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Journal of Marine Systems xx (2004) xxx–xxx

JOURNAL OF MARINE SYSTEMS

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The recent evolution of the Aral Sea level and water properties: analysis of satellite, gauge and hydrometeorological data

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Received 7 May 2003; accepted 31 December 2003

Abstract

The recent drop of sea level in the Aral Sea of about 0.6 m year^{-1} during the last 40 years represents one of the most dramatic example globally about the possible consequences of man-induced environmental changes. This extremely strong signal, as well as the constantly changing hydrological and meteorological fluxes in this area are missing from the seaborne observations in the 1990s because the observational network developed by the Former Soviet Union has almost not been operating during one decade in the new independent states. Fortunately, the Aral Sea level has been regularly monitored from space, in particular by satellite altimetry. In this study, we present observations of the Aral Sea level and analyze the observed trends and shorter term variability based on TOPEX/Poseidon altimeter data. This data set (available since early 1993) is complemented by hydrometeorological data and gauge data (since 1950) allowing to quantify the evolving water balance of the Aral Sea. It is shown that even though the river runoff almost ceased recently, the rapid drawing of the Aral Sea is substantially reduced by the compensating discharge of ground water. The analysis of the available data makes it possible to address the changing salt balance and to identify the major control on this balance exerted by ground water discharge. The major event of ground water discharge is identified in the period 1993–1994 and resulted in a substantial increase of the salt content. The rapid drop of salt content thereafter could indicate an increase of salt precipitation.

Keywords: Sea level; Ground water discharge; Aral Sea desertification

1. Introduction

The Aral Sea, located in Central Asia, is a completely enclosed sea (lake) with a large inland catchment area, the water coming basically from two big rivers—Amu Darya and Syr Darya. Most of the surrounding land is desert thus the sea and the two rivers are the only water sources providing moisture to the atmosphere. The constantly increasing agricultural activity since 1950s has lead to overconsumption of water from the two rivers, thus the river runoff reaching the sea decreased dramatically. Consequently, the Aral Sea level has dropped of ∼20 m,

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doi:10.1016/j.jmarsys.2003.12.005

its surface area (Fig. 1) shrank from 70,000 to 25,000 km^2 and its salinity increased about four times (Micklin, 1988). These changes affected the pathways of moisture into the atmosphere and resulted in a dramatic change of the local climate (Small et al., 2001).

The desiccation of the Aral Sea is recognized as one the most acute environmental problems globally, which has been caused by man-induced changes in regional water balance. The great impact of the recent environmental changes on the population living in this part of the world explains the large scientific interest

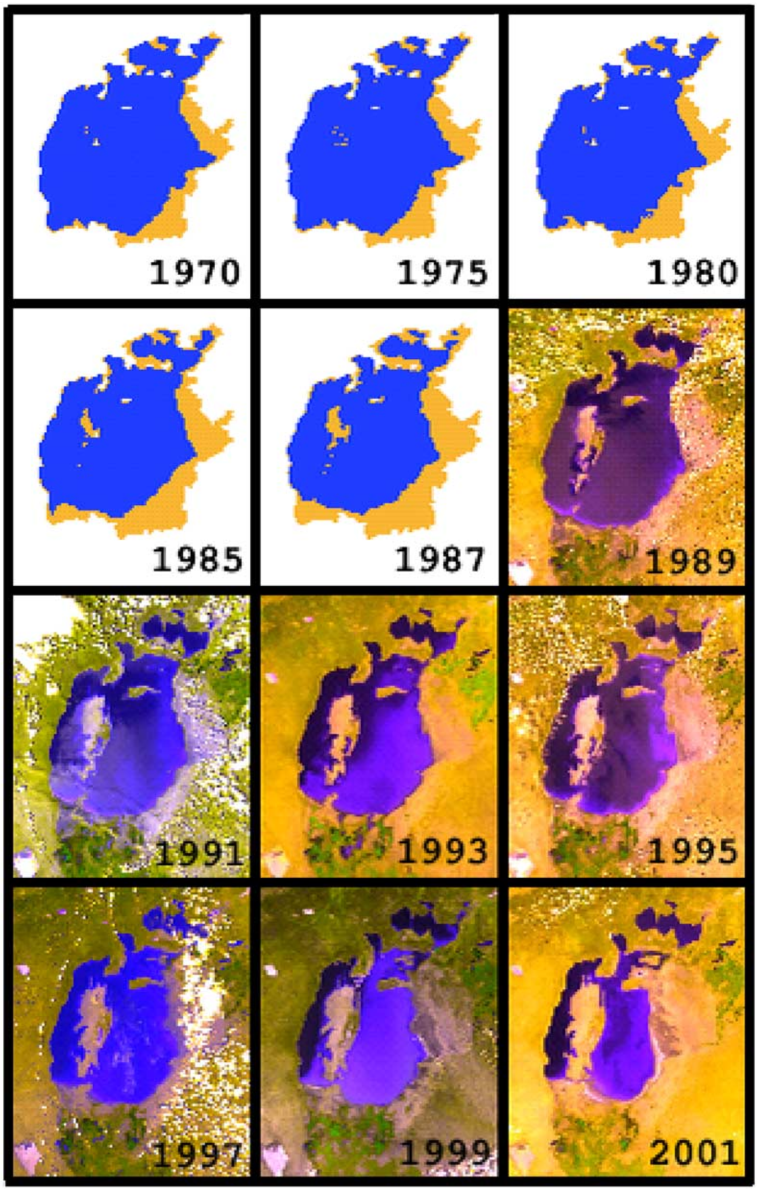

Fig. 1. The chronology of shrinking of the Aral Sea area in the recent decades. The coastline in the first five panels is calculated using bottom topography and sea-level data which are discussed further in the paper. The shoreline in the period after 1987 is derived from the NOAA satellite images in the visible range.

and the increasing number of international scientific projects focusing on various aspects of regional meteorology and hydrology (Glantz, 1995; Aladin and Williams, 1996; Micklin and Williams, 1996; see also the bibliography book of Kostianaya et al., 2002). The large regional changes, observed during the last 40 years are measurable with various observational techniques, providing an excellent opportunity to quantify the complex multiple interactions between atmosphere, land and lake, as well as the feedback between the anthropogenic impact and climatic response.

The Aral Sea has been formed during the Holocene, about 10 thousand years ago, and since then underwent number of transgressions and regressions. According to Bortnik (1996), the range of water level fluctuations in the Holocene exceeded 20 m. At the beginning of the period when continuous instrumental observations have been initiated (1911) the level of the lake was stable (~53 m above sea level) and remained so until 1960 (~53.4 m).

The decreasing depths in the last five decades resulted in constantly changing coastline. The water exchange between the northern and southern parts of Aral Sea through the Berg Strait was also continuously decreasing because of the shallowing of the strait. In order to maintain the level of the northern part of the sea stable, a dam has been built which additionally decreased the water supply to the southern part of the sea. In 1999 the dam has been destroyed by a storm, but nevertheless in 2000 the northern basin became a separate basin (Small Aral Sea, see Fig. 1) because of the too low sea level. This basin has a much smaller area than the southern basin, and the runoff of Syr Darya River is sufficient to keep its level stable. Nowadays, water from the Small Aral Sea is exported into the southern basin (called Big Aral Sea) either by ground waters or by sporadic discharges of surplus water under high water conditions. In this paper, most of the interest is focused on the evolution of Big Aral Sea, although some analyses (before the time of decoupling) are valid for the Small Aral Sea.

The hydrological situation in the Big Aral Sea is much less stable. Its eastern part is very shallow and acts as a huge evaporator. In 2000, the southern passage connecting the eastern and western parts of the Big Aral Sea also felt dry. From the sequence of satellite images in Fig. 1 and bottom topography (Fig. 2) one sees clearly that the northern passage will fall dry soon and then this sea will be decoupled into two separate basins.

What is clear nowadays is that the hydrological situation in this area is far from being steady (as this was the case before 1960) and thus a large number of processes associated with environmental transition in this region are mostly driven by the evolving water cycle. The observations carried out in the western basin in 2001 and 2002 by Friedrich and Oberhansli (2004), and Zavialov et al. (2003) give for the salinity of the western basin values between 85 and 95. These authors speculate (personal communication) that the salinity in the eastern basin may have reached already 160, a figure still to be confirmed by additional data.

It is not only the transition in the processes of exchange between land, sea and atmosphere, but also the critical (hypersaline) conditions which have a profound impact on the environment in this region. As known from the geological observations, this sea underwent extreme changes many times in its recent history leading to hypersalinity situation, which resulted in a pronounced salt precipitation on the

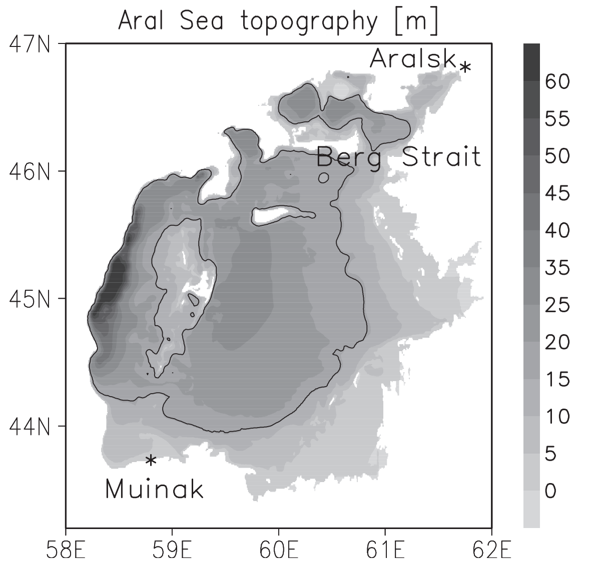

Fig. 2. Aral Sea bottom topography. The horizontal resolution is 0.5×1 km in longitudinal and latitudinal direction. The zero depth represents the coastal line in 1960. The contour 15.8 indicates the coastal line in 1993 when T/P observations have been initiated. The locations of Aralsk and Muinak meteorological station are shown with stars.

bottom. However, these changes have been driven by natural climate variability rather than by anthropogenic impacts. All this demonstrates that although the reasons for the recent deterioration of the Aral Sea's environment are clearly anthropogenic, climatic impacts are also very important, particularly when addressing longer time changes of its critical water balance.

At present, a number of research projects aim at developing analyses of the evolution of the regional climate, anthropogenic impact analysis (including regional atmospheric modelling), as well as analysis of the future evolution of the regional climate under different scenarios of water use. It is important to note that most of the models developed in the past gave (in their most pessimistic scenarios) more optimistic estimates for the present state of the dynamics of water level and salinity than what is observed nowadays. This is the major motivation to reconsider here again the water budgets of the Aral Sea.

In order to quantify and forecast the evolution of water balances, one needs reliable measurements of meteorological and hydrological characteristics both for identifying the trends, as well as a base for verification and validation of models. Unfortunately, systematic measurements in the Aral Sea region exist only with sparse coverage in time and space. The period of the 1990s is particularly poorly covered by observations because the ground-based measurements existing in the former Soviet Union were interrupted in the new independent states. The constant retreat of coasts makes the local sea-level measurements extremely difficult (most of old stations have fallen dry) and necessitates the establishment of new stations in this mostly unpopulated and desert area.

The available satellite data can provide an important substitute for the missing gauge observations in the 1990s. Recently, some encouraging reconstructions of the sea-level changes based on satellite images in the visible range have been provided (Ressl, 1996). The method uses accurate topography map and observed coastal line like the one shown in Fig. 1. These two-dimensional functions can be combined in order to obtain the actual sea level.

In the present paper, we use a more direct approach based on altimeter data obtained from the TOPEX/Poseidon (further in the text T/P) altimeter. T/P altimetry provides water level measurements with a few km along track resolution at 10-day interval (the duration of an orbital cycle). The reliability of this data in studying the small inland water bodies is addressed by Birkett (1995), Cazenave et al. (1997), Mercier et al. (2002), Maheu et al. (2003). For large enough inland water bodies, such as the Great Lakes in North America and the Caspian Sea on the border of Europe and Asia, comparison with in situ tide gauges indicates that the accuracy is quite satisfactory, better than 10 cm (rms 3–4 cm for 10-day averages). For smaller inland water bodies like rivers crossed by short T/P track segments (i.e. with few data points available) the accuracy—based on comparison with in situ hydrographic data—is less good, on the order of 20 cm (e.g. Maheu et al., 2003). In the case of the Aral Sea, with a rather favorable coverage of the T/P tracks (see Fig. 3), one can assume the former accuracy class. So far, the altimeter data for the Aral Sea have not been thoroughly analyzed, neither intercomparisons with gauge data have been carried out basically because of the difficulties in obtaining gauge measurements for verification.

The Aral Sea has most of the important characteristics of ocean basins, but also one major difference: it is completely enclosed. The components of water balance at sea surface include precipitation, evaporation and river runoff. We remind here that in desert areas precipitation is small and the major balance is between river runoff and evaporation. Thus knowing the above three components of water balance we can in principle compute the changes in sea volume, or sea level. Then the misfit between the computed and observed variations in sea-level height could be used to calibrate methods used to compute air–sea exchange (e.g. bulk aerodynamic formulae used to compute evaporation).

The above ideas sound less optimistic if one accounts for the new arising problems in the case of non-steady water balance. The first big problem is associated with the fact that the new (after 1960) river runoff is not well known. The observation stations, which still operate along rivers clearly demonstrate that the river runoff decreased dramatically. However, most of the water is lost in the sandy bed between the last operating river stations and the new (evolving) sea shore, that is before directly reaching the sea. The reconstruction of the present day river runoff is thus a

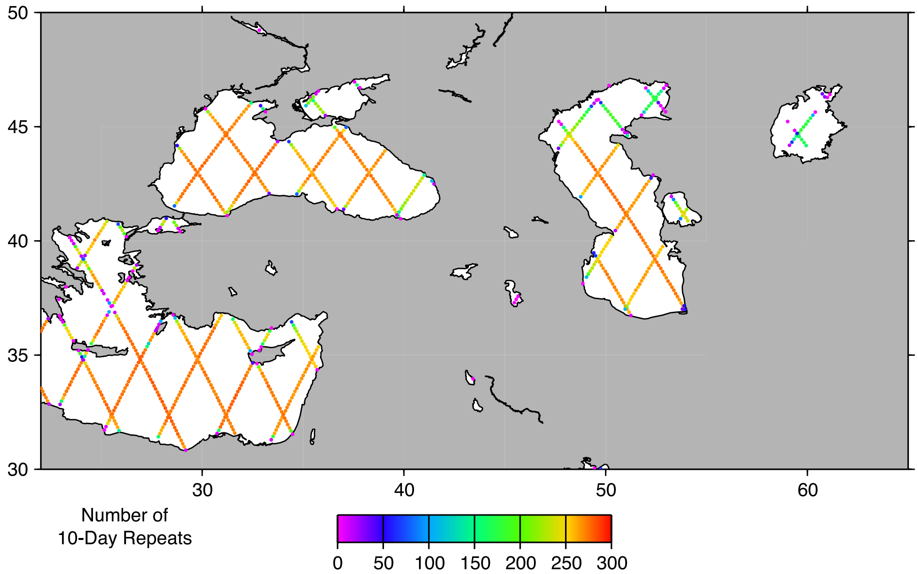

Fig. 3. T/P tracks over Eastern Mediterranean, Black, Caspian and Aral Sea. The small circles on the tracks give the positions of sampling, and the colors represent the number of measurements during the period 1993–2000. The figure was made available by Brian Beckley from GSFC.

difficult task (particularly if high accuracy data are needed).

We will demonstrate in this paper that, in this collapsing water system, another unknown term of the water balance becomes important, the ground water discharge. The latter increases constantly and partially compensates the effect resulting from the reduced river runoff. However, this variable is also not well known. The problems mentioned above make the estimates of water budget extremely difficult, but also demonstrate that we deal with an unique test area where we can investigate concepts of evolving water and salt balance provided measurable controls exist. The major (well known) control variables are thus sea level and salinity (the estimates for evaporation, as computed variable, are not perfect). This motivates us to address here the variability of Aral Sea hydrological system, using data from T/P altimeter and gauges, as well as salinity observations. The focus will be on seasonal and decadal variability of sea volume and salt content.

The paper is structured as follows: the changes in the Aral Sea level with short time variability are first discussed in Section 2, followed by the analysis of the observed trends after 1950s in Section 3, and finally brief Conclusions.

2. Aral sea level and volume during 1993–2001

2.1. Satellite observations

There are two sources of satellite data available, which can be used to compute the Aral Sea level and volume. The first data source is the T/P altimeter providing sampling along tracks over the Aral Sea with a time resolution of 10 days for the period 1992–2001. In contrast to larger seas, where the distance between T/P tracks enables resolving the spatial sea level variability (Le Traon and Gauzelin, 1997; Ducet et al., 1999; Stanev et al., 2000), the Aral Sea seems to be under sampled by T/P (Fig. 3), but this issue will be subject of a future study. Another serious data problem is that the amount of valid data is much smaller than in open ocean basins (at some points only half of the measurements are reliable). Several reasons may be invoked: the presence of sea ice in winter and the presence of an island in the middle of the sea (see also Fig. 1), approximately where the tracks cross, additionally biases the observations. The area of this island grows with time as a result of shrinking sea area, which further reduces the amount of data.

Selection of valid T/P data on water was performed using the topography. We systematically excluded data where the current depth was less than 5 m. By spatially averaging all valid data for each satellite orbital cycle we produce time series of the Aral mean sea level, with a temporal resolution of 10 days.

The second satellite data source which complements the T/P data in this paper comes from the NOAA satellite images in the visible spectral range (Fig. 1). The image in the eight panel is taken in the beginning of 1993 (the time when the T/P satellite measurements have been initiated) and its coastline compares with the isobath 15.8 m in the topography map (Fig. 2), the latter is based on measurements prior to 1960. The comparison between the coastal contour, as seen by NOAA satellite, and isobath 15.8 m (the sea level in 1993 was at −15.8 m) gives a proof that: (1) the satellite data resolve the process of shrinking of the sea, and (2) the relative depths have not changed from 1960 to 1993, and we assume further that the topography prior to 1960s is representative for the next five decades. Thus, coastal line contours have been identified from satellite maps and used further in combination with the topography map (Fig. 2) for estimating the corresponding sea level or basin volume.

Time series of the mean Aral Sea level with time resolution 10 days is plotted in Fig. 4 with the solid line. The annual mean values are plotted on the same figure with a dashed line. The total drop of sea level for the period 1993–2001 of ~4.5 m corresponds to 60 cm year^{-1}.

The T/P data resolve variations with seasonal and intra-annual time scales. The rms deviation due to the seasonal variability is ~5 cm month^{-1}, which is comparable to the trend in the sea level. The intra-seasonal fluctuations (with high amplitudes) seen on the sea level curve are most likely due to errors rather than real processes. An alternative explanation would suggest that a sudden change in the wind direction and magnitude could lead to accumulation of waters at some locations. This hypothesis has been checked using the National Center of Environmental Predictions (NCEP) reanalysis winds. Some of the spikes in the sea-level curve appear when strong northwesterly wind (magnitude ~10 m s^{-1}) dominates the atmospheric circulation. However, there are deviations from this "rule", which necessitate further analysis.

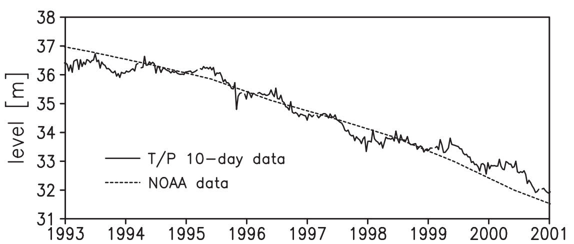

Fig. 4. Area mean Aral Sea level, calculated from T/P data. The solid line is plotted with 10 days time resolution. The estimates based on sea-level reconstruction from NOAA satellite images in the visible spectrum and bottom topography map (Fig. 3) are plotted with dotted line.

The dotted line in Fig. 4 represents the trend of sea level calculated independently from the coastline contours based on the NOAA-satellite data in the visible spectral range. Deviations between the two estimates of ~1 m are observed during some periods, in particular by the end of observations. This can result either from errors in observations or insufficient accuracy in topography (the latter is used to identify sea level from coastal contours). The corresponding errors could thus amount to ~20%, which proves that these data could give only a first order estimate of the Aral Sea's level drop in the last decade. However, in the absence of gauge data for the period 1993–2001 these coarse estimates are of particular value. In the following, we will base the analysis of water balance in the Aral sea on the T/P data because they are direct sea level measurements and their precision is expected to be as good as 10 cm for a 10-day average sea level determination.

2.2. Sea volume variability

In this section, we shall address the volume of the Big Aral Sea. This basin has been decoupled from the northern basin (Small Aral Sea) in 1988 and since then the sea level of the Small Aral Sea is stable. As we already demonstrated, this is not the case in the Big Aral Sea, and in the following we analyze its properties referring for brevity to it as the Aral Sea.

When analyzing the past and predicting future changes of the sea level, it is important to compare also the trends in the volume and basin area. Knowing the Aral Sea level variations and topography of the area one can calculate its volume and surface, using as a starting level in 1993 the isobath 15.8 m. For the period 1993–2000, the sea volume decreased from

270 to 130 km^3 ($\sim$2 times), and the surface decreased from 35,000 to 22,000 km^2 ($\sim$1.5 times). These different slopes are due to the specific hypsometry (Fig. 5). They indicate that further reduction of the basin area below 5000 km^2 will be slower than what has been observed in the period 1960–1990 because the remaining part of the basin is deep.

The decrease of volume and basin area depicts a similar course to the one of sea level in Fig. 4, because they are linked by the hypsometric relation; therefore, we do not show them here. For the period 1993–2001, the annual mean decrease of sea volume is $\sim$15 km^3. This number is about two times smaller than what one would expect assuming that presently no river and ground water reaches Aral Sea. We will first remind that the river runoff reaching the sea prior to the 1960s was $\sim$50–60 km^3. At that time the sea level of the Aral Sea was stable and evaporation less precipitation was $\sim$50–60 km^3 (we will show further that precipitation is much smaller than evaporation). By taking for the present day basin area the half of the 1960s area we obtain for the annual evaporation $\sim$25–30 km^3. The difference between this number and the observed decrease of volume is $\sim$10–15 km^3 suggesting that either: (1) evaporation over the "new basin area" is less intense than in 1960s, (2) the river plus ground water runoff is still large $\sim$10–15 km^3, or (3) the above two possibilities appear at the same time. Because it is well known that the river runoff was reduced dramatically in the last decades, (2) would suggest increasing ground water flow. The analysis of the above hypotheses is central to this paper.

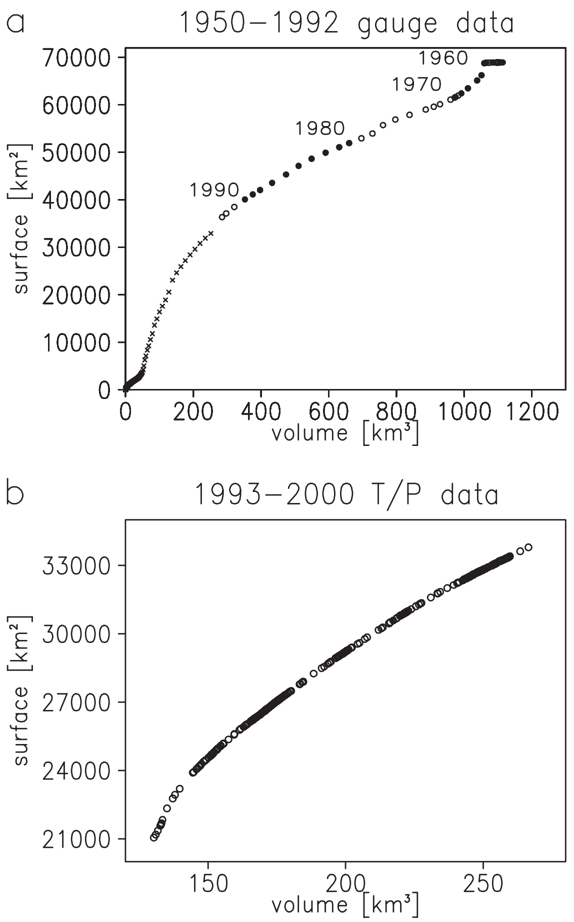

Fig. 5. (a) Time series of Aral Sea volume (x-axis) and area (y-axis), reconstructed from gauge (a) and T/P data (b). The curve in (a) is continued with crested symbols giving the hypsometric relation for the remaining deep part of basin (supposing that the level changes constantly with 0.5 m between two crest symbols). The line defined by crested symbols is calculated from the topography in Fig. 3.

2.3. Seasonal variability in meteorological forcing and the sea-level response

Fig. 6 shows the monthly mean values of sea volume for 1993–2001 after removing the trend. The corresponding mean for the period seasonal signal is plotted with a solid line in Fig. 7a, and yields variations of 2 km^3 month^{-1}.

For the enclosed basin the volume curve represents the response to hydrometeorological forcing, and the corresponding water balance equation is:

$$\frac{dV}{dt} = Q_r + Q_p + Q_e + Q_g \tag{1}$$

where V is the Aral Sea volume, Q_r, Q_p, Q_e and Q_g are water fluxes due to river runoff, precipitation, evaporation and ground water (Q_e<0).

We show in Fig. 7b the seasonal variations in precipitation and evaporation computed from data taken in Aralsk station (near the Syr Darya mouth, see the location in Fig. 2). The data are available for the period 1986–1995. The annual mean evaporation less precipitation of 87 cm year^{-1} compares well with data for the period before the 1960s when the hydrological balance was in a quasi steady state. However,

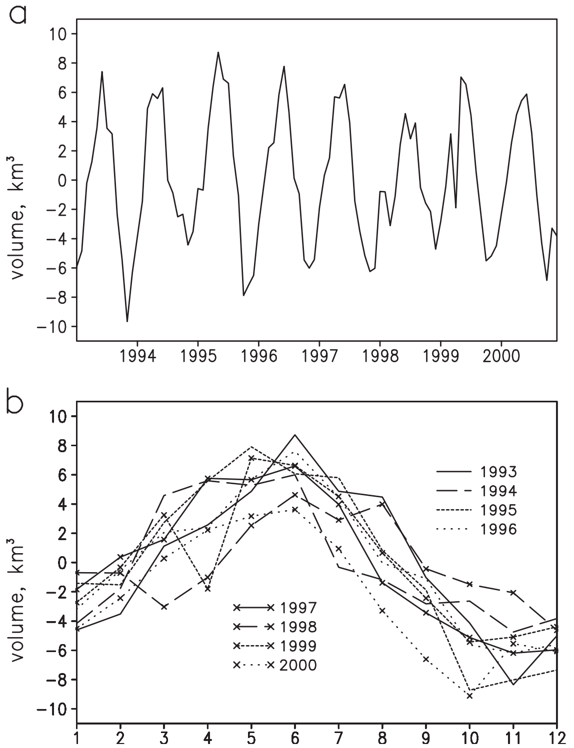

Fig. 6. (a) Monthly mean values of detrended Aral Sea volume (shown in Fig. 5). On (b)—the same, but all individual years are shown together.

we have to keep in mind that errors in computations based on bulk aerodynamic formulae, or extending the local observations over large regions in order to compute the components of water balance for the sea could affect the estimates.

The analysis below gives a first order idea about the hydrological balance in the region. In order to enable comparison between forcing (Fig. 7b) and response (Fig. 7a) we convert the fresh water fluxes from mm month^{-1} to km^3 month^{-1}, using for the averaged Aral Sea area in this period the value of 39,800 km^2. The comparison between E (evaporation) and P (precipitation) curves demonstrates that the surface flux of fresh water due to precipitation is negligible, which is the typical case in arid areas. Thus the variations in sea volume should reflect the changes in the fresh water flux due to evaporation. Obviously, there is a correlation between the time derivative of sea volume and evaporation, and as seen in Fig. 7 the volume variations follow the inverse evaporation course (compare dashed lines in Fig. 7a,b). However, we note that there is a time lag between the two curves. If we suppose that the two data sets were perfect, the difference between the two curves would give us the missing component in the water balance.

From Eq. (1) we can obtain an approximate estimate of the total river and ground water runoff (e.g. by subtracting the two dashed curves in Fig. 7). The result is presented in Fig. 7b with the dotted line. It reflects the well-known seasonal course for the river runoff of arid climate regions, i.e. significant increase in May–July to the value of 12 km^3 month^{-1}, and then a rapid decrease. However, during the past 5 years the river flux reaching directly the

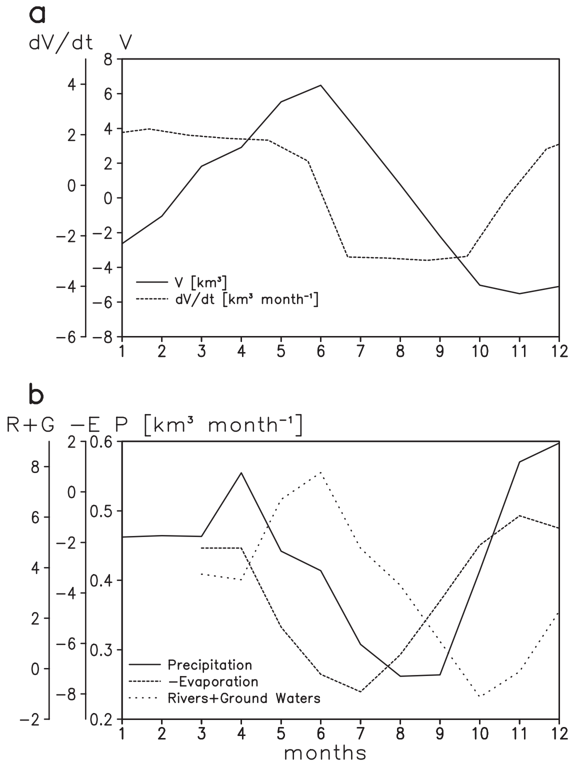

Fig. 7. (a) Monthly mean values of detrended Aral Sea volume, averaged for the period 1993–2000 (solid line) and its time change. (b) Monthly mean precipitation (solid) and inverse evaporation (long dashed line) measured in Aralsk (see for the location Fig. 3) averaged for the period 1986–1995. Short dashed lines correspond to the difference between long dashed lines in (a) and (b). There are no evaporation data available in winter months, which explains why some curves do not reach the vertical axis.

Aral Sea is small, thus the dotted curve gives rather a measure of the variability of the ground water flow. The above qualitative description of the relationship between the fresh water flux at the sea surface and the sea-level response concerns the seasonal variations only. However, the observations reveal that in 1994 and 1998 the volume variations had smaller amplitudes and the maximum was reached in March and August, correspondingly (Fig. 6a). Unfortunately, the lack of reliable (observed) meteorological and hydrological data overlapping the T/P lifetime precludes the quantification of the interannual variability of the water balance.

3. Long-term variations

3.1. Sea level and volume in the period 1950–2000

Although the T/P altimetry and gauge data in the Aral Sea do not overlap, it is interesting to see how the two data types complement each other. Fig. 8a shows the sea level for the period 1950–1992 (dashed line) in the Big Aral Sea based on observations (Chub, 2000). The lines are continued using T/P sea level (the solid line). The sudden sea level fall after the 1960s is well resolved by the gauge data. The gradient in the curve is the largest during the period 1970–1990, ~80 cm $year^{-1}$, than earlier and later. However, the T/P data give slightly smaller values ~60 cm $year^{-1}$. The slowdown of the decrease of sea level during the period 1993–1995 is supported also by data, based on sea level reconstruction from coastline contours.

The long-term trends in Aral Sea volume and surface area are also shown in Fig. 8. These curves have been constructed in the same way as described in Section 2 with two differences: (1) gauge data have been used instead of T/P data, and (2) the sea area for periods before 1960 is assumed constant in time and equal to the basin area in 1960.

3.2. Salt balance

In this section, we shall address the evolution of the salt balance. This is an interesting issue because: (1) the variability of salt balance in this sea is very different from the case of basins having connections with the ocean, (2) the signals are measurable and very strong, and (3) the control of the salt balance is spread over a vast catchment area and includes the ground water discharge. The latter argument implies that the river runoff and precipitation "wash out" the salt accumulated on the dry sea bottom after the sea retreated (or in larger area), and via the ground flows the salt is continuously brought back into the sea. Additionally, the catchment area where the ground water accumulates increases with shrinking the sea, that is with lowering sea level (Salokhiddinov et al., 2001). Our observations show that the depth of the groundwater table changed from 4.52 to 3.39–5.20 m in the period 1995–1997, and from 4.5 to 6.75 m in the period 1998–2000. Also, there is no groundwater discharge from the first flour aquifer directly into the

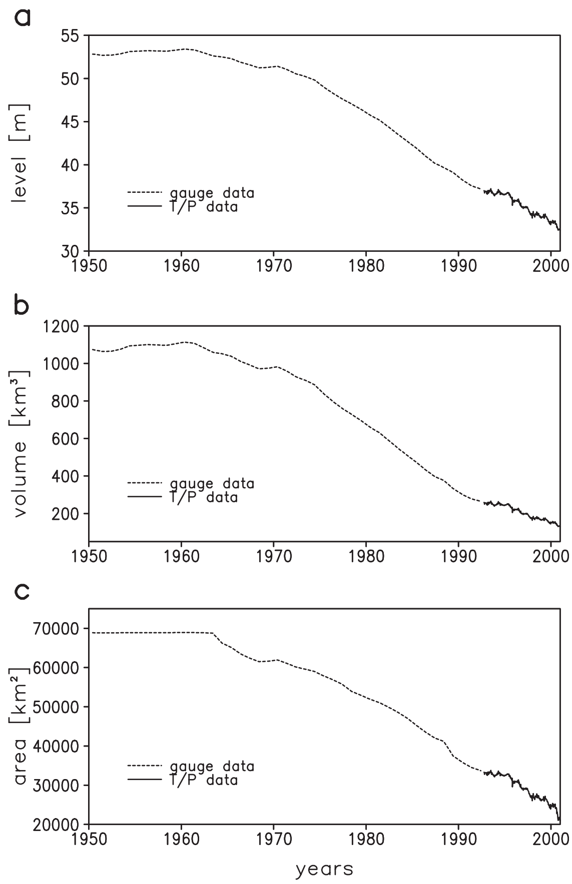

Fig. 8. (a) Annual mean Aral Sea level obtained from gauge measurements (dashed line), and T/P data with 10 days time resolution (solid line). (b) Volume and (c) area calculated using bottom topography from Fig. 3 and sea level from (a).

Aral Sea itself which could substantially contribute to the water balance. This is explained by the fact that this water is completely evaporated in the area of backwater belt. It is the second flour groundwater aquifer which presently contributes to the water and salt budget of Aral Sea.

The hydrological trends in the drainage basins result in an increase of mineral supply to the sea. In this way, the water body of the lake tends to conserve (or sometimes increase) the total amount of salt which was available before the sea level started to drop. Below we will focus on the entire sea before 1988, which is the approximate time of detachment of the Small Aral Sea and on the Big Aral Sea only, after 1988.

In most of the water balance analyses, the fluxes of ground water are usually neglected, but there is a significant research interest in this field as documented by Burnett et al. (2002). The salt balance equation can be written as

$$\frac{\mathrm{d}VS}{\mathrm{d}t} = S_\mathrm{g}Q_\mathrm{g} - F_\mathrm{dep} - \varepsilon \qquad (2)$$

where S is the basin mean salinity, S_g is salinity of the ground water, Q_g is the ground water flux, and F_dep is the amount of salt remained on the dry bottom. In Eq. (2), we neglect the input of minerals from rivers because their concentration of $\sim$0.65 mg l^{-1} is much smaller than that of the ground waters, and (for generality) add a small term ε accounting for the precipitation of salt on the wet sea bottom. The latter two effects could be important for the long-term evolution of salt balance (Tuchin, personal communication).

It is reminded that the available salinity data during the last years of observations are for the western basin, where the coastal line has not changed much and the former measuring stations can still be used. This is not the case in the eastern (shallow and flat) sub-basin where the constant retreat of coast makes the access to the water body very difficult. In this part of the sea, salinity values are expected to be larger because this area acts as evaporator and the mixing with the waters of western (deep) basin decreases because the connecting straits shallow or even fall dry. Unfortunately, the missing data precludes very high accuracy of computations.

The most difficult for direct estimation are the values of S_g and F_dep. The remaining variables can be estimated either from direct measurements (V and S) or as a residual from water balance equation (Q_r+Q_g). If the direct river runoff is small compared to the ground water discharge, and either S_g or F_dep is indirectly estimated, Eq. (2) will be closed.

The data used here to analyze the salt balance include volume and salinity variations from literature which were compiled by D. Sirjacob (personal communication), as well as the data of Chub (2000). Unfortunately, regular salinity measurements exist only before 1992, and until recently they were interrupted. For the present-day salinity (2001), we take the value of 90 (Zavialov et al., 2003; Friedrich and Oberhansli, 2004) and the analyses below (Fig. 9) start first with this value (the solid lines).

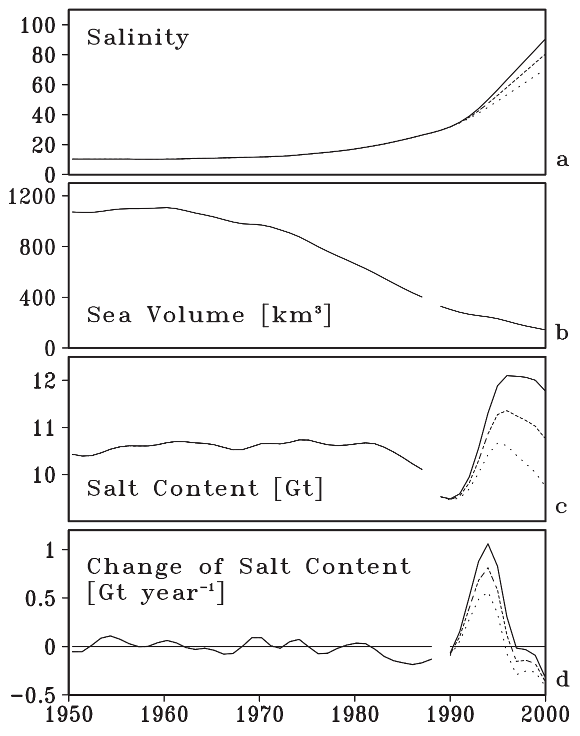

Fig. 9. Annual mean salinity (a), volume (b), the total salt content (c), and the time change of salt content (d). The different curves correspond to S = 90—solid, S = 80—dashed, and S = 70—dotted lines.

The annual mean basin volume and salinity time-series are given in Fig. 9a,b. The negative correlation between the two curves is self explanatory; however, the temporal variability of the total salt content *SV* is less clear, in particular the decreasing salt content in the 1980s. The curve in Fig. 9c displays the integral amount of salt, which is controlled by the ground flow minus the loss of salt remained on land after the sea shrunk. The time derivative of this curve (d*SV*/d*t*) in Fig. 9d gives the corresponding flux that is the right-hand side of Eq. (2). Oscillations with periodicity of ~5 years dominate the flux pattern.

Although large errors and inconsistency between data of different types makes the following discussion speculative, one could perhaps insist that the first large change in the salt content occurred in the beginning of 1980s. This decrease (Fig. 9c) might reflect the deposition of salt on the drying shallow sea bottom (during this period the area surface decreased almost two times compared to the area surface in 1960). We interrupt the curve in 1988 because at that time the connection between Small and Big Aral closed and the sea levels of both basins took different courses: while the sea level of Small Aral stabilized the one of the Big Aral continued to descend. Further, we continue the computations only for the Big Aral (the right parts of the curves). Obviously, a great transition in the salt content occurred in 1980s. In order to answer the question whether the changes in salt content displayed in Fig. 9c are common to the coupled system of Big and Small Aral Seas we repeated the computations only for the area of Big Aral Sea (not shown here). Then it became clear that, also for this basin only, the salt content dropped dramatically. Actually, the continuation of the curve in Fig. 9c after 1990 illustrates the decreasing trend in the salt content of the Big Aral Sea (in 1990–1992).

The most unexpected result from the analysis of salt budget is the rapid increase of salt content in the period 1991–1995. This result gives a strong support to some local studies (Salokhiddinov et al., 2001) about the increasing ground water discharge in last years. The peak in Fig. 9d during 1994–1995 could be taken as an indication that during this time the drainage basin of ground water rapidly increased resulting in an increase of ground water discharge. An alternative explanation of this phenomenon could assume that during this period the increased precipitation in the area "washed out" large amount of salt which was previously deposited on the dry bottom. However, only in the Big Aral Sea, the salt content after 1993 became larger that the one in the entire Aral Sea in 1960–1980. This gives a convincing proof that the input of salt is due to ground water transport originating out of the area which was previously covered by the sea (and not to the re-introduction of the deposited on the bed salt).

The above analysis becomes clearer with the help of water balance estimates in Fig. 10. The upper panel gives the forcing term (air–sea water exchange) which, for simplicity, is taken as equal to the mean evaporation minus precipitation times the sea surface. Thus the slope of the curve gives the variations in basin area. Using the available data for sea level we can compute the change in sea volume (Fig. 10b). The

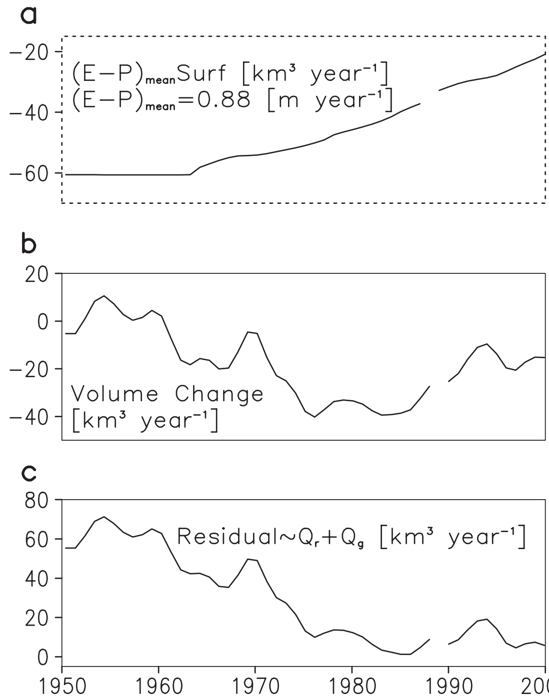

Fig. 10. Water balance. (a) Annual mean water air–sea exchange calculated as a product of climatic evaporation less precipitation (0.88 m year^{-1}) and basin area, (b) time rate of change of the Aral Sea volume (from Fig. 9), (c) the residual, which accounts for the ground plus river water runoff.

difference between the two upper curves gives then the residual, which is equal to the river plus ground water discharge.

Although there is a clear decreasing trend from 1950 to 1970, the changes of the river runoff during this period are only about two times the range of its interannual oscillations (about 10–15 $km^3\ s^{-1}$). The most dramatic decrease of the river runoff is observed in the period 1970–1985 when the water supply by rivers almost ceased. Assuming that after 1985 the direct river discharge is small, we see from Fig. 10c that the ground water discharge has taken over. This was particularly strong in 1993–1994.

Fig. 9d, which gives the right-hand side of Eq. (2), demonstrates that there are only two periods in the last 20 years, that is after the river runoff reduced to very low values, when the salt supply with ground water exceeded the deposition on the dry bottom (positive values in Fig. 9d). The first one (in 1979–1981) is small and could have been due to the large precipitation at that time and the corresponding ‘‘wash-out’’ of the salt deposited on the dry bottom. The second event occurred in the 1990s. However, the increase of precipitation is less clear during this period therefore we conclude that the runoff during this time is due to ground water (the increase of residual in Fig. 10c in 1993–1994), the latter shaped by the hydrological processes over a large catchment area (Salokhiddinov et al., 2001).

The above discussion triggers another fundamental question: what could be the reason of the rapid drop of salt content thereafter. Different answers are possible, which in the absence of observations could sound too speculative. However, we shall mention only two possible ones: the reverse process after 1994 could be due to (1) redistribution of salt content between eastern and western basin, or (2) increased salt precipitation on the bottom, something which is known from the long-term evolution of this basin.

We recall that the analyses above have been done for annual mean conditions. However, seasonal variability in the sea volume is quite large, as seen in Fig. 6a. Obviously, the correlation between salinity and volume could have a net contribution to the right-hand side of Eq. (2), but the lack of data makes impossible to check this hypothesis. When discussing the variations in the salt balance we have to bear in mind that the seasonal variations of the ground plus river water discharge (see the dotted line in Fig. 7b) are quite high, and their correlation with ground water salinity could also have substantial contribution to the salt budget. This is something which we cannot check with the data presently available.

The discharge of ground water into the sea is still largely unknown over vast areas, as well as the salinity of ground water. Closing Eq. (2) is not an easy task; therefore, in the following we will only analyze the sensitivity of the estimates as dependent on sea water salinity. We assume that some inaccuracy could exist in the available salinity data: either (1) the existing ones are not representative for the whole basin (e.g. no account has being taken of possible redistribution of salt between the two sub-basins), (2) because of insufficient record we assume that the change in the basin mean salinity is monotonous process, or (3) the relationship between conductivity and salinity is not well established for the regional hypersaline waters. We show with different lines in Fig. 9 the estimates obtained assuming that salinity in 2001 is 80 (dashed line) and 70 (dotted line), correspondingly. The results are qualitatively similar to the ones in the case S=90 (there is a peak in the ground water runoff in 1993–1994), but the total salt content does not reach values larger than the ones in 1980.

From here on one could ask the question about the salinity of ground water. Assuming that the we can keep in the right-hand side of Eq. (2) only the runoff of ground water, which seems to be the dominating term, we can then estimate the salinity of ground water. The result varies from $\sim$35 to about half of this value depending on whether we take for salinity in 2001 the value of 90 or 70. According to the measurements in several locations done by one of the authors of this paper (A.S.), the ratio between the groundwater mineralization and the one of Aral Sea water varied from 0.6–0.9 (at the pre-1960 shoreline) to about 1.6 (close to the present shoreline). Obviously, the estimates of our simple model are at the low end of the rates estimated by observations. This could be due to the fact that (1) measurements have been taken in few locations only, (2) working with the basin mean (for the two parts of the sea) salinity could cause problems, or (3) the deposition term ε in Eq. (2) cannot be anymore neglected. With respect to the latter argument we recall that the formation of crystalloid halite and mirabilite could play an important role under hypersaline conditions.

The speculations about the contribution of the ground water discharge to the salinity budget could seem too theoretic if not supported by direct observations in larger areas. This problem can, at least partially, be addressed using available satellite data. Fig. 11 gives an idea about the possible spatial distribution of ground water discharge. This figure is based on the data from AVHRR optical channels of NOAA-16 satellite and gives vegetation, soil and water optical properties. There are several large areas on the former bed which are characterized by larger soil moisture protruding toward the basin. Although the relationship between soil humidity and the amount of the discharged ground water has to be further established, the remote sensing data give a strong motivation to develop methods making possible to, at least, trace the major pathways of ground water discharge.

4. Conclusions

The recent evolution of water and salt budgets in the Aral Sea are obviously due to a water policy, which neglected the possible environmental degradation. However, along with the large number of negative consequences of this policy there is one positive: the processes developing in the region are unique and give a large spectrum of possibilities to address problems in environmental systems under transition. The bad coincidence is that the largest transitions (including the increasing contribution of ground water

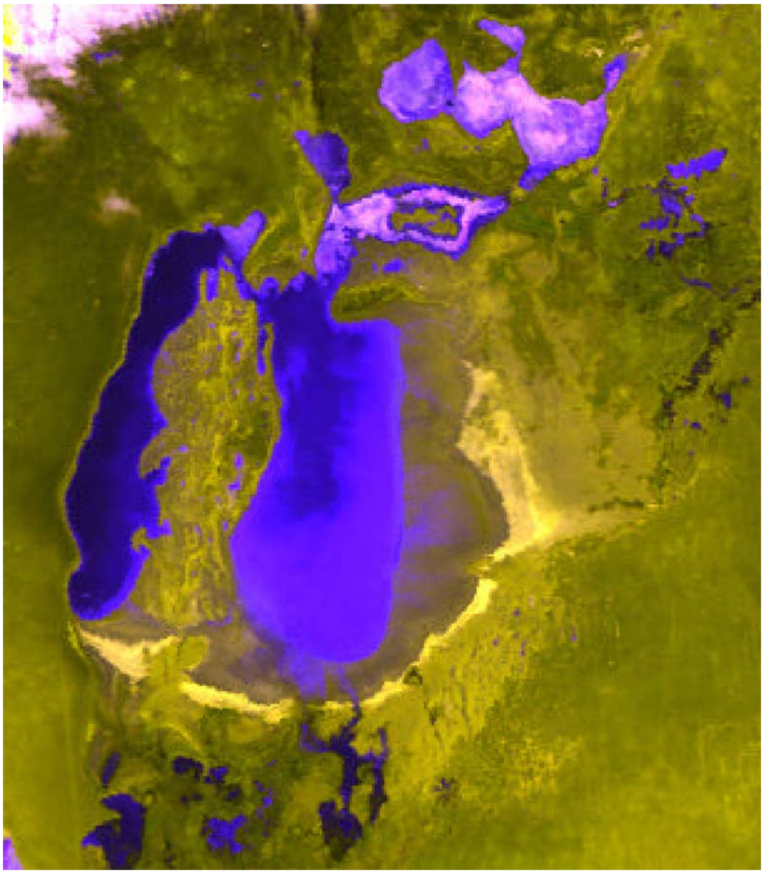

Fig. 11. Color index map calculated from AVHRR optical channels data (3 April 2003, NOAA-16 visible band).

to water budgets) occurred in the 1990s when the observation system in the Former Soviet Union was not functioning. Thus due to the bad record of processes it is not only the question "how the changes occurred" but also "what exactly happened" remaining largely unanswered.

We demonstrated in this paper, that using indirect observations (remote sensing data) one can, to some extent reconstruct some events in the recent evolution of the Aral Sea. The most dramatic and new ones, which we identified in this paper are: (1) the slowdown of the sea level drop controlled not only by hypsometry, but also by the increasing discharge of ground water, (2) the "burst" in ground water discharge in 1993–1994, (3) the spills of ground water on the former bottom seen by satellites.

We submit that the insufficient amount of data or their poor quality could strongly affect some of the main conclusions. Therefore, further analyses and introduction of new data would be necessary, in particular concerning the different functioning of the Aral Sea sub-basins and the exchange between them.

Acknowledgements

We thank F. Mercier who made the T/P data available to us and D. Sirjacob, who compiled and made available to us the historical data for Aral Sea. Thanks are also due to Brian Beckley who provided Fig. 3 and A. Cazenave for the useful comments. This work has been carried out in the frame of the EC-funded project Aral-Kum (contract ICA2-1999-10024).

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