Continental Shelf Research 30 (2010) 1211–1225

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Impacts of freshwater on the seasonal variations of surface salinity and circulation in the Caspian Sea

A. Birol Kara [a], Alan J. Wallcraft [a,*], E. Joseph Metzger [a], Murat Gunduz [b]

[a] Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS, USA
[b] Institute of Marine Sciences, Middle Eastern Technical University, Erdemli, Icel, Turkey

ARTICLE INFO

Article history:
Received 21 July 2008
Received in revised form
23 March 2010
Accepted 29 March 2010
Available online 2 April 2010

Keywords:
Caspian Sea
Heat flux
Freshwater flux
The Volga River
HYCOM

ABSTRACT

A fine resolution (≈ 3.3 km) version of the HYbrid Coordinate Ocean Model (HYCOM) is developed for the Caspian Sea. The model consists of a hybrid $\sigma - z$ coordinate system, with $\sigma-$coordinates for the upper layers and z-levels below a user-specified depth and in very shallow water. General features of the Caspian Sea HYCOM are presented including the bottom topography, initialization and atmospheric forcing along with river discharge. The climatologically forced model simulation reveals that there is net heat loss (gain) during winter (summer), and that rivers can have significant influence on the freshwater fluxes, especially on the northwestern shelf. There is a strong seasonal cycle in the net surface heat fluxes. The freshwater fluxes are found to be locally dominated by river discharge. In particular, the Volga River, which has very high discharge rate during the summer months, is found to play an important role in driving the seasonal cycle of freshwater fluxes in the North Caspian Sea. Over the basin, the buoyancy fluxes calculated from net heat and freshwater fluxes indicate that buoyancy is much more sensitive to variations in heating than precipitation–evaporation since thermal buoyancy fluxes are much greater than the haline buoyancy fluxes. A set of model simulations further investigates the impact of evaporation, precipitation and river flow on the upper ocean quantities. It is demonstrated that the discharge rate from the Volga River controls the monthly variations in surface salinity fields in the North Caspian Sea.

Published by Elsevier Ltd.

1. Introduction

The Caspian Sea has several unique characteristics, making it a very challenging enclosed body of water for examining seasonal variations of upper ocean variables. It consists of three distinct basins (north, central and south regions), having their own physical conditions and biological diversity (Fig. 1). The northern part of the Caspian Sea covers about 25% of the total surface area. The Caspian Sea has no connection to any other major ocean basin. Upper ocean variables, such as surface salinity and currents, are therefore locally influenced by the seasonally varying impacts of river discharge, evaporation and precipitation in addition to heat and momentum fluxes. Long-term climatic effects are of particular importance in the Caspian Sea as well. For example, Rodinov (1994) relates variations in sea level to cycles of North Atlantic Oscillation (NAO).

There are many small and large rivers (nearly 130), but the majority of them have small discharge rates. The largest inflow of fresh water comes from the Volga River (Fig. 1). It accounts for about 80% of the climatological mean river discharge of $\approx 250\,\mathrm{km^3\,yr^{-1}}$ (Kosarev and Yablonskaya, 1994). The outflow in the Caspian Sea is mainly by evaporation at the sea surface and to Kara-Bogaz. The sea level in the Caspian Sea displays a clear seasonal cycle, generally reaching its lowest seasonal value in winter and increasing during May–July, following the spring floods (e.g., Domroes et al., 1998). Thus, it is mainly a function of evaporation–precipitation (Rodinov, 1994) and these local effects can be important in predicting the upper ocean variables.

The Northern Caspian Sea is very shallow, with average depths shallower than 5 m. Having a large extent of shallow water over most of the coastal regions in the Caspian Sea points to the importance of properly representing stratification and mixing processes, which can be influenced by atmospheric forcing. Since greater constraints need to be imposed in the formulation of boundary fluxes in an enclosed basin in comparison to a semi-enclosed or open ocean, improperly accounting for mass or buoyancy fluxes could lead to unrealistic estimates of total stored heat, salt and mass in a numerical ocean model of the Caspian Sea.

Despite its small size, the above mentioned factors make the Caspian Sea a challenging region to investigate the impact of various variables, such as river discharge, heat and freshwater fluxes, on the seasonal variations of salinity. There are several

* Corresponding author.
E-mail addresses: alan.wallcraft@nrlssc.navy.mil (A.J. Wallcraft), joe.metzger@nrlssc.navy.mil (E. Joseph Metzger), gunduz@ims.metu.edu.tr (M. Gunduz).
URL: http://www.7320.nrlssc.navy.mil (A.J. Wallcraft).

0278-4343/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.csr.2010.03.011

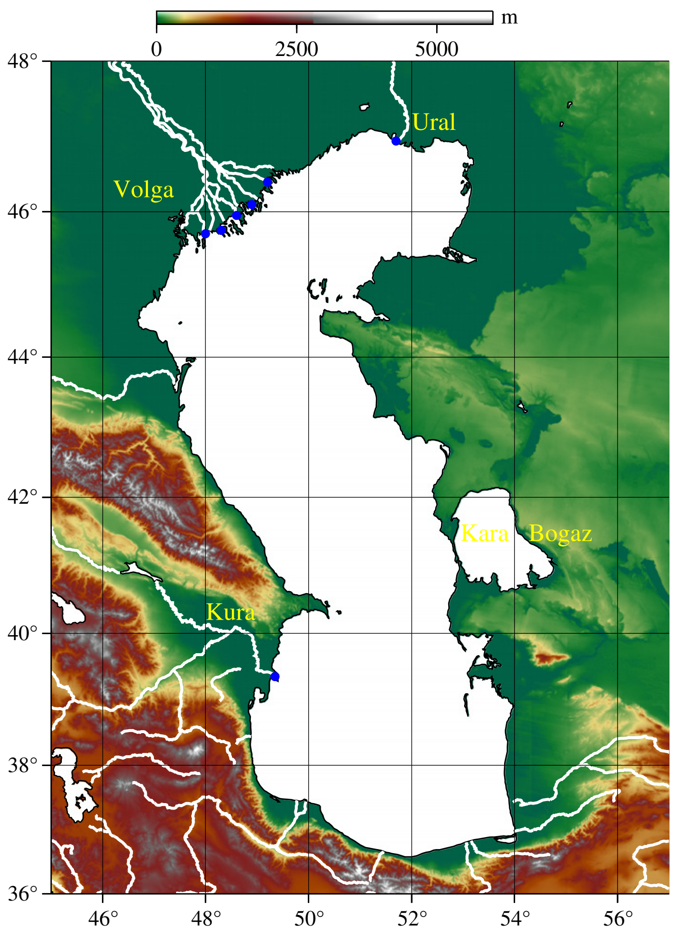

Fig. 1. The geography of the Caspian Sea. Locations of the major rivers discharged into the Caspian Sea are also provided. The length of the coastline is $\approx$7000 km, and the surface area is 386,400 km^2.

operational atmospheric models from which heat and freshwater fluxes at the sea surface can be obtained. Examples of such models include $1.125^\circ \times 1.125^\circ$ resolution European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Re-Analyses (ERA-40) and $1.875^\circ \times 1.875^\circ$ resolution National Centers for Environmental Predictions (NCEP) Re-Analysis. On the other hand, their grid resolutions are too coarse to resolve many small scale features for the relatively small Caspian Sea which is $\approx 4^\circ$ in width. For this reason, the use of much finer horizontal resolution products is of particular importance. In addition, the general circulation in the Caspian Sea is reported to be cyclonic based on both indirect estimates of currents (floats, bottles or dynamical methods), and a few hydrodynamic interpretations (Terziev et al., 1992; Bondarenko, 1993). However, results from these studies are limited in time and space. Thus, there is lack of information about upper ocean quantities in the Caspian Sea, making an eddy-resolving ocean model essential to examine the spatial and temporal variability of various variables over the seasonal cycle.

Given the lack of reliable eddy-resolving numerical ocean models for investigating the main oceanographic features in the Caspian Sea, including their dynamical and physical processes, there is a strong motivation to develop one, which is one major focus of this study. Therefore, we introduce a fine resolution Caspian Sea model and use it to study the main oceanic features in the region. The model combines the advantages of different coordinate systems within a single framework to allow for the optimal coordinate choice in simulating coastal and open ocean features in the Caspian Sea. Along these lines, the main objectives of this paper are to examine (1) the general and mesoscale ocean circulation features over the seasonal cycle, and (2) the impact of rivers, evaporation, precipitation and salt fluxes on the sea surface salinity (SSS).

2. Caspian Sea HYCOM

While a fine resolution ocean model is essential due to reasons mentioned above, at present, the enclosed Caspian Sea is a forgotten component of a global ocean system. It is included neither in high resolution eddy resolving ocean models nor in existing operational models. Examples of such fine resolution models are provided in Table 1. In addition, the existing modeling studies in the Caspian Sea have been limited in scope. Earlier studies used shallow water and diagnostic models, which have very coarse resolutions (e.g., Shkudova, 1973).

Here, we introduce a HYbrid Coordinate Ocean Model (HYCOM) configured for the Caspian Sea. The model is based on a primitive-equation formulation (Bleck, 2002). It contains five prognostic equations: two for the horizontal velocity components, a mass continuity or layer thickness tendency equation and two conservation equations for a pair of thermodynamic variables, such as salt and potential temperature or salt and potential density.

HYCOM uses a generalized (hybrid isopycnal/terrain-following (σ)/z-level) coordinate system. In particular, it behaves like a conventional σ (terrain-following) model in very shallow oceanic regions, like a z-level (fixed-depth) coordinate model in the mixed layer or other unstratified regions, and like an isopycnic-coordinate model in stratified regions (e.g., Bleck, 2006). The model uses the layered continuity equation to make a dynamically smooth transition to z-levels in the unstratified surface mixed layer and σ–levels in shallow water. The optimal coordinate is chosen at every time step using a hybrid coordinate generator. The model presented here is a stand-alone ocean model with no assimilation of any ocean data, including SST, and no relaxation to any other data except SSS to keep salinity balance on track as will be explained later.

2.1. General features

The Caspian Sea HYCOM is set up with a grid resolution of $1/25^\circ \cos(\text{lat}) \times 1/25^\circ$ (latitude $\times$ longitude) on a Mercator grid. Zonal and meridional array sizes in the model are 354 and 204, respectively. The Mercator grid has square cells with a resolution of $0.04 \times \cos(\text{lat}) \times 111.2$ km. This corresponds to 3.5 km resolution at the southern regions (at 38°N) and 3.1 km resolution at the northern regions (at 46°N). Thus, the average grid resolution can be considered as $\approx$3.3 km.

Table 1
Examples of OGCMs excluding the Caspian Sea.

Resolution	OGCM	Reference
1/32°	NRL Layered Ocean Model (NLOM)	Shriver et al. (2007)
1/16°	Mediterranean Forecasting System (MFSTEP)	Pinardi et al. (2003)
1/12°	Danish Meteorological Institute (DMI)	Buch and She (2005)
1/12°	HYbrid Coordinate Ocean Model (HYCOM)	Wallcraft et al. (2008)
1/8°	Navy Coastal Ocean Model (NCOM)	Barron et al. (2006)
1/3°	MERCATOR	Ferry et al. (2007)
1°	Forecasting Ocean Assimilation Model (FOAM)	Bell et al. (2006)