4. Tidal Current in the Bering Sea: Shelf-deep Basin Exchange

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Abstract

The focus of investigations is a description of the enhanced tidal currents and their possible role in the exchange between shelf and deep Bering Basin. Dynamics of the tidal currents are shown to be closely related to the tidal period. In both semidiurnal and diurnal bands of oscillations, the tides travel from the North Pacific through the deep basin onto the shelf. The enhanced tidal currents for both bands of oscillations are generated due to topographic amplification. Examples of such amplification occur during propagation of tides from deep to shallow water over the continental shelf slope, in proximity to the land and islands and also in the narrow passages and straits. The most conspicuous topographic enhancement occurs in the triangular-shaped Bristol Bay where M2 tide current increases to about 100 cm/s. In the diurnal band of oscillation, the enhanced currents are generated not only due to the topographic amplification but also due to the tidal shelf waves trapped against the continental shelf slope. Numerical computations and observations are applied to identify diurnal tidal currents related to the trapped shelf waves. Investigations revealed two major regions of diurnal tide enhancement: a) off Cape Navarin, and b) close to the Aleutian Islands between 170°W and 173°W. The lesser regions of diurnal tide enhancement are located along the shelf break where diurnal tides depict local maxima in the sea level distribution. Nonlinear interactions of the strong tidal currents also have been investigated. To study tidal current rectification over the bottom topography, we used locally a high-resolution numerical model.

Introduction

A region of high, sustained, production of phytoplankton lies just seaward of the continental shelf in the Bering Sea during summer (Springer *et al.*, 1996). This region supports an enormous biomass of resources, including seabirds, mammals and fish. The sustained biological productivity is related to an oceanographic front which extends some 1000 km and overlies the continental slope of the Bering Sea year round (Kinder & Coachman 1978). The front marks the transition between deep basin and shelf physics, *i.e.*, change from geostrophic flow over the deep basin versus a tidally dominated flow over the shelf (Pearson *et al.*, 1981, Mofjeld 1986, Liu and Leendertse 1990, Kowalik 1998). Four physical mechanisms can play important role in the material transport between shelf and deep basin waters in Bering Sea. These are: (a) permanent currents, (b) mesoscale eddies traveling from deep water to the shallow water, (c) topographic enhancement of the tidal current, when tides propagate from deep to shallow water and, (d) local enhancement of the diurnal tidal currents caused by the local resonance at the shelf break.

Because the Bering Slope Current is often slow, the tidal currents dominate in the water motion in this region. Long series of current data in the Pribilof Canyon analyzed by Schumacher & Reed (1992) showed that the Bering Slope Current is modulated by fortnightly tidal oscillations generated through an onlinear interaction of diurnal tidal constituents. During spring tides, low-frequency current speeds approached 20 cm/s; whereas during neap tides, there were weak reversals in the flow. The interaction of the tidal currents with the steep shelf break generates upwelling (Coachman, 1986) maintaining exchange of water between deep and shallow domain. Both measurements and high resolution computations suggest that diurnal tidal currents are trapped as shelf waves in small local domains along the shelf break. In the Bering Sea, the major areas of enhanced diurnal tidal currents are located in Amukta Pass (Aleutian Islands) and close to Cape Navarin (Kowalik, in press). Smaller domains are located in proximity to Pribilof and Zhemchug canyons (Kitani & Kawasaki 1979, Schumacher & Reed 1992). The occurrence of the enhanced currents in the local regions along the shelf break also modifies the exchange mechanism between shelf and deep oceanic waters (Kowalik, in press).

Numerical Model

We began computation in the entire Bering Sea with a resolution of about 10 km because this resolution is sufficient to describe tidally generated trapped shelf waves. Even so, this grid size does not resolve fully the nonlinear tidal interactions. For the proper investigation of the nonlinear terms, the tidal ellipse (tidal excursion) length ought to be resolved. Often tidal excursion of the water particle is of the order of several kilometers. This limits resolution to several hundred meters. In the Bering Sea, high resolution bathymetry is available only around islands and close to the Alaska shoreline. In vast areas of the Bering shelf and in the deep basin, the bathymetry is poorly known. The model domain includes the Bering Sea and a small portion of the North Pacific, from 48°N to 67°N and from 154°E to 142°W (Fig. 1, upper panel). The depth distribution for the numerical model is based on an ETOPO5 (5 ¢ grid spacing) file with many corrections compiled from the available charts. To study nonlinear effects, a domain around the Pribilof Islands was chosen. Here the fine horizontal grid step of 1.852 m was introduced and afterwards, around one of the islands (St. Paul Island), the super-fine grid of 617 m was used to obtain results for comparison against measurements (Kowalik and Stabeno, in press).

The basic tidal equations and boundary conditions are described by Kowalik (in press). Generation of the tidal constituents is done through the open boundaries of the computational domain and through astronomical forcing given in equations of motion. The boundary condition at the coast is defined as no normal flow. Along the open boundaries, amplitudes and phases for every tidal constituent are specified. This is accomplished through the results obtained by Kantha (1995) and Schwiderski (1979). The computations of mixed tides (seven waves) were carried out for a two-month period. After one month, the full energy of the system became stationary. During the second month, the sea level and velocity were recorded every hour for the harmonic analysis.

Results

The tides enter the Bering Sea as progressive waves from the North Pacific Ocean, principally through the central and western passages of the Aleutian-Komandorski Islands. These tides are dominated by four constituents: M2, N2, K1 and O1 (Pearson *et al.*, 1981). The important features of tidal dynamics which were examined with the help of the model, are:

a) Distribution of enhanced currents in the semidiurnal band of periods.These often occur in shallow water, resulting in enhanced local mixing and tidal fronts.

b) Distribution of the tidal currents and regions of near-resonant trapped tidal waves in the diurnal band of periods.Trapped tidal waves often occur at the edges of continental shelves. Therefore, they are important in the dynamical coupling and exchange of properties between shelf and deep ocean.

c) Position and patterns of the residual currents. These currents occur permanently along horizontal and vertical directions. Often, along the horizontal direction, the residual motion occurs as clockwise and counterclockwise eddies. Residual currents play a considerable role in both small and meso-scale transport of nutrients and plankton in shallow water and between shelf and deep waters.

Propagation of the M2 constituent follows bathymetric division of the Bering Sea into the deep basin, where a small change in amplitude and phase occurs, and the shelf basin with many amphidromic points due to partial reflection of the tide wave in the semi-enclosed water bodies. The amplitudes increase in the narrow and shallow bays. The most conspicuous amplitude enhancement, up 150 cm, occurs in triangular-shaped Bristol Bay. All islands, small and large, introduce disturbance into otherwise smooth distribution of amplitude. The different velocity magnitude at the shelf and in the deep Bering Sea is obviously due to bathymetric enhancement of the tidal currents (Fig. 1, middle panel). Strong currents greater than 100 cm/s develop between Aleutian Islands due to narrow passages, and in Bristol Bay due to the elongated triangular shape of the bay. Also, high velocity of the order of 50 cm/s occurs close to the Pribilof Islands, St. Matthew Island, and in the strait dividing Nunivak Island from Alaska (Etolin Strait). The major constituent in the diurnal band K1, when compared against M2, shows a stronger tendency for interaction with the bathymetry. Over the deep Bering Sea basin at the Shirshov Ridge, where the M2 tide generated currents close to 5 cm/s, the K1 current is enhanced up to 10 cm/s. The strongest currents of the order of 100 cm/s occur in the Amukta Pass, Aleutian Islands. The

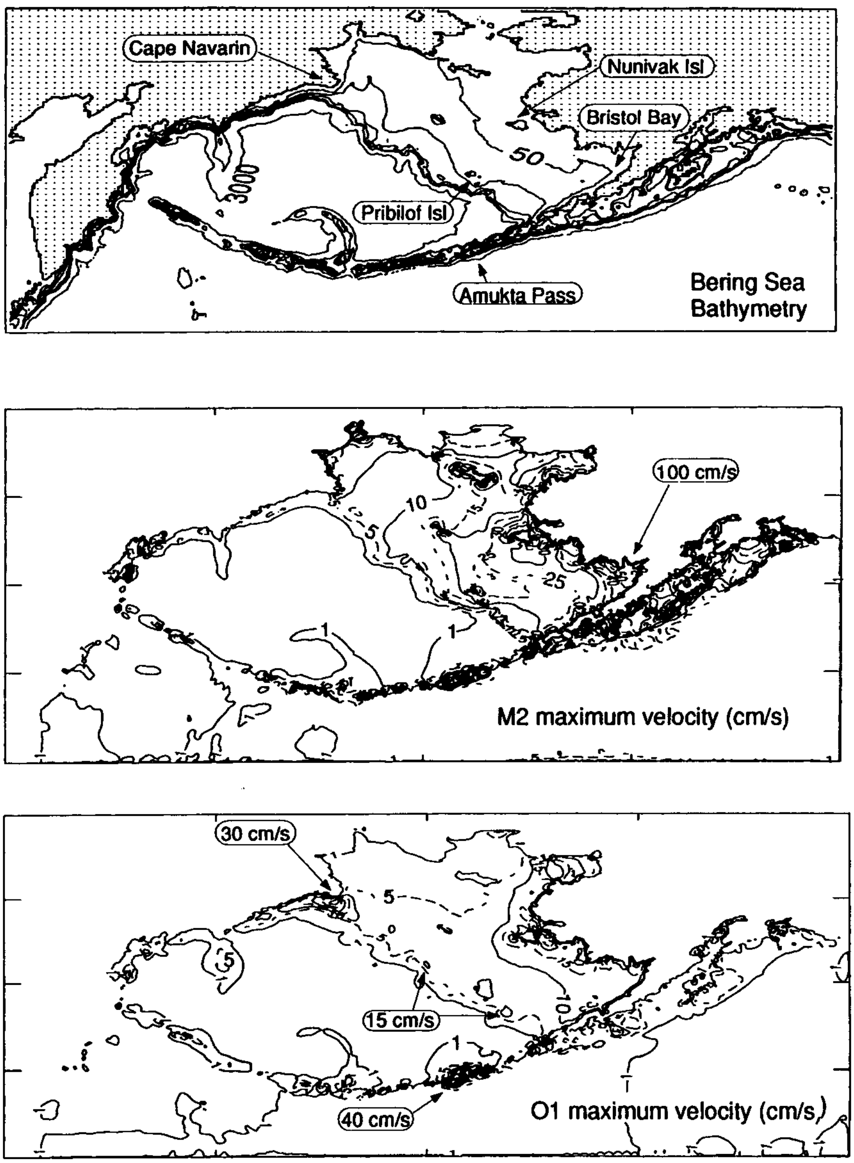

Fig. 1. Bathymetry and maximum velocity components of M2 and O1 tide in the Bering Sea.

currents of about 50 cm/s are located south from Cape Navarin and in Etolin Strait. The maximum velocity for the O1 tide is shown in Fig. 1, lower panel. This constituent depicts even more effectively the three dominant regions of current amplification: off Cape Navarin, Amukta Pass and Etolin Strait. The largest currents are close to 40 cm/s.

The nonlinear interactions of the tidal currents result in the new dynamics, which often differs from linear dynamics. The energy of the basic tidal constituents is transferred toward shorter and longer periods and the tidal currents averaged over tidal period generate steady (residual) current. In numerical computation, the residual velocities for the several constituents interacting together have been obtained by averaging an hourly time series over a period of 29 days. Even computations carried out with a numerical lattice of 9.26 km in the entire Bering Sea show quite developed residual motion. Most interesting is residual current along the Bering Sea shelf break. The local residual currents generated in proximity to the shelf break are interconnected, resulting in a single flow-through along the Bering Sea shelf slope from southeast to northwest. The average velocity of this current is less than 1 cm/s. Strong tidal currents, through nonlinear interactions, generate quite strong residual currents at two regions where the wide Bering Sea changes into the narrow shelf, *i.e.*, close to Cape Navarin and in proximity to the Aleutian Islands. Residual currents off Cape Navarin are generated due to trapped diurnal shelf waves. The pattern of a mean circulation depict a pair of eddies rotating in opposite directions with a speed close to 5 cm/s. These eddies are not confined to the shelf domain only, they extend below the depth of the shelf break as well. This is probably an indication that these eddies play an important role in the exchange of properties between shelf and deep ocean.

Discussion

Maximum production in the northwest Bering Sea occurs, according to Springer and McRoy (1993), in pools of especially prolific growth. The investigations carried out during ISHTAR (Coachman and Hansell, 1993) suggest an advective supply of nutrients to these pools via a north-flowing current that originates along the continental slope and bifurcates at Cape Navarin. This is a source region and the pathway for elevated primary production throughout spring, summer and fall (Iverson *et al.*, 1979). At the present time, the pathways for the nutrients and phytoplankton in this region are not clear. Computations off Cape Navarin show strong tidal currents not only at the shelf but at the shelf break as well. This suggests the possibility of tidal pumping of nutrients from the deeper water to the shelf domain and subsequent transport of nutrients and plankton by residual tidal currents into the Gulf of Anadyr.

Mean residual flow can be a major driving mechanism for circulation around islands and in the passages between the Aleutian Islands. The presence of the strong residual currents in the Aleutian passages will certainly have a bearing on how tidal effects are to be incorporated into mechanisms that contribute to exchange of properties between the North Pacific and the Bering Sea.

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