Modeling spring hydrodynamic regime of surface waters in Kamchatka Strait

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On the basis of numerical modeling, an analysis of the average multiyear pattern of the spring circulation of surface waters in the Kamchatka Strait is performed. It was revealed that in the spring period the winter regime of water circulation continues here, however, the transition to the summer circulation mode begins and the influx of warm Pacific water masses to the Bering Sea is intensifying. The results obtained are somewhat different from the generally accepted ones. *KEYWORDS:* Aleutian Island Arc; Kamchatka Strait; Kamchatka Current; winter and summer monsoons; water circulation.

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Introduction

The straits of the Aleutian island arc are important for the formation of many natural processes in the Bering Sea and the North-Western Pacific, providing water exchange between them.

The Aleutian Islands are located in the zone of temperate latitudes, which creates the basic features of its climate (Figure 1).

This region is under the constant influence of the Polar and Hawaiian atmospheric maxima and seasonal large-scale baric formations (Aleutian Low, Siberian High, and Asian Depression). The winds of the north, north-west and north-east directions prevail in winter, and the winds of the south, south-west and south-east directions dominate in summer. Cyclonic eddies forming between the Polar and Hawaiian atmospheric maxima largely create the climate and weather of the Aleutian Islands. 50–60 cyclones reach the Barents Sea during the year, a significant number of which passes over the western islands of the Aleutian Arc (Figure 2).

The Aleutian Island arc is separated from the Kamchatka Peninsula by the Kamchatka Strait. It is the deepest strait of this region (see Figure 1). The Kamchatka Current carries cold, slightly saline waters of the Bering Sea through this strait into the Pacific Ocean.

It is known that the general circulation of the Bering Sea is formed by the cyclonic gyre, which is a continuation of the large-scale stationary subarctic gyre in the Pacific between 40°–60°N. [*Arsenyev,* 1967; *Cokelet et al.,* 1996; *Khen,* 1989; *Khen and Basyuk,* 2005; *Khen et al.,* 2013; *Reed,* 1995; *Solomon and Ahlnas,* 1978; *Stabeno and Reed,* 1994; *Stabeno et al.,* 1999; *Takenouti and Ohtani,* 1974]. The Kamchatka current is the western link of the indicated cyclonic circulation. This current is characterized by active spatial-temporal variability, in connection with which large-scale variability of water exchange with the Pacific Ocean also occurs. The results of the analysis of these processes are described in [*Khen and Zaochniy,* 2009].

The harsh climate, large-scale baric formations, unstable hydrodynamics, a large number of cyclones, and rugged bottom relief complicate the study of water circulation in the Kamchatka Strait. In this connection, only some aspects of the summer spatial-temporal hydrological characteristics and water exchange in the Kamchatka Strait have

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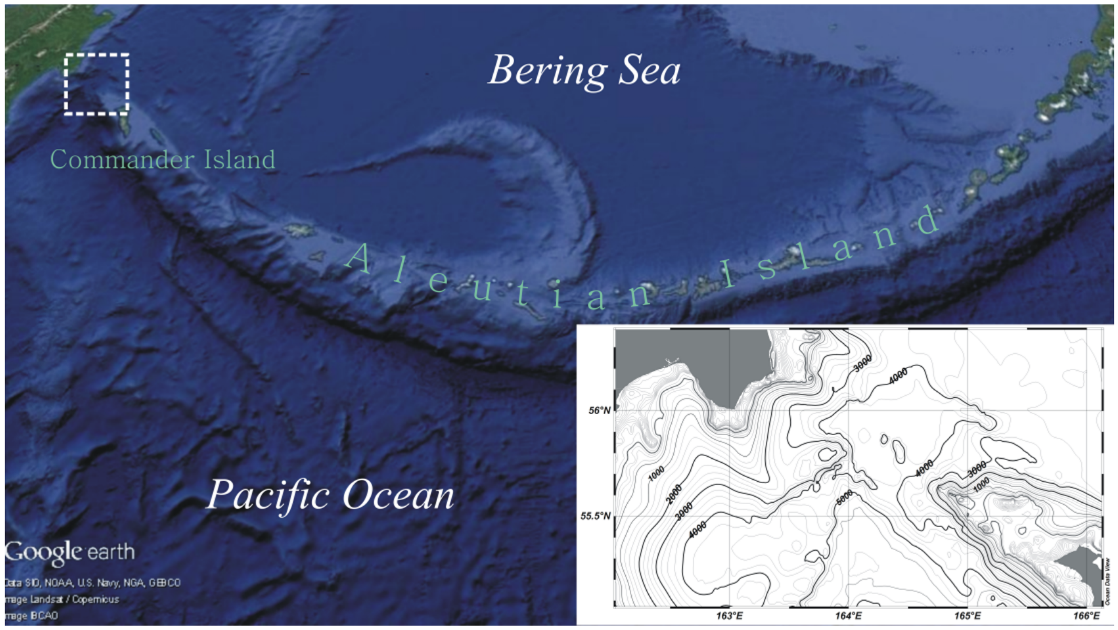

Figure 1. Map of the Aleutian Archipelago. The dotted line shows the research area.

been studied at present [*Khen and Zavolokin,* 2015; *Khen and Zaochniy,* 2009; *Luchin,* 2008; *Overland et al.,* 1994; *Prants et al.,* 2014; *Rogachev and Shlyk,* 2008, 2010; *Solomon and Ahlnas,* 1978; *Zhabin et al.,* 2010]. Spring transitional period (April–July) is practically not been studied. This determined the purpose and objectives of our research.

The purpose of our research is to study the average multiyear pattern of the spatial and tempo-

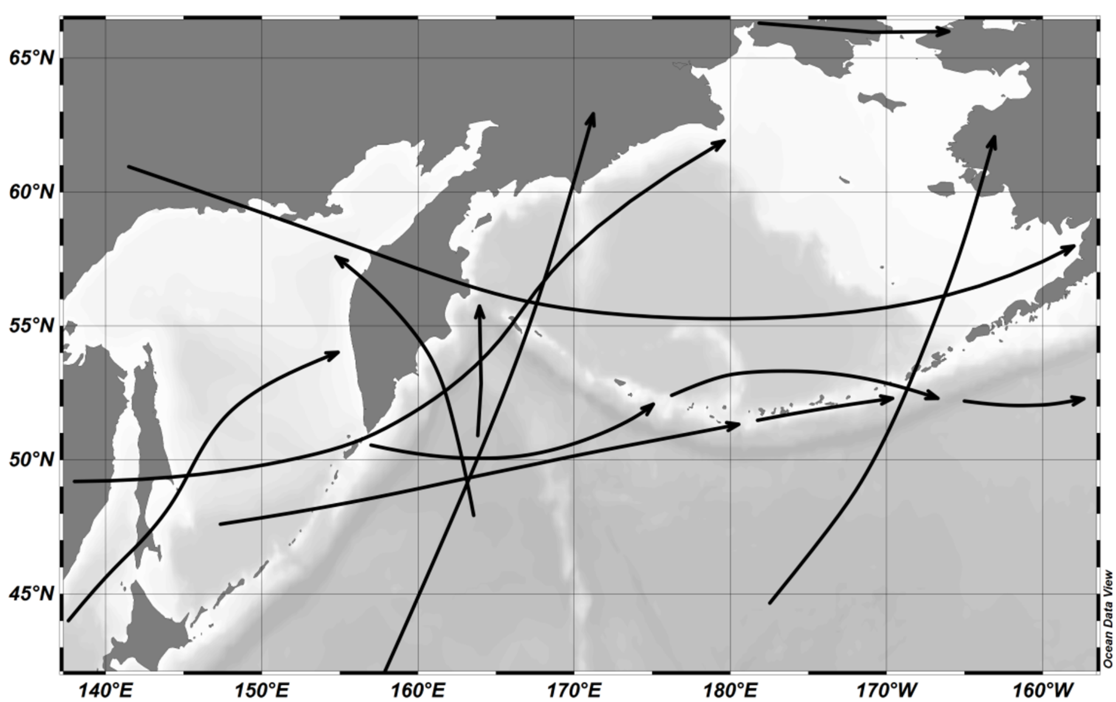

Figure 2. Cyclones trajectories in the Pacific (Polyakova A. M., 2010, Calendar of synoptic situations over North Pacific, http://pacificinfo.ru/en/climate/calendar/).

ral variability of surface water circulation in the Kamchatka Strait in the spring season using hydrodynamic model and software "Ocean Data View" (ODV).

The cell size of the grid was chosen taking into account the bottom relief of the study area, which includes not only the shelf, where the Rossby baroclinic radius is 2 km, but also depths over 4000 m.

The study area is limited to coordinates 54°–57°N and 162°30′ – –166°30′ E (see Figure 1).

Data and Methods

To solve these problems, a known quasi-geostrophic model of water circulation was used [*Felsenbaum,* 1956, 1970; *Shapiro,* 1965; *Vasiliev,* 2001, et al.]. This model has been repeatedly described in monographs and articles [*Polyakova et al.,* 2002; *Vlasova et al.,* 2008, 2016a, 2016b, et al.], so here we are limited to its main characteristics.

This model allows to calculate the integral circulation of water in the form of a field of total flows ($S_x = -\partial\psi/\partial x$, $S_y = -\partial\psi/\partial y$) by the tangential wind stress (T) and the density of water (ρ^0) on the sea surface. The calculation of the currents structure and the density of water masses for given parameters T and ρ^0 leads to the solution of the equation for the integral current function $\psi(x, y)$ using the minimal discrepancy method. The function ψ applied on solid boundaries of the water area (coastline), and its normal derivative applied on the liquid boundary.

The model takes into account the vertical distribution of water density, bottom relief, coast orography and the state of the atmosphere over the studied area. Water consumption was determined on the basis of the calculation of the total flows normal to the liquid boundaries of the studied area.

For processing and graphical display of used oceanographic data [*Schlitzer,* 2002, Schlitzer R., Ocean Data View, 2016, https://odv.awi.de], this model has been adapted to the software "Ocean Data View".

Within the framework of this model, the integral functions of the current in the surface layer were calculated. As a result of calculations, the values of surface temperature, salinity, vertical component of current velocity, as well as tangential stress and wind speed, drift and gradient components of current velocity, depth of the homogeneous layer, and other oceanographic and meteorological values in a given period of time were obtained.

The following information was used as the initial information:

- monthly mean values of atmospheric pressure at sea level for May and June from the data set NCEP Reanalysis (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html);
- depth values from the GEBCO30 dataset;
- calculated monthly mean values of surface temperature and salinity based on ODV algorithms (DIVA-gridding) at 5-minute grid nodes according to WOD2013 data for the period 1950–2017.

For the calculations, the spring hydrological period (May, June) was used as an example of the transition from the winter subarctic regime of waters to moderate summer.

Results and Discussion

As noted above, works devoted to oceanographic research directly to the Kamchatka Strait is very few. Nevertheless, the results of these works show that in the Kamchatka Strait there is not only one-sided movement of the Bering Sea waters into the Pacific Ocean, but in different years and seasons there is also two-way water exchange between these basins [*Dobrovolsky and Arsenyev,* 1961; *Wang et al.,* 2009].

In our case, the spring period (May, June) is considered as a transition from winter to summer, when the process of breaking ice begins. Off the southern coast of the Kamchatka Peninsula, the destruction of ice begins in the second decade of May [*Polyakova et al.,* 2002]. In the winter season, the flow of freshened waters is considerably weakened. In May, the ice edge slowly recedes to the north, starting from the eastern coast of the Kamchatka Peninsula. In June, the process of ice destruction accelerates (Figure 3).

Our calculations have shown that in the period under consideration (May–June) a complex hydrodynamic situation is simulated in the studied area.

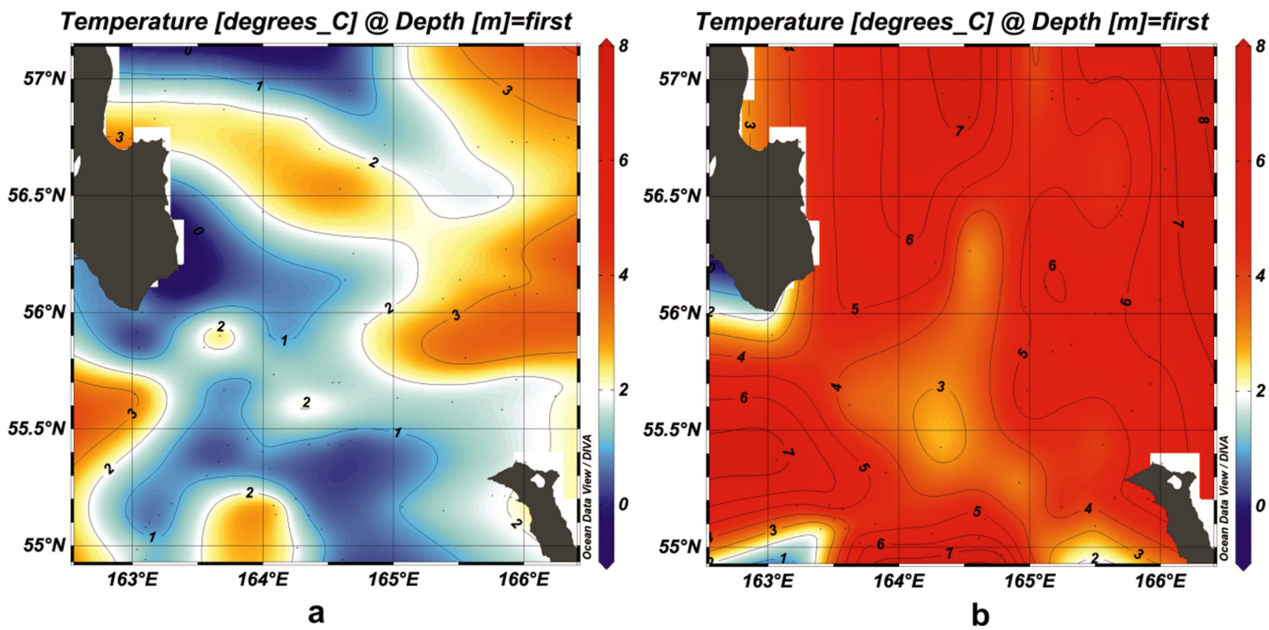

Figure 3. The average monthly surface temperature values calculated on the basis of ODV (DIVA-gridding) algorithms at the 5-minute grid nodes according to WOD2013 data for the period 1950–2017 in May (a) and June (b).

Against the background of a general cyclonic motion, the Kamchatka current does not constitute a single unbroken flow of water masses in the model area. Instead, several hydrodynamic gyres of a different sign are formed here (Figure 4).

Consider this in more detail. First of all, mixed structures form here in surface waters in May and in June. However, the picture of their location and configuration during this period changes.

For example, in May (see Figure 4a) a powerful

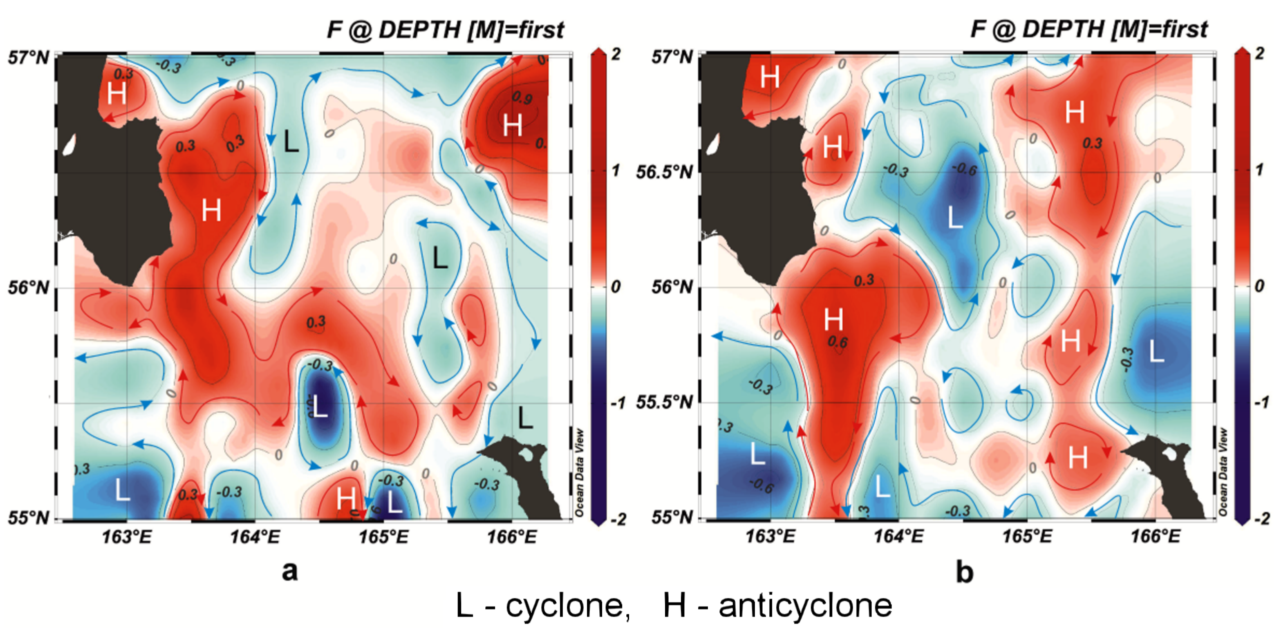

Figure 4. Scheme of surface water circulation in the Kamchatka Strait in May (a) and June (b) according to the simulation results (current functions, 1×10^6 cm^3/s).

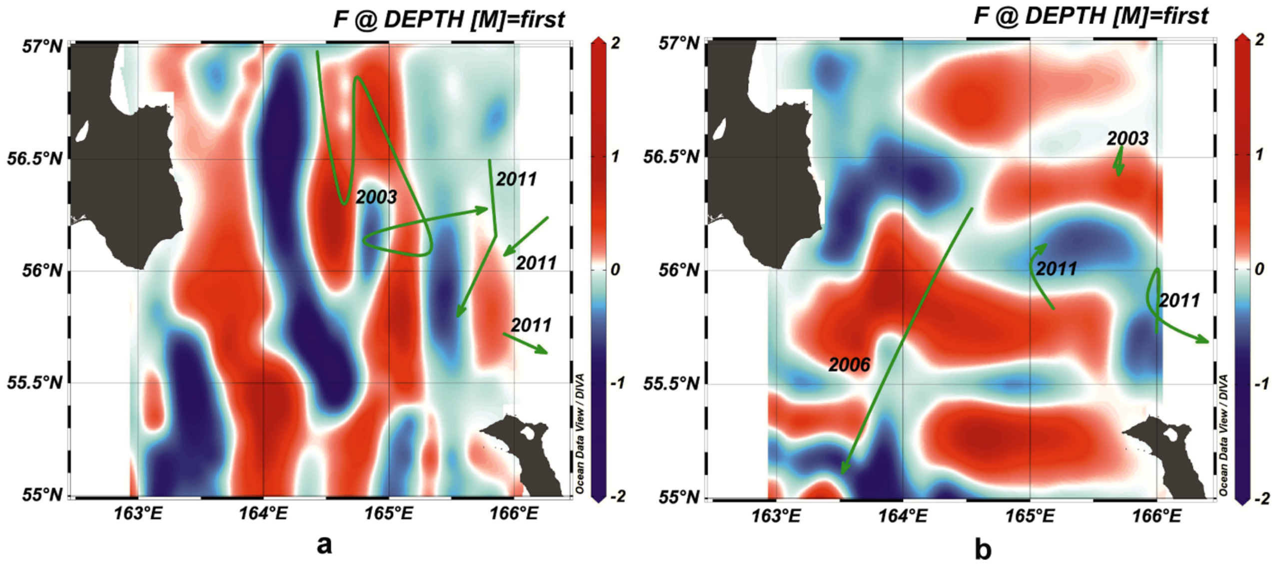

Figure 5. Buoy drift (green lines) at a depth of 200 m in May (a) and June (b), plotted on the water circulation map in the 200th layer.

and extensive anticyclonic gyre forms in the western part of the strait and extends along the coast of Kamchatka between $\approx 55^\circ - 57^\circ$ N. Accordingly, the warm waters of the Pacific Ocean move into the Bering Sea along the shores of Kamchatka; on the contrary, in the eastern part of the strait, the waters of the Bering Sea move into the Pacific Ocean. The formation of this anticyclonic gyre, as well as the pattern of movement of the water masses within it, can be explained by the beginning of the reorganization of the synoptic processes, passing into the regime close to the summer one.

In the eastern part of the strait, near Bering Island, small anticyclonic eddies are modeled with a predominant moving of cold Bering Sea waters into the Pacific Ocean. Thus, in the eastern part of the strait, the winter mode of waters should prevail.

In the center of the strait there are two small whirlwinds of different signs. This provides both a weak runoff of the Bering Sea waters and a weak inflow from the Pacific Ocean.

In June (see Figure 4b), the hydrodynamic pattern changes somewhat, which can be attributed to increased solar activity, accelerated ice destruction and the continuation of surface layer formation processes [*Khen and Zaochniy,* 2009].

In the western part of the strait, the presence of the May anticyclonic gyre remains, however this structure is significantly deformed: it is divided into separate, equally powerful submesoscale gyres. At the same time, the current pattern remains the same; near the Kamchatka Peninsula, it corresponds to the summer mode of waters, and within the eastern branch of the anticyclone – to the winter mode.

In the eastern part of the strait, near Bering Island, the May anticyclonic vortex is preserved and, consequently, the winter mode is preserved.

In the central part, the May anticyclonic eddy is destroyed, which should initiate the preferential runoff of Bering Sea waters into the Pacific Ocean (winter mode).

Despite the diversity of hydrodynamic structures, in the Kamchatka Strait are prevailing anticyclonic activity.

Similar anticyclonic circulation around all the Commander Islands, which includes Bering Island, was noted earlier in the works [*Dobrovolsky and Arsenyev,* 1961; *Zhabin et al.,* 2010; *Prants et al.,* 2014]. In the middle of the last century, an explanation of this phenomenon was given: it is associated with the existence and convergence of the Alaskan and Aleutian currents, the waters of which flow in opposite directions. Transverse irregularity (vorticity) of the wind also affects this phenomenon [*Shtokman,* 1954]. According to other studies [*Timonov,* 1960], this circulation is also supported by tidal phenomena due to the uneven spatial distribution of tidal flow velocities since the study area is located in the zone of active tidal processes [*Zhabin et al.,* 2017].

During the indicated spring period, the atmospheric situation is extremely unstable; therefore, the runoff of desalinated Bering Sea waters does not appear clearly on the circulation maps of surface waters. This can be explained by drift buoys at a depth of 200 m. Thus, Figure 5 shows that buoys practically do not cross the strait (one section in June), but rotate near it or move across.

Conclusion

The results of numerical modeling of spring water circulation in the Kamchatka Strait led us to the following conclusions:

- The modeled structure and dynamics of water circulation in the Kamchatka Strait is somewhat different from the generally accepted one. So, for example, the Kamchatka Current, at least during this season, does not constitute a uniform, unbroken flow of water masses, but is an active vortex zone;
- In the study period, the current system is transformed towards the summer mode. In this regard, the influence of warm Pacific waters is increasing. This is explained by increased solar radiation, the start of ice destruction and the continuation of the formation of the surface layer;
- Despite the diversity of hydrodynamic structures, in the Kamchatka Strait are prevailing anticyclonic activity;
- The differences in the May and June flow patterns are shown.

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