, snow and soil models. Roeckner et al. (2003, 2006) give a comprehensive description of these models. These runs were forced with increasing greenhouse gas concentrations as observed for the 20th century and predicted by IPCC SRES scenario A1B for the 21st century (Special Report on Emissions Scenarios; Nakicenovic et al., 2000). The changes in aerosols are prescribed but two-way interactions are not considered in the experiments discussed in this study. Before the scenario simulation could be started, the coupled system had to run for a couple of hundred years until a quasi steady state without any trends has been reached. Then it was run a few hundred of years further and the results had to be studied to see if the model is producing weather and climate data that are realistic. The model was restarted from 3 different randomly chosen initial atmospheric and oceanic data sets for January and these initial data sets were assigned the date 1 January 1870. The models were run without any external varying forcing, except an increasing concentration of greenhouse gases and aerosols from 1870 onward. The initial data sets do not have any information on the true atmosphere from 1 January 1870, because they are not available. Three experiments have been carried out. Below they will be called X1, X2 and X3. At least three experiments have been used because one would like to get some statistical information about the internal variability of the model and to find out if possible trends are independent of the initial data.

4. Global warming - global impacts

Quite a few simulations using different models forced with increasing greenhouse gas concentrations - as observed up to the present and estimated for the future - have been carried out and all show an increase of atmospheric and oceanic temperatures. As for many other scenario simulations, ~~also~~ the present one shows an increase of global 2 m (above ground) temperatures (T2m) of about 4°C until 2100. If one uses only land points for calculating the global mean, the increase is even reaching 5°C in annual means and 6°C for the northern hemisphere in winter. With increased air temperatures, the atmosphere is able to carry more water vapour and increased greenhouse gas concentration forces a shift of energy transport between the surface (especially the ocean) and the atmosphere from radiative transfer to evaporation. Accordingly one finds as well an increase of precipitation. This increase is larger over the oceans probably due to the unlimited availability of water for evaporation at the surface.

The geographical distributions of T2m and precipitation trends develop, however, quite differently. The T2m increases more uniformly all over the world with a clear land-sea contrast of 1-2°C higher values over land. The patterns of precipitation changes are much more structured. In DJF one finds a strong increase of precipitation north of about 45°N and south of 50°S and in a belt around the equator while over the subtropical belts the precipitation decreases. This nonlinear impact on the precipitation is illustrated in Figure 2, showing the latitudinal variability of zonal and annual means of T2m, precipitation, evaporation (LHFX) and precipitation minus evaporation (P-E). This nonlinearity is anti-social, i.e. areas that already have a lot of precipitation get even more while areas with insufficient precipitation get less. This applies also for P-E because the LHFX increases more uniformly like the T2m. P-E is the water that is available for life and which leads over continents to river discharge. It is therefore the most important quantity in our further discussion.

The increase of precipitation with global warming in equatorial areas can be explained by the ability of a warmer atmosphere to carry more water vapour and a shift of energy transport from radiative transfer to evaporation. Increased precipitation near the equator releases more latent heat that is warming the atmosphere and enhances the updraft leading to a further enhancement of precipitation, a positive feedback. In the 21st century the Hadley circulation will increase with enhanced Trade Winds in the lower troposphere, its counter flow in the upper troposphere around 200 hPa, an updraft in connection with more precipitation near the equator and an enhancement of the downdraft at around 30°N and 30°S. This is connected also with an enhanced Ferrel cell in mid-latitudes. Enhanced downdraft means less precipitation as shown in Figure 2.

This general impact of increased greenhouse gas concentration applies as well for the CS area because the CS lies in the down draft area. Figure 3 shows annual mean maps of changes in 100 years (2070-2099 minus 1961-1990) of precipitation, LHFX, P-E and cloudiness over the area of interest. Precipitation increases north of 50°N and decreases south of it to the border of the map (at least to 20°N). Over land the LHFX shows the same patterns as for precipitation, i.e. where there is more water available in the ground due to enhanced precipitation more water can be evaporated and vice versa.

Over the Mediterranean, Black and Caspian Sea, one finds a clear increase of LHFX, independent of the precipitation changes because of unlimited water availability. In the area of downdraft the air becomes drier and that favours more evaporation. More LHFX requires for compensation more energy input at the sea surface. This results from the fact that downdraft reduces cloudiness as well, which leads to less reflection of solar radiation. Therefore more solar energy reaches the ground/sea-surface that is then available for enhanced evaporation. From the panel showing P-E (Fig. 3), one can see that a future climate would have enhanced Volga River discharge (positive numbers at 50°-60°N) and enhanced loss of water over the CS itself (negative numbers south of 50°N) that is shown explicitly below.

Generally the warming of the oceans in a future climate is relatively uniform; however, a closer inspection reveals that the eastern equatorial Pacific is warmed up more than the western Pacific, 2021-2050 by 0.3°C and 2070-2099 by 0.5°C, i.e. a warming pattern similar to El Niño events (see also van Oldenborgh et al., 2005). Accordingly one can find world-wide impacts on several quantities that are typical for El

Niño events. Especially an increase of the CSL can be expected, as discussed by Arpe et al. (2000). It is worth mentioning that the El Niño type pattern does not result from one more or less El Niño event within the investigated periods of 30 years, it results more from a steady differential increase of SSTs during the 21st century.

5. Global warming - impacts on the Caspian Sea

If one takes the data of scenario simulations with growing greenhouse gas concentrations, one can easily calculate the future development of the CSL though the interpretation might be a problem. Figure 4 shows time series of P-E for the Volga, all rivers of the CS basin and all rivers plus the CS for the scenario runs. P-E for the Volga and all rivers is eventually resulting in a river discharge into the CS and further together with P-E over the CS itself into CSL changes if a long-term average is investigated. Here a 9 year running mean is shown. The river discharge of the Volga River will clearly increase during the 21st century due to enhanced precipitation as expected from the discussion above. In the units given here, all rivers provide lower values than the Volga alone; but the amount of water delivered to the CS is of course larger by all rivers because of the larger catchment area. For the whole CS catchment, this is at least partly compensated by increased evaporation over the sea and reduced precipitation over the sea and the more southerly rivers. Integrating this curve in time, as will be shown below explicitly, results in nearly constant CSL except some large decadal variabilities.

An immediate question is, if one can rely on these results. We are looking here at model results and it is well known that models are not perfect. A known deficiency refers to the lake model, which is the same for all lakes on continents, which does not consider salinity, thermocline and depth of the lakes. The model addresses the anthropogenic influences only from the point of greenhouse gases; but also important for the CS and the rivers is irrigation that is extracting water from the rivers and might result in a water deficit that is not accounted for in these simulations. Moreover the dam building had an impact on the hydrological cycle. In addition there is a negative feed back in reality, which is not yet modelled, i.e. with reduced river-flow into the CS its level will drop and consequently its area will shrink and hence the evaporation will decrease. A further feedback not yet included is a possible higher efficiency of plants in their photosynthesis with increased CO_2 that might reduce the evapo-transpiration (Gedney et al., 2006). To address the question of realism of the simulations, we will look at different processes that are important for the CS and investigate if the model is representing them well and if possible deficiencies might influence the conclusions.

6. Validation of the Volga River discharge

The only good observational data for validating the model results are precipitation over the Volga River basin, its discharge into the CS and the CSL measurements. The variability of P-E for the whole CS catchment area is dominated by the Volga River (Fig. 4). This agrees with what was already found for observations by many authors, e.g. Arpe et al. (2000) as discussed above. In Ffigure 5, we compare the precipitation over the Volga River catchment as analysed from observations (CRU) with that from the three scenario runs (X1, X2, X3). The error margin of precipitation analysis is very large - GPCP values are 20% higher than CRU, of which the reasons have been given above. The values of the simulations exceed the analysed ones generally by less than 10%. This means that the model is able to reproduce the amount of precipitation quite well within the margin of uncertainty. Important for the discussion below is the difference in variability between analysis and simulations. In the simulations, there are two events of multi-decadal variations of 10 mm/month while in the observations only a maximum of 5 mm/month is reached. This can also be found when comparing P-E and the observed river discharge. The time series of observations are too short to make a statement about its statistical significance.

If one compares P-E in the simulations over the Volga catchment area with the observed river discharge one gets a confirmation of the above findings: The converted river discharge as observed (Dümenil et al., 2000)in P-E units is 147 mm/month while the model gives 157 mm/month for the same time period, i.e. the values of the simulations exceed the observed ones by less than 7% as found above for the precipitation.

7. Evaporation from the Caspian Sea

The inflow from the Volga River into the CS is compensated in long-term means approximately by the evaporation on the surface of the sea (including the Kara-Bogaz Gol). In Figure 4 it was clear that P-E averaged over the whole CS catchment including the sea is very small compared to the river discharge, although there are no constrains in this respect in the model. This balance is astonishingly well fulfilled by the model, which is an improvement with respect to older models. The averages for the two centuries are -0.05 and 0.20 mm/month respectively. These numbers are small compared to the decadal variability but a 0.2 mm/month increase means a 2 m increase of CSL over a 100 year period as will be shown below.

The evaporation itself cannot be validated because there are no observational data available. One important component for calculating the evaporation is the SST and because of the rather simple lake model used in the simulations it is worth looking into this.

We have investigated the annual cycle of the SST of the CS for two extreme grid points, one in the north where the sea is quite shallow (5m on average), and one in the south where the sea is very deep (on average 400 m). The annual cycle of the SST is generally well simulated for the present. Over the northern grid point where the sea is quite shallow the model produces for the present a too weak annual cycle with 1.5°C too low SSTs in summer and allows too little ice building in winter. This can be expected from a lake model that assumes a deeper lake than in reality. In the south the annual cycle is only slightly too weak (0.7°C too low summer and 0.5°C too high winter values, i.e. within the margin of observational accuracy of SST). In reality the sea at the southern point is much deeper than in the model and one might have expected the model to produce a too large annual cycle. However, the real sea develops a thermocline (20-30 m) by which the vertical exchange is inhibited or at least hampered and one has a much smaller effective depth (Tsuang et al., 2001). Model experiments have shown that temperature differences of up to 1.5°C are not important for the evaporation and the water balance of the CS and that the general circulation of the atmosphere is not significantly affected (Tsuang et al., 2001). So we assume that the SST of the CS is simulated well enough for our purposes.

8. Summing up P-E to calculate the CSL variation

The ultimate aim of the present study is the simulation of the variation of the CSL that can be calculated by integrating P-E in the scenario runs in time. Figure 6 displays the results from the three single scenario runs, their average and the observed CSL values. One finds inter-decadal variabilities in the mean simulations that are comparable to the real variability range (upper panel). In fact the similarity between the observations and mean simulation is extremely good. The only forcing which might have led to an initial drop of CSL during the first half of the 20th century is the increase of aerosols. If one examines the single simulations in the lower panel one finds a much longer, perhaps a centennial variability already in the 20th century. This has to be seen in connection with the very large variability of precipitation over the Volga River, which was already discussed above. The fact that the variability in the single scenario runs has nothing in common, except its amplitude, is not surprising, as there is no common forcing for timing events except the increase of greenhouse gases and aerosols. Also the initial data for the three runs were randomly chosen.

Already when discussing P-E over the whole CS catchment area, it was mentioned that the average of the three simulations shows a slight increase for the 21st century which would lead to an increase of the CSL. However, from Ffigure 6 it can safely be concluded that this increase is not statistically significant because of the large variability between the single runs and adding another simulation run for creating an average might give quite different values.

Elguindi and Giorgi (2006) have used the same model data and included the same mean over the CS plus river catchments in their figure 3, but the results are quite different from those shown here. They calculated from the same input data a strong decrease of the CSL. The two results are different because of problems with the numerics in their calculations as documented in their Table 3. They give a precipitation value of 18.6 cm/yr change of CSL and an evaporation value of 16.0 cm/yr. The difference P-E, if calculated from these numbers, is +2.6 cm/yr change of CSL, i.e. a small increase for the 21st century similar to that in the present study (2m in 100 years), but in their Table 3 P-E is given as -9.2 cm/yr, i.e. a strong decrease of CSL as in their figure 3.

From what has been said above, drastic changes as in the 1930s and 1970/80s might reoccur in the 21st century. This statement could have been made safely without carrying out such scenario simulations. In this study a slight increase of the CSL for 21st century has been demonstrated but it was shown as well that this statement cannot be made with confidence.

9. Conclusions

It has been shown that the precipitation during the summer plays a dominant role for the variability of the CSL and that it can explain the two main events that happened in the 1930s and after 1977. Although ENSO has its largest signal in the northern hemisphere winter, it remains the only forcing which can explain the CSL variability.

The most recent MPI coupled atmosphere-ocean model can reproduce features relevant for the CSL variability quite realistically. They are among others:
a) The CSL is dominated by the Volga River discharge.
b) The simulated and observed mean Volga River discharges agree well.
c) Long-term means of P-E over the whole CS catchment including the sea are small compared to the precipitation over the Volga River and the evaporation over the CS.
d) The annual cycle of the SST of the CS is generally well simulated.

The variability of the Volga River precipitation and discharge in the simulations is very large. This is not understood and we even do not know if it is a model deficiency or if it might happen also in reality. It prevents us making a statement concerning the impact of the global warming on the CSL with confidence. A larger ensemble of scenario runs could remedy this problem, if the large multi-decadal variability of precipitation is a random model error. The fact that the simulated variability for the 20th century is so realistically simulated suggests that already the mean of three experiments may be useful also for the 21st century.

Although our results remain statistically insignificant, it is nevertheless important to present them. Our research indeed summarises the present state of our knowledge. It is therefore hoped that our publication will stimulate further research in this field as it is crucial to be able to make some prediction regarding the CSL in order to improve preparedness in a region of rapidly developing demography and economy.

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References

Allen, A., Jackson J., Walker, R., 2004. Late Cenozoic reorganisation of the Arabia-Eurasia collision and the comparison of the short-term and long-term deformation rates. Tectonics 23, TC2008, doi: 10.1029/2003TC001530.
Arpe, K., Bengtsson, L., Golitsyn, G.S., Mokhov, I.I., Semenov, V.A., Sporyshev, P.V., 2000. Connection between Caspian Sea level variability and ENSO. Geophysical Research Letters, 27: 2693-2696.
Cazenave, A., Bonnefond, K., Dominh, K., Schaeffer, P., 1997. Caspian Sea Level from Topex-Poseidon altimetry: Level now falling. Geophysical Research Letters, 24: 881-884.
Dümenil Gates L., Hagemann, S., Golz, C., 2000. Observed historical discharge data from major rivers for climate model validation. Max Planck Institute for Meteorology, Hamburg, Report no. 307, 93 pp.
Elguindi, N., Giorgi, F., 2006. Projected changes in the Caspian Sea level for the 21st century based on the latest AOGCM simulations. Geophysical Research Letters, 33,

Gedney, N.,P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, P.A. Stott, 2006. Detection of a direct carbon dioxide effect in continental river run_off records. Nature 439, 835-838
Golitsyn, G.S., 1995. The Caspian Sea Level as a problem of diagnosis and prognosis of the regional climate change. Izvestiya. Atmospheric and Oceanic Physics. Engl Transl., 31: 366-372.
Golitsyn, G.S., Panin, G.N., 1989. The water balance and modern variations of the level of the Caspian Sea. Soviet Meteorololgy and Hydrology, English Translation, 1: 46-52.
Huffman, G.J., Adler, R.F., Arkin, P.A., Chang, A., Ferraro, R., Gruber, A., Janowiak, J., Joyce, R.J., McNab, A., Rudolf, B., Schneider, U., Xie, P., 1996. The Global Precipitation Climatology Project (GPCP) combined precipitation data set. Bulletin of the American Meteorological Society, 78: 5-20
Kazanci N., Gulbabazadeh T., Leroy S., Ileri O., 2004. Sedimentary and environmental characteristics of the Gilan-Mazenderan plain, northern Iran: influence of long- and short-term Caspian water level fluctuations on geomorphology. Journal of Marine Systems 46, 1-4: 145-168.
Leroy S., Marret F., Giralt S., Bulatov S. A., 2006. Natural and anthropogenic rapid changes in the Kara-Bogaz Gol over the last two centuries by palynological analyses. Quaternary International, in press.
Mitchell, T.D., Carter, T.R., Jones, P.D., Hulme, M., New, M. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901-2000) and 16 scenarios (2001-2100). Tyndall Working Paper 55, Tyndall Centre, UAE Norwich,UK. http://www.tyndall.ac.uk
Nakicenovich, N., and Coauthors, 2000. IPCC Special Report on Emission Scenarios. Cambridge University Press, Cambridge, UK, 599pp.
Rayner, N.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C., Kaplan, A., 2003. Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century, Journal of Geophysical Research, 108, (D14),4407,doi:10.1029/2002JD002670.
Rodionov, S.N., 1994. Global and regional climate interaction: the Caspian Sea experience, 241 pp., Kluwer Academic Publications, Dordrecht, The Netherlands.
Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., Tompkins, A., 2003. The atmospheric general circulation model ECHAM5, Part I: Model description. Max_-Planck Institute for Meteorology, Hamburg, Report no. 349.
Impact of Carbonaceous aerosol forcing on regional climate change. Journal of Climate Dynamics, doi:10.1007/s00382-006-0147-3.
Sevruk, B, 1982. Methods of correction for systematic error in point precipitation measurement for operational use. Operational Hydrology Rep. 21, World Meteorological Organization, Geneva, 91p.
Sidorenkov, N., Shveikina, V., 2006. Changes in the climate regime on the Caspian Seaa regions over the past century. http://balwois.mpl.ird.fr/balwois/administration/full_paper/ffp-539.pdf
Tsuang, B-J, Tu, C-Y, Arpe, K., 2001. Lake parameterization for climate models. Max Planck Institute for Meteorology Report No. 316, 72pp.
van Oldenborgh, G.J., Philip, S.Y., Collins, M., 2005. El Niño in a changing climate: a multi-model study. Ocean Science, 1, 81-95.

Figure captions:

Fig. 1: Caspian Sea Level (CSL) during the 20th century as observed and estimated from the observed precipitation anomalies over the Volga river catchment. Contributions from annual (year) and seasonal (spring, summer, fall and winter) mean precipitation are shown separately.

Fig. 2: Latitudinal variability of zonal mean 2 m temperature (T2m), precipitation, evaporation (LHFX) and P-E. Simulated values for the present (1960-1991, now) are compared with values in 60 years (2021-2050, +60) and in 100 years (2070-2099, +100).

Fig. 3: Change of annual mean precipitation, LHFX, P-E and cloudiness in 100 years time (2070-2099 minus 1961-1990). Contours for precipitation, LHFX and P-E at +/- 2,5,10,15,20,25 mm/month and shading for > 2 and < -2 mm/month. Contours for cloudiness at +/- 1,2,4,6,8,10 % and shading for > 2% and < -2 %. Negative contours are dashed.

Fig. 4: P-E in the scenario simulations averaged for the area of:
Volg: Volga catchment basin
allR: all rivers discharging into the Caspian Sea
R+Ca: all rivers discharging into the Caspian Sea plus the Caspian Sea.
A smoothing over 9 years has been applied and the values from three experiments are averaged.

Fig. 5: Annual mean precipitation over the Volga catchment area in the 20th century as observed (analysed by CRU) or simulated (X1, X2, X3). A smoothing over 9 years has been applied

Fig. 6: CSL as observed and simulated.
Upper panel: Observation and mean of three scenario simulations.
Lower panel: Three single scenario experiments.