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The role of ocean dynamics in the Arctic water contamination*

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Using a rough resolution model of the ice-ocean interaction and seasonal atmosphere climate data, the main feature of the Arctic ocean circulation and ice drift were reproduced. On the basis of the restored dynamics the transport of contaminated materials from the Yenisey river mouth in the Kara Sea was investigated. Two general pathways were finally found: the first one is a passage through the Denmark Strait into the North Atlantic circulation system, and the other is the involvement into the Canadian anticyclonic gyre with a long-living ice as a core.

1. Introduction

The Arctic region waters are now under the threat of gradual contamination with such materials like heavy metals, petrol hydrocarbons, radionuclei and other man-made materials. This fact encourages investigators from many countries to intensify their research into two parallel directions. The first is to determine sources of anthropogenic contamination, and the second is to predict its further development and propagation over the region. It is now recognized that the most significant to contributor polluted materials is the intense atmospheric motion. In winter and spring the Arctic front is moving down to the south, so that the most industrialized areas happen to be involved into the Arctic air mass exchange. The winter atmosphere circulation is the one that keeps contaminating particles in the air when carrying them to the north for a long distance. Most of them are further condensed as snow cover on the icy surface there. Another potential source of contamination is the siberian river system. Flowing down through industrialized areas of Siberia, they transport their waters to the Russian part of the Arctic ocean. The spring season is most dangerous, as too much water moves along its way disturbing the bottom sediments and bringing them down the river into the Arctic shelf zone. This area is suspected to be a contamination source for several reasons. The shelf zone is where the ice is generated and melting down. In summer there is a high fraction of the open surface, so that the exchange between the air and the sea water is allowed. If the formed ice becomes a part of the pack ice, then the pollution drifting into the interior regions is staying there as a continuous source of pollutant

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materials. It can circulate in the Arctic region several decades before living the area and melting down in the warm Atlantic waters. The nuclear waste damping in this area is another source of potential danger.

The contamination moves in the Arctic region according to the main circulation pattern. It consists of an anticyclonic gyre in the Beaufort Sea and the Transpolar drift – a wide-spread area starting from the Bering Strait and moving through the pole region down to Greenland and Iceland.

To respond to the pathways, spreading and live time of contamination, many efforts should be undertaken in many areas of knowledge, involved into the problem of environmental protection. The numerical modeling is one and the most powerful tool in performing scenario calculations to determine contamination trajectories and to evaluate its concentration.

2. Numerical experiment

The propagation of contamination materials and its modelling needs to take into account their specific properties. It is assumed that a special module responsible for describing or parameterizing these materials should be incorporated to the Arctic model. Nevertheless, we consider as a first approach the contamination to be a passive tracer carried by the ice and the surface ocean currents.

The first task is to numerically reproduce a large-scale circulation pattern and ice drift in the Arctic basin. The model of the World ocean hydrothermodynamics was adopted to be an ocean modeling module. It was developed in the Institute of Computational Mathematics and Mathematical Geophysics in Novosibirsk, Russia [1–3]. The region includes the Arctic ocean along with the North Atlantic with 10°N as southern boundary. The grid in the North Atlantic is regular with spacing of 3.75° in longitude and 4.5° in latitude. At 65°N it is merged with a polar region grid. It is an asymmetrical bipolar grid with the poles at 65°N, 10.625°W $\pm$ 90° built according to Murray [4]. The resulting grid has 91×146 km resolution at the North pole. The vertical gridding consists of 25 layers with a finer resolution at the top. The model bathymetry varies from 50 m at the Siberian shelf seas to 4500 m in the North Atlantic.

The adopted ice model is CSIM v.2.2 from the National Center for Atmospheric Research (NCAR) [5]. It should be noted that this model is very similar to the sea ice component used by Washington and Meehl [6] in a fully coupled model of the atmosphere, ocean, and sea ice. Many of the thermodynamic ice growth and melting processes are taken from the previous work, namely, Semtner [7] and Pollard and Thompson [8]. The ice dynamics is based upon the cavitating fluid solution described by Flato and Hibler [9], and used by Pollard and Thompson [8], where the shear and the tensile strength of the ice are neglected and the compressive strength is used to iterate to a representative ice velocity at each time-step. The CSIM code is placed at the NCAR web-site

`http://www.ccsm.ucar.edu/models/ccsm1.4/.`

There is an initial condition data set available on this site as well.

The interaction between the lower atmosphere and the sea and/or ice surface is calculated using the drag law equations. The data set by da Silva et al. [10] presents the climatic lower atmosphere state in terms of wind velocity, air temperature, sea surface pressure, long-wave and short-wave radiation, cloudiness and precipitation rate. The surface flux parameterization differs in case of the free surface and the one covered with ice.

The seasonal salinity data on the ocean shelf boundaries are used to parameterize the fresh water inflow brought by the land river system runoff. These data are the global ocean hydrography data from the PHC [11]. The wind stress from the ECMWF reanalyses data [12] are also used to spin-up the ocean model.

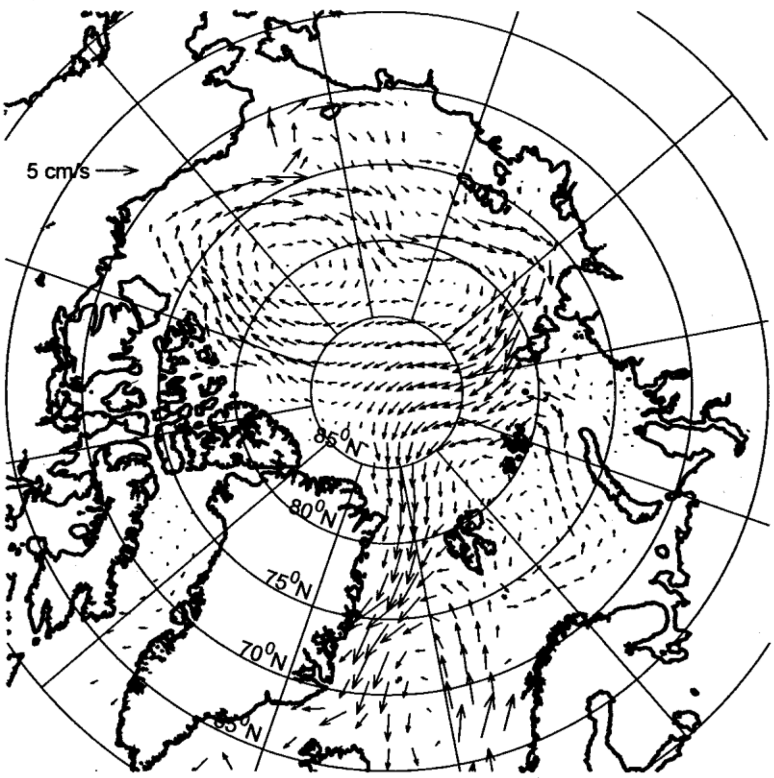

Figure 1. Top ocean currents. Seasonal variations are minimal, because of sea surface is mostly sheltered from varying wind stress by slowly moving ice cover

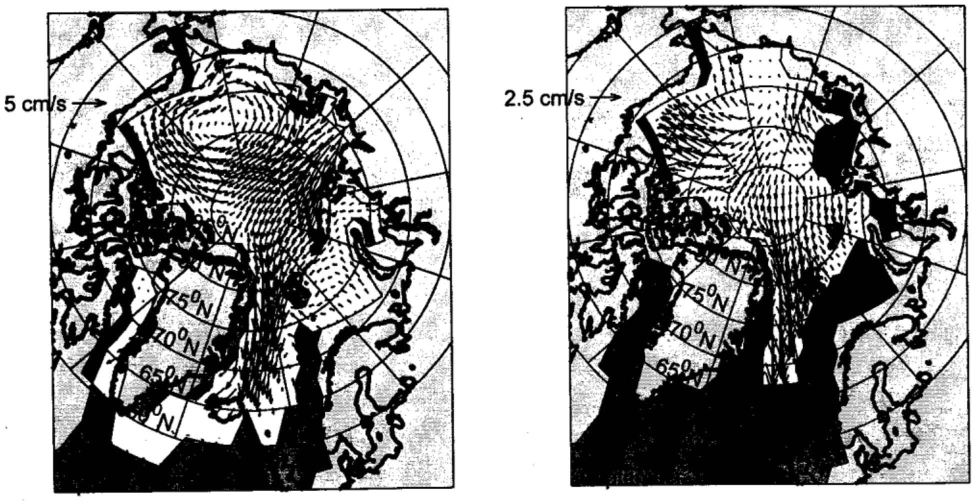

Figure 2. Ice drift velocity. Its seasonal changes are more distinct than that of ocean currents. It ranges from almost typical in winter (left panel) to almost chaotic and slowed down in summer (right panel). White area is the same with any ice presence. Light shadow corresponds to model land area, while dark area is one completely free of ice

We started with homogenous temperature and salinity distribution. After 100 years of the model time simulation the seasonal ocean circulation and the ice drift were reproduced (Figures 1 and 2). The sea surface current (see Figure 1) is not ideal according to a commonly known circulation pattern. Nevertheless, despite of a rough model resolution, the main features of the Arctic water dynamics are reproduced sufficiently well. Among them, the large-scale anticyclonic gyre around the Canadian basin, the Transpolar drift current starting from the Chukchi Sea then following the Lomonosov ridge cross the North pole down to off the Greenland coast, the surface water transport from the Laptev Sea and a stream of Atlantic waters flowing along the Norwegian coast and through the Barenz Sea towards the Novaya Zemlya islands. In the Atlantic, there is a subtropic anticyclonic gyre along with subpolar cyclonic gyre. All these features are out of our current interests except for the part responsible for the water coming from and to the Arctic basin.

Using this circulation pattern as background we can consider the problem of contaminant propagation. Assumingly, it was formed for some reason in the ice cover at the mouth of the Yenisey river. Figure 3 shows the result of the simulation of its propagation. This initial source is placed at the Yenisey river mouth. Upper panels represent the polluted area after 1 year, the middle ones – after 2 years and the lower – after 4 years. The shaded area on plots corresponds to location of more than 10% of maximum

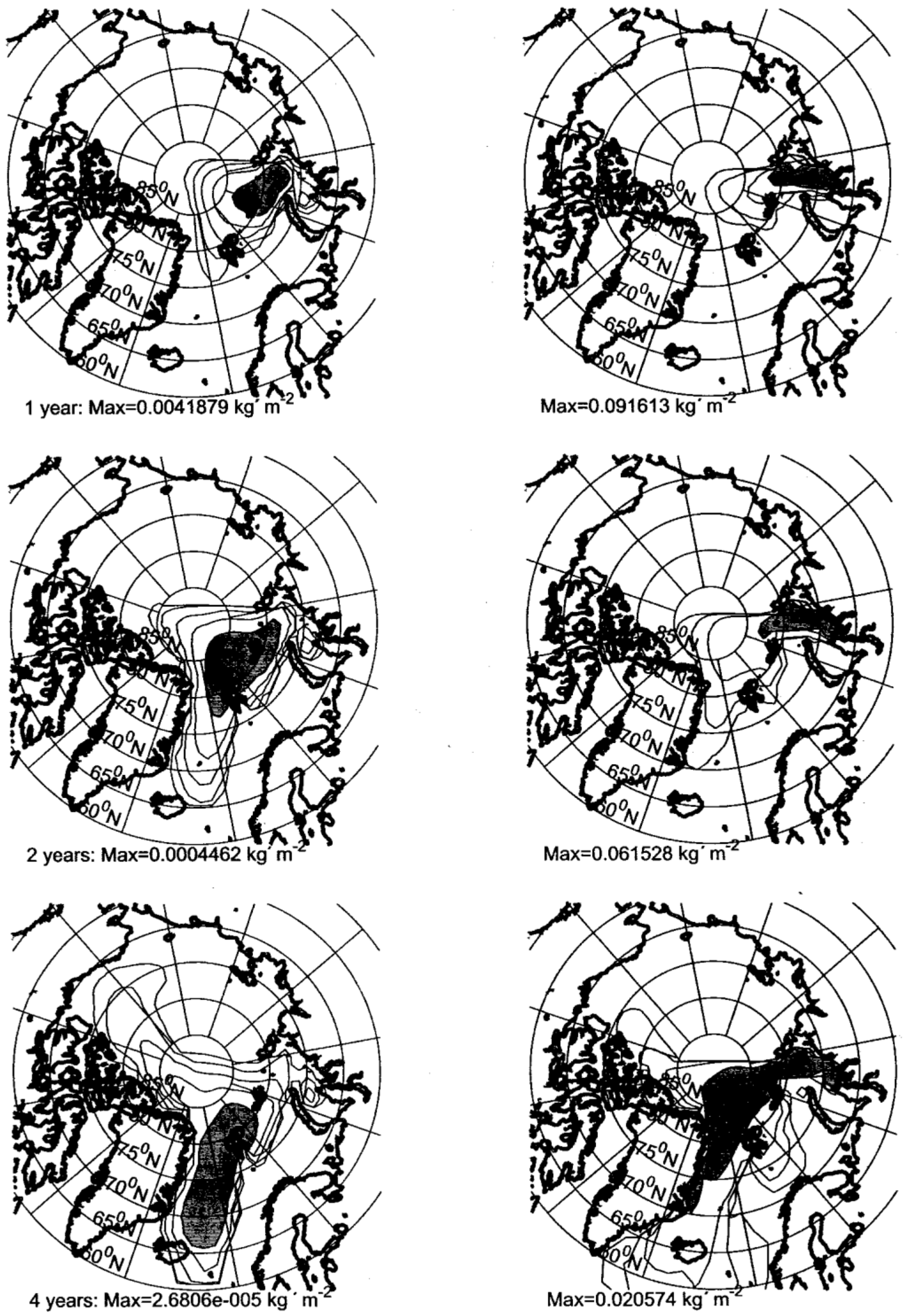

Figure 3. Contamination transport by the ice drift (left panels) and by the upper ocean velocity (right panels)

concentration for ice and more than 1% for water. Maximum concentration is subscribed. Isolines are in logarithm scale with minimum 10^5 of maximum concentration. Due to the large-scale ice drift this contaminant ice moves towards the North pole. According to the ice thermodynamics in spring and in summer a part of this ice melts down and the contamination penetrates into the ocean water. Thus, the ocean currents also becomes responsible for its propagation. It should be noted that according to the model results most of the pollution is carried towards the Greenland coast and further into the North Atlantic both by the ocean current system and the ice drift. In two years or so the dirty ice reaches the Fram Strait and in four years it goes down to the Denmark Strait. In succeeding years the dirty ice appears again off the Greenland coast, and after melting during the spring and summer warmings contributes to the North Atlantic water contamination. This will happen until all this ice disappears because of melting. Another part of contaminated materials comes into the Canadian basin. The concentration here is substantially smaller, but ice in this area is almost permanent. Hence, the contaminated ice once coming to this region will stay here for several decades with almost constant concentration. In contrast to this scenario, the contamination formed at the Lena river delta mostly stays in the Canadian gyre system with a negligible part flowing out to the North Atlantic.

3. Conclusion

Using the rough resolution model of the ice-ocean interaction and the seasonal atmosphere climate data we reproduced the main feature of the Arctic ocean circulation and ice drift. On the basis of reproduced dynamics we investigated the transport of contaminated materials from the Yenisey river mouth in the Kara Sea. Two general pathways were eliminated:

- inclusion into the Canadian anticyclonic gyre system and transport into the central part of the Arctic basin by the ice drift system
- ice transport to off the Greenland coast with subsequent transformation of the contaminated ice into the water fraction during the warm seasons and further propagation by means of the sea surface currents and involvement into the subpolar gyre system of the North Atlantic.

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