Temporal and spatial patterns of sea level in inland basins: Recent events in the Aral Sea

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1. Introduction

[1] We demonstrate in this paper that satellite altimeter data resolve the drop in the Aral Sea level during 1993–2000 of about 0.6 m per year resulting in a change of surface area from 35000 to 22000 km² and volume from 270 to 130 km³. The sudden drop in the sea level of the Northern basin on 04.21.1999 resulting from dam break-up is also clearly resolved. The temporal and spatial variability of sea level reveals response patterns which are characteristic for friction dominated shallow sea dynamics. The combination of salinity and sea-level data enables to identify the major events of environmental transition, which are associated with the temporal variability in the total salt content: (1) a peak in 1993–1994, and (2) an increasing trend in the last decade. These events are indicative of an increase in the discharge of ground water, but could also reveal overestimated salinity estimates from recent observations. 


2. Topex/Poseidon data

[4] The period of 1990-s is poorly covered by observations because the in-situ measurements of the former Soviet Union were interrupted in the new independent states. However, available satellite data provide an important substitute for the missing gauge observations, and as shown by Ressl and Micklin [2004], the sea-level change can be reconstructed using accurate bathymetric map (Figure 2) and satellite observed coastal line change. Here, we use a more direct approach based on Topex/Poseidon (T/P) altimeter satellite. These data are provided by the AVISO altimetry project of the French Centre National d’Etudes Spatiales (CNES) and give the altimeter range measurements along tracks at 1 s intervals (~6 km resolution). The sea surface height is first calculated as a difference between the radial component of the satellite orbit and the altimeter range measurements. Then, it is referred to the geoid using the JGM-3/OSU91A model. Finally, we compute a mean
sea level per T/P 10-days orbital repeat cycle. For further
details on the T/P data processing, we refer to
Birkett [1995], Cazenave et al. [1997], and
Mercier et al. [2002]
who demonstrated the reliability of this technique over
small inland water bodies. The monitoring of the Aral Sea
level from altimetry measurements has been addressed by
Cretaux et al. (IUGG-2003, Volume of Abstracts),
Peneva et
al. [2004] and
Kostianoy et al. [2004]. It is already
established that for water bodies with similar dimensions,
the accuracy is better than 10 cm. Here, we find an average
value of ±3.9 cm for the error bars of the T/P derived level
time series.

3. The Recent Chronology

[5] The recent chronology of the Aral Sea is displayed by
Figure 2 and Figure 3 using data from gauge station (before
1990) and T/P data. In the last five decades the water
exchange between northern and southern parts of the Aral
Sea has continuously decreased because of the shallowing
of the connecting strait. In 1990-s several efforts have been
undertaken to build a dam maintaining the sea level of the
northern part stable (compare the different elevation signa-
tures in Figures 3a and 3b). On 04.21.1999 the dam was
destroyed by a storm and the associated rapid drop of sea
level was well recorded by the T/P altimeter (Figure 3b). In
the last decade the northern and southern basins (Small Aral
and Big Aral Seas respectively, see Figures 1 and 2) are
practically separate water bodies because the sea level in
both basins fell below the sill depth. At present, the runoff
of Syr-Darya River is sufficient to keep the level of
Small Aral Sea stable. A certain amount of water is
exported into the Big Aral Sea either by groundwater or
by sporadic surface discharge of surplus water under high
water conditions.

[6] In this paper most of the interest is focused on the
evolution of the Big Aral Sea, where the hydrological
situation is 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 dried up (Figures 1 and 2).

4. Sea-Level Slope and Barotropic Circulation

[7] The T/P data resolve reasonably well the variations of
sea level $\eta$ in seasonal and intraannual time scales
(Figure 3), which in this particular area have large ampli-
tudes. The rms deviation due to the seasonal variability is
~5 cm.month$^{-1}$, that is comparable to the trend in $\eta$. The
high resolution of T/P data along tracks enables to resolve
also some important spatial patterns of $\eta(x, t)$, where $x$ and $t$
are coordinate and time (Figure 4). To avoid possible
misinterpretations of satellite observations in the very
shallow areas we excluded from the whole data set the
locations where the depth by the end of observations

Figure 1. Color index map calculated from AVHRR
optical channels data (5 June 2001, NOAA-16 visible
band). This picture gives vegetation, soil and water optical
properties. The green colors in the desert area indicate the
irrigated land along Amu-Darya and Syr-Darya Rivers.

Figure 2. The chronology of shrinking of the Aral Sea.
Bathymetric map (depths are in meters) is shown in the first
panel. The periphery of yellow shading gives the coastal
line in 1960 (zero depth). The solid line gives the position
of the isobath 15.8 m, which was the coastal line in 1993.
The coastal line before 1995 is calculated using detailed
bottom topography and sea-level data from gauge stations.
In the last two panels satellite altimeter data are used
instead. The ground tracks are also shown.

Figure 3. Sea level referred to the geoid based on T/P data
for Big Aral Sea (a) and Small Aral Sea (b).
was less than 5 m. We display in Figure 4 the evolution of Sea-Level Anomaly (SLA) \( z(x, t) = h(x, t) / C_0 \) on two ground tracks (No 107, denoted on the figure as 1–2, extends from South-West \( x_{\text{start}} \) to North-East \( x_{\text{end}} \) and No 142 extends in an almost perpendicular direction and is denoted as 3–4). The slope of SLA is \( /C_24 \) m per 100 km, and suggests a piling up of water in the southern and western part of basin caused by predominating north-northeasterly winds.

Because the shallow sea dynamics are friction-dominated, and the Western basin is indeed very shallow, we can present the governing momentum balance by the following well-known formula

\[
g \zeta = \frac{\tau}{h}
\]

where the left-hand side gives the pressure gradient and the right-hand side gives the wind stress \( \tau \) normalized by the depth \( h \). The extremely shallow depth explains the large values of sea-level slope (Figure 4).

The temporal patterns become more clear from the results based on EOF analysis. This statistical technique, which is widely used in Meteorology and large-scale Oceanography, as well as in some studies of small ocean basins [Stanev and Peneva, 2001], is applied here to analyze along track T/P data. The first two modes describe most of the variance (see Figure 4). The shape of the EOF-curves demonstrates that a model assuming sloped sea level could well represent the major spatial pattern. Because the slope changes along the ground tracks, and because the principal component (PC)-curves change sign in time one could expect that the curvature of sea level also changes sign resulting thus in changing the intensity or even the sense of circulation. This approach to estimate the circulation complements another method already used by Zavialov et al. [2003], which is based on remote sensing data from other source. The temporal variability is dominated by the annual signal in the PC-s, however this variability is modulated by pronounced interannual changes.

5. Water and Salt Content

From the mean sea level time series and topography \( H \) we can calculate the surface area \( A_r(z = \eta) \) and volume \( V = \int_{z_{\text{min}}}^{z_{\text{max}}} A_r(z) dz \), where \( A_r(z) \) is the basin area corresponding to different depths \( z \). During 1993–2000 the sea volume decreased from 270 to 130 km\(^3\) and the surface decreased from 35000 to 22000 km\(^2\), which is consistent with the estimates of Ressl and Micklin [2004]. The different trends in \( V \) and \( A_r \) are explained by the specific hypsometry (Figure 5) and indicate that a further reduction of the basin area below 5000 km\(^2\) will be slower than that observed in the period 1960–1990 because the remaining part of the basin is deep.

The hypsometric curve in Figure 5 displays the major events in the recent evolution of Aral Sea (decoupling between Small and Big Aral Seas and decoupling between the eastern and western parts of Big Aral Sea). The slopes \( \Delta V / \Delta A_r \) are \( /C_24 \) times larger in the Western basins than in the Eastern one ensuring much longer life times of the former under the present day water balance. It is expected that this basin will not disappear but transform into a basin of the type of the Dead Sea.

We can compute the total salt content using values for the volume of the sea and available salinity data [Mirabdullayev et al., 2004]. A measurement error of 3.9 cm for the T/P data would result in an error in the basin volume of \( /C_24 \) km\(^3\). The rms difference between mean sea-level estimated from the two tracks and only from track “1–2” (taken as an error due to undersampling) results in

Figure 5. Hypsometric relations. The overlapping computations done with the same sea level (with and without considering the decoupling) give an indication about the switch of hypsometric relations in the moment of decoupling of the basins. This could be interpreted as an error resulting from problems with basin determination.
an error of volume estimate of \( \sim 4 \) km\(^3\). Both errors are small compared to the volume change of \( \sim 17 \) km\(^3\) due the annual trend.

[13] The estimations of basin mean salinity suffer from bad temporal and spatial coverage of observations, in particular in the last decade. The most complete (in time) data of Mirabdullayev et al. [2004] does not provide enough spatial coverage to accurately reconstruct the basin mean salinity. By 2001 this data set gives \( S^{2001} \sim 65 \) psu while the observations of Zavialov et al. [2003] and Friedrich and Oberhansli [2004] using vertical profiling give \( S^{2001} \sim 90 \) psu. The shading in Figure 6 represents the uncertainties of the estimates. Three important results follow from Figure 6b: (1) the salt content decreases in 1980s, (2) there is a pronounced peak in 1991–1992 associated with a slow-down in the sea-level drop [Peneva et al., 2004], and (3) there is an increasing trend in the salt content if we assume \( S^{2001} \sim 75 \) psu. The first result indicates that part of the salt has remained on the dry bottom after the sea retreated. The second one indicates that the ground water discharge, which provides the main source of salt, peaked. This could be a result of the increasing catchment area for the groundwater [Salokhiddinov et al., 2001; Benduhn and Renard, 2004] and explains why the total amount of salt exceeds the one which was available before 1992. However, the result (3) opens again the question about the quality of salinity determinations in hypersaline waters and how representative the local values are for the basin mean salinity.

6. Discussion

[14] In spite of the problems with data availability and quality, with the use of satellite altimetry some promising estimates are presented in this paper. These results identify important dynamical controls and events in the recent evolution of Aral Sea: (1) The wind tends to establish a steep slope of sea level, and its dynamics describes most of the variance in sea surface, (2) the slow-down of the sea-level drop is controlled not only by hypsometry, but also by the increasing inflow of groundwater, (3) the “burst” in groundwater discharge in 1993–1994 resulted in an absolute maximum in salt content. The last result would imply unexpectedly high mineralization and fluxes, and motivates deeper analysis on salinity measurements in hypersaline basins.

[15] The interest to investigate the non-steady geophysical processes in this region is strong because changing water policy might result in inverse trends. If that happens, we advocate a reorganization of the research potential in the region and worldwide enabling a better record of the transition processes. In this way the Aral Sea would realize its potential of a natural laboratory where one could address important climate change and oceanographic issues.

References


