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On thermohaline structure and circulation of the Western Large Aral Sea from 2009 to 2011: Observations and modeling

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ABSTRACT

The shrinkage of the Aral Sea in the second half of the past century has significantly affected the hydrophysical regime of the lake. The objective of this paper is to report on a hydrological structure and circulation of the today's Aral Sea based on both direct field observations and modeling results. We focus on the results of three field surveys to the Aral Sea which took place in the period from 2009 to 2011. In addition, series of numerical experiments using Princeton Ocean Model adapted to the Aral Sea was undertaken to investigate the contributions from bathymetry and water stratification in the formation of the basin scale circulation. The hydrological structure of the Aral's western basin in autumn season exhibited a three-layered pattern with two local salinity maxima, separated by a fresher intermediate layer. According to direct observations, water circulation in the surface layer has anti-cyclonic character, while circulation in the bottom layer has cyclonic sign under the predominant northerly winds. The simulation experiments demonstrated clearly that the main cause of the anti-cyclonic circulation in the surface layer of the lake is the "asymmetric" bathymetry with broad shallow area along the eastern coast and relatively steep and deep western slope. However, strong stratification is a necessary condition for the formation of the cyclonic circulation gyre in the bottom layer.

1. Introduction

Until 1960, the Aral Sea, a terminal lake in Central Asia, was the World's fourth largest inland water body by area. Mainly because of intensive water diversion from the Amu-Darya and Syr-Darya rivers for irrigation, the Aral Sea began to shrink dramatically in 1960. In comparison with pre-desiccation state, to the date of this writing, the overall level drop was about 26 m. Nowadays, the Aral Sea has lost more than 90% of its volume (Zavialov et al., 2012). The shrinkage resulted in profound changes of the lake's ecosystem and desertification of the surrounding areas. The ecological crisis of the Aral Sea has attracted attention of mass media and international scientific community. Moreover, the significance of the ongoing changes of the Aral Sea is not limited to the applied, regional aspects. The lake can be thought of as a "natural laboratory", where the evolution of a large inland water body under anthropogenic intervention through diversions of the river runoff can be investigated. Such an investigation could be also instructive with respect to other similarly exposed regions all over the World.

The Aral Sea was covered by data relatively well in the times of the former USSR. However, during the period of the most rapid changes of the Aral Sea hydrological system, i.e., the 1990s, the in situ observations in the lake were extremely sparse. The reason was the well-known political and economic troubles following the collapse of the USSR, as well as the complete cessation of the navigation in the Aral Sea at advanced stages of desiccation. This resulted in a practically total lack of data about many basic characteristics of the rapidly changing Aral Sea environment at the beginning of the new millennium. Most works published after the early 1990s were confined to either modeling or remote sensing (e.g., Ginzburg et al., 2002). In 2002, the Shirshov Institute of Oceanology of the Russian Academy of Sciences (SIORAS) launched a long-term program of field research and monitoring of the Aral Sea. The field observations are conducted in collaboration with a number of other institutions in Russia and Central Asia's states of Uzbekistan and Kazakhstan.

The objective of this article is to report on a hydrological regime and circulation of the today's Aral Sea based on both direct field observations and some modeling results. The paper is centered on the results of the 3 latest field surveys of SIORAS to the Aral Sea which took place in August, 2009, September, 2010 and November, 2011. Similar data collected in the surveys since 2002 through 2008 have been published previously (e.g., Zavialov, 2005, 2009), and in this paper we recall them only briefly,

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mainly focusing on the results of 2009, 2010 and 2011 presented here for the first time.

The paper also reports on numerical model simulations of the Aral Sea circulation. The properties of basin-scale circulation gyres in major lakes have been subject of a number of previous studies. For example, Schwab and Beletsky (2003) investigated relative importance of different mechanisms to explain the large-scale gyres in Lake Michigan and found that wind stress curl and the baroclinic effects were the dominant factors, but the topographic effects were also significant. The effects of bathymetry on circulation patterns in lakes have been addressed in early works by Shtokman (1953). Pickett and Bermick (1977) studied Lake Ontario during the stratified season and reported a circulation consisting of a major counterclockwise gyre complemented with a smaller clockwise gyre in the northern part of the lake. In the case of Great American Lakes (whose geographic and morphological settings are in some respects similar to those of the Aral Sea), Beletsky et al. (1999) argued that the observed cyclonic circulation pattern was associated with the vorticity of the wind stress field. However, smaller lakes tend to manifest two-gyre rather than a single gyre circulation patterns. For example, double gyre circulations were observed in the Lake Tahoe (e.g., Rueda et al., 2005; Strub and Powell, 1986). A combination of an anticlockwise gyre and a weaker clockwise gyre has also been reported for the Lake Kinneret (Marti and Imberger, 2008). Shimizu et al. (2007) studied the Lake Biwa during the stratified period and identified anticyclonic sub-basin scale gyres. Beletsky et al. (2006) concluded that in general, the density effects added to the wind action led to a more complex circulation pattern in lakes.

In the present paper, we investigate the circulation of today's hyperhaline, highly stratified Aral Sea and attempt to quantify the underlying mechanisms based on in situ measurements as well as numerical modeling. Information about geographical and physical conditions of the Aral Sea as well as the historical background of the problem are summarized in Section 2. Details of the field campaigns and the model experiments are given in Section 3. The thermal and salinity structures across the main lobe of the Aral Sea are presented and analyzed in the Section 4. Investigation of water circulation based on observations is analyzed in Section 5 and numerical modeling results are presented in Section 6. Conclusions are drawn in Section 7.

2. Geographic settings of the lake

The Aral Sea in its original, pre-desiccation state was a brackish lake whose salinity varied only slightly around 10 g/kg. The minimum values were mainly associated with river mouth areas, while the highest were distributed in the deepest western part of the basin. The seasonal cycling of salinity was largely insignificant (Kosarev, 1975). In contrast with the salinity values, the temperature demonstrated strong spatial and temporal variability. High seasonal range of SST (about 25 °C) and steep thermocline with maximum vertical gradients up to 1 °C/m were characteristics for the lake in the summer season

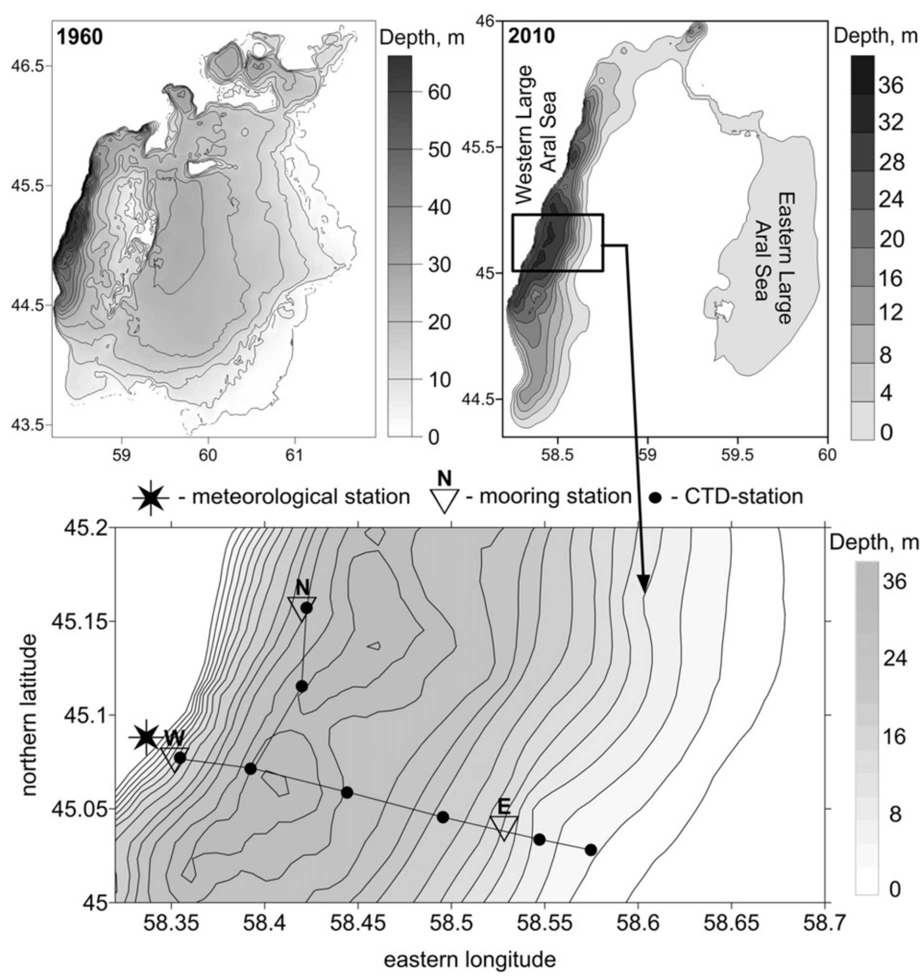

Fig. 1. The Aral Sea bathymetry for 1960 and for 2010, the Eastern Large Aral Sea is shown schematically (upper panel). Schematic illustrating the locations of 6 CTD-stations on the annual cross-section, two additional CTD-stations north, 3 mooring stations and meteorological station (lower panel). The positions were retained during every field survey.