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Modelling of Tracer Transport in the White Sea

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Abstract. We consider advection of floating passive tracer in the White Sea using a hydrodynamical model of sea circulation JASMINE. Simulations show that the Onezhskiy Bay is a hydrodynamical trap for tracers: concentration there decrease more slowly. Typical times needed to remove concentrated tracer completely from bays are estimated. General scheme of tracer advection is described.

Keywords: tracer transport, numerical advection, pollution, hydrodynamical trap, White Sea, JASMINE.

I. INTRODUCTION

The White sea is interesting from a number of points of view. It completely belongs to Russian national waters and is an important object for mariculture, fishery, tourism. Also the White Sea is the gateway to the Arctic, because here the Northern Sea Route begins, an important transport system of Russia that connects Europe and Asia by sea.

The White Sea is a unique hydrodynamical object due to strong currents with stable pattern, high tides, high level of available potential energy; also sea bottom configuration influences significantly on the sea dynamics because the sea is shallow. The Sea can be considered as a model of the Arctic [1] and is a convenient model basin for developing and testing numerical models, software, equipment, and algorithms. Small size and depth, high current velocity, strong level oscillations are a serious challenge to numerical stability of mathematical models and algorithms: time step needs to be small due to the Courant stability condition. Therefore some models suitable for oceans or the Global Ocean are hardly useful for the White Sea. On the other hand, relatively stable pattern of circulation due to strong tides implies low dependence of the Sea state on initial distributions: this facilitates modelling significantly.

The White sea is relatively close to the Atlantic Ocean, belongs to the Arctic basin, this sea is small (600 km from the Kanin Nos cape to the river Kem' mouth), shallow (mean and maximal depth are 67 m and 340 m, respectively). Tidal motion dominates in the sea, though wind currents are also important. The coastline is highly indented. In Summer the Sea is free of ice. River discharge, which is 4% of the Sea volume per year, is quite important. This implies lower salinity of the Sea compared to the neighbour Barents Sea. Subbasins, coasts, and rivers of the White Sea are shown in Fig. 1.

Fig 1. The White Sea. Coasts, subbasins, rivers

Although a large amount of data has been accumulated [2], the distribution is highly heterogeneous both in space and in time; this makes choosing precise boundary conditions and model verification serious challenges.

In this paper we pretend to answer the following questions:

1. How does initially concentrated in a single grid node tracer propagates?

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2. Does a pollution in some region of the Sea disappear from the Sea after some time? What are typical times needed for that?
3. What regions are cleared faster than others, for given initial concentration of pollutant? Are there regions that are cleared faster than others for wide range of initial conditions?
4. Are there hydrodynamical traps in the White Sea, i.e., regions that need more time to be cleared from tracers compared to other regions?
5. What are the roles of wind and tidal motions in tracer advection?

To answer these questions we use numerical modelling. Experiments in this area hardly can be performed and amount of data on this subject is low [3, 4]. One more aim of this article is to offer some observable phenomena that can be proved to exist in future expeditions.

II. MATERIALS AND METHODS

Numerical software complex *JASMINE* is based on the Finite-Element Model of the Arctic Ocean [5]. It allows to evaluate state of the Sea, including sea ice. The early version of the model participated in model intercomparison projects (*AOMIP*, now the Forum for Arctic Ocean Modeling and Observational Synthesis (*FAMOS*), http://web.whoi.edu/famos) and was adapted for the White Sea [6]. The model is described in detail in [7]. External forcing includes atmospheric data from open sources (*NCEP*), run-off of five main rivers (Northern Dvina, Onega, Kem', Kovda, and Mezen'), M_2 tide induced from the Barents Sea. Tide and wind are the most important for our purposes. Boundary values for temperature and salinity on liquid boundaries are monthly mean, provided by expeditions of Northern Water Problems Institute. Horizontal distribution was either 50x50 or 80x80 equidistant points which is equivalent to 8 or 5 km step. Vertical grid consists of 16 levels with smaller step near the surface. Time step is 6 minutes. Tide is described as harmonic oscillation of the outer sea level with phase delay from East to West taken into account. Only the most important M_2 tide is taken into account.

Boundary conditions for scalars in straits (including rivers) are of radiation type if the water goes out and of the third kind if it goes in [8]. Therefore boundary values for all scalar fields, including water temperature, salinity, and all biogeochemical tracers, are necessary. We implicitly assume that the matter disappear in the Barents Sea so that clean water is coming in. This assumption is valid because the Barents Sea is much bigger so that concentration indeed quickly dissipates. However, if we study tracer advection near the sea boundary, the assumption leads to too quick reduction of concentration. For other distributions it works well enough. Boundary condition answers question 2, because any concentration would reduce to arbitrary low values after sufficiently long time. However, typical time of this process is still unknown.

The transport scheme of scalars is based on the Taylor-Galerkin two-layer method [9], with the flux correction transport (*FCT*) according to [10]. This scheme guarantees non-negative solution in a case of the right choice of the “mass diffusivity” parameter in low-order time scheme [10]. Being computationally expensive, the *FCT* approach nevertheless conserves the second order of spatial approximation for smooth solutions and dumps nonphysical oscillations in high-gradient regions.

The open boundary condition for velocity and sea level is the generalized Flather condition [11], with specified M2 tidal component for level (assuming relatively low tidal currents in the Barents Sea), and quazi-geostrophic low-frequency velocities, calculated using observed monthly temperature, salinity, wind stress and sea level. The open boundary is located in the Gorlo. At solid boundaries and at the bottom there are zero fluxes for scalars and quadratic drag for momentum.

Advection is the most time-consuming numerical procedure; therefore it is done in parallel using the MPI paradigm on the cluster of the Karelian Research Centre (http://cluster.krc.karelia.ru).

III. RESULTS AND DISCUSSION

Transport of floating and three-dimensional tracers

Wind, tidal, and other currents are able to transfer tracers. Tracer can be two-dimensional: matter of positive buoyancy distributed over the sea surface; three-dimensional: zero-buoyancy matter distributed in the bulk of the sea; sinking tracer: matter heavier than water; variable-buoyancy tracer with density similar to that of water so thermohaline density fluctuations yield vertical accelerations of either sign. In this article we consider, mostly, two-dimensional tracers. An example is sea-ice (only the drift velocity field can differ from the current surface velocity). By density of a tracer we mean that of dry matter which influences only on buoyancy; concentration is amount of matter of mass per unit water volume. Mathematical description of transport deals only with concentration. A source/sink is any process that increases/decreases concentration in a volume provided that there is no flux through its boundary. River mouths can be considered as sources or sinks (e.g., of salinity), propagation or death of planktonic organisms, chemical reactions, flux of matter from atmosphere to the sea surface of from the sea bottom into the water, different physical sources.

By *floating tracer* here we understand a two-dimensional scalar field of an abstract matter that does not influence on other fields, such as velocity, temperature or salinity, etc, and is influenced only by two-dimensional field of horizontal current velocity.

So the sea state is independent on the tracer which changes only due to transport and sources or sinks. Of course, these assumptions simplify the real situation; however, they look reasonable provided that concentrations are not too high and time span of numerical experiment is not too big. Later we are planning to take into account tracer capture and transport by floating sea-ice, interchange with atmosphere, change of sea water transparency because of the tracer, and so on.

An important example of a tracer is oil films on sea surface. A large class of pseudo-two-dimensional tracers is phytoplankton that lives in the relatively thin euphotic layer. Ichthyoplankton also can be considered as a tracer in areas with strong currents where larvae are not able to resist currents.

Transport of floating tracers differs from that of three-dimensional ones, mostly by dynamism.

Transport in the White sea

Typical pattern of currents in the White Sea was described by Timonov [12] and Derugin [13] and later was improved in [14, 15, 16]. This pattern is formed by tidal quazi-geostrophical circulation. Dominating M2 tidal wave comes from the Barents sea creating high-energy motion in the Voronka, quick currents of changing direction in narrow shallow Gorlo, and quazi-geostrophical circulation in the Bassein and bays of the White sea. Semenov [6] showed that period of this circulation is close to that of the tidal wave, which makes this pattern quazi-geostrophical.

Wind currents are also important. As the Sea is small and shallow, wind is able to create level gradient and change the circulation pattern significantly. Influence of wind currents on transport of the floating tracers is more important compared to three-dimensional ones.

Main components of stable surface circulation pattern of the White Sea is:

- bi-directional current in the Gorlo, which is closer to the right (with respect to current velocity) coast;
- cyclonic rotation in the Bassein;
- eddies in bays;
- chaotic motion in the Voronka;
- currents along Onezhskiy, Letniy, and Zimniy coasts. It is reasonable to guess that these currents are able to take matter from the Onezhskiy Bay to the Dvinskiy Bay and then to Gorlo and to the Barents Sea.

Tracer advection paths agree with typical patterns of sea currents, though it is much disturbed by wind. Tracer initially concentrated in a grid node at the surface spread over the sea up to relatively homogeneous distribution (with less concentration in tops of bays). 3D tracer is dispersed more propagating also to the sea bulk and is less influenced by wind.

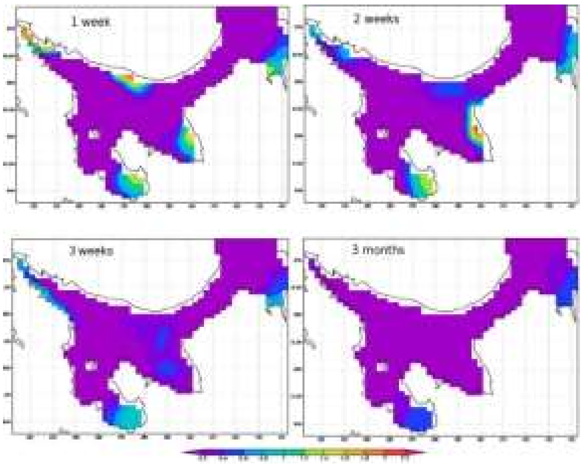

Fig 2. Tracer dynamics

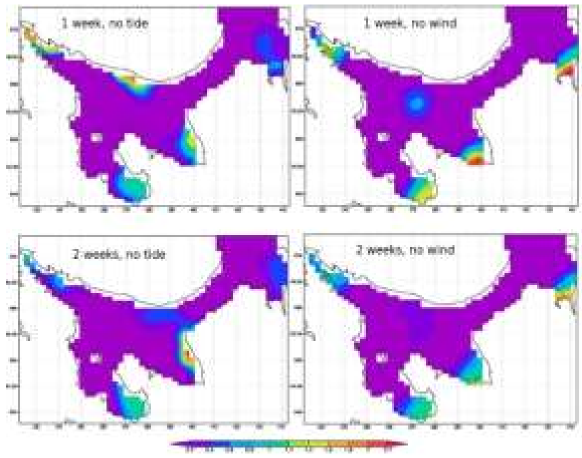

Fig 3. Pure tracer dynamics: wind only and tide only

Let us define sea clean-up by reducing of the concentration 100 times compared to the initial field. Then the Sea is cleaned up of a homogeneous slick covering all surface after 42 months. With no wind (with only tidal circulation) this time is still less than 48 months. With no tide wind currents also clean up the Sea by 42 months. It is interesting that most area of the Sea is cleaned up after 24 months; the rest of the time is needed to clean up the Onezhskiy Bay. Slick on the surface of this bay needs the same amount of time than the whole Sea to be cleaned up. This and other numerical experiments show that the top of the Onezhskiy Bay is a hydrodynamical trap: concentration of matter (both floating and three-dimensional) there reduces much more slowly compared to any other region. Tracer concentrated in one grid node in the top of the Bay needs 6 months to be cleaned up; on the other hand, not more than 3 months are needed to clean up similar tracers from other regions (top of the Kandalakshskiy Bay), while for the Dvinskiy and Mezenskiy Bays, the Gorlo, and the Bassein this time is at most 2 months or less, see Fig. 2. In this figure we show surface concentration of four tracers initially concentrated in a single grid cell in tops of Bays. Left to right, time passed is 1,2,3 weeks and 3 months. Trapped matter is clearly seen.

Matter can enter the Dvinskiy Bay but is not able to leave it: so the term “trap” is valid. There have been no (up to our knowledge) observations that confirm or reject this phenomenon. A consequence of matter caption is pollution of water of the top part of the Bay, because floating litter can be considered a tracer. The Bay indeed is quite polluted; however, this can be also explained by function of Onega and Belomorsk harbours. The mouth of the Onega River can capture pollutants due to shallowness and kennels [17]. Another supporting fact is results of ichthyological observations of larvae of the White Sea herring: in the summer of 2016 they concentrated near the Uhta Bay and were almost absent to the north of it (data of the joint expedition of Oceanology Institute and Northern Water Problems Institute).

Numerical experiments also show that tidal currents take tracers from to the top of the Mezenskiy Bay. Even with no wind, tracer initially concentrated in the Onezhskiy or Dvinskiy Bay concentrates in the Mezenskiy Bay. If a tracer was initially concentrated in this Bay, it leaves it after about 2 months; however, this is rather long because the Bay is near the inter-sea boundary and matter disappears after crossing it. Such behaviour agrees with typical pattern of the White Sea currents, though there are no direct observations of matter transport to the Mezenskiy Bay. Permanently high concentration of dissolved matter in the Bay (optics.ocean.ru) implicitly supports this conclusion.

General pattern of tracer transport is as follows. First the concentrated tracer distributes over the sea surface; then concentration decreases in the Kandalakshskiy and Dvinskiy Bays. The matter is dissipated and carried out of the Sea; however, concentration in the Onezhskiy and the Mezenskiy Bays, as well as near the Terskiy Coast, remains rather high (in these bays it remains higher than in the neighbour parts of the Sea up to complete dissipation). Wind is able to carry the spot into the Kandalakshskiy or Dvinskiy Bay for a short time.

We compared tracer transport in realistic conditions (tide and wind) and that with one of the factors absent (Fig. 3). This figure compares no-wind and no-tide dynamics, while realistic dynamics is in Fig. 2. Wind is very important for floating tracers and is able to change the pattern significantly; however, it is also important for 3D tracers (influence of wind and tide are comparable). For example, evolution of 3D tracer initially concentrated in a single grid node in the Dvinskiy Bay is similar for a long time (up to rather uniform distribution)for these three types of dynamics: realistic, pure wind, or pure tidal. General pattern of floating tracer transport described above changes little if there is no tide, though pure tidal transport preserves pattern in general.

Tracers are diluted by river discharge, more if wind is absent.

IV. CONCLUSION

We considered advection of passive tracers (focusing on floating ones) due to tidal and wind currents by numerical simulations. The Onezhskiy and Mezenskiy Bays are shown to be hydrodynamical traps: they take more time to clear from tracers compared to neighbour regions. They capture matter just due to special circulation patterns and bathymetry. Typical times needed to clear up the Sea and different bays were estimated and shown to be tightly dependent on that for the traps. These times are less than half a year for the Sea in total and the Onezhskiy Bay and less than a few months for other regions. The Kandalakshskiy and Dvinskiy Bays are cleared up more quickly (though the top of the Kandalakshskiy Bay need 3 months to clear up, which is more than that for other Bays excluding the Onezhskiy). This is also true for both purely wind and purely tidal dynamics. Wind was shown to be more important for floating tracers than tide, though qualitative pattern is provided by both mechanisms.

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