Modeling of $\delta^{18}O$ and ^{99}Tc dispersion in Arctic and subarctic seas

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The combined use of observations and numerical modeling of tracers marking water masses from different sources provides a powerful tool for the investigation of the Arctic and Subarctic Seas. On one hand even rather sparse observational coverage enables to use the tracers for model validation. On the other hand, realistic model simulation of tracer dispersion is able to assist the interpretation of observations due to the embedding into the consistent model physics. Two of such tracers are the oxygen isotope ratio $\delta^{18}O$ and the anthropogenic radionuclide ^{99}Tc.
$\delta^{18}O$ has been widely used in observational oceanography to infer river water concentration in the Arctic Ocean surface waters (Bauch et al., 1995; Schlosser et al., 2002) and to distinguish it from ice melt water. The fractionation process occurring during phase changes leads to the precipitation of low $\delta^{18}O$ water over the continent. The river water runoff from Siberia and the North American continent is therefore marked with low $\delta^{18}O$ values while the Atlantic Water in the Arctic Ocean exhibits higher $\delta^{18}O$ values.
^{99}Tc is a soluble radionuclide which has been released since half a century into the Irish Sea and the English Channel by European reprocessing facilities. It disperses into the North Sea and subsequently northward with the Norwegian Coastal Current and the Norwegian Atlantic Current. In the Arctic Ocean it can serve as a tracer for water of Atlantic origin. There has been extensive observational coverage for ^{99}Tc in the North Sea and along the Norwegian coast, with only minor coverage of the Nordic Sea or the central Arctic Ocean (Brown et al., 2002; Kershaw et al., 2004).

Experimental Setup
We have introduced $\delta^{18}O$ and ^{99}Tc as tracers into a hindcast experiment with NAOSIM, the coupled North Atlantic/Arctic Ocean Sea Ice Model developed at the Alfred Wegener Institute for Polar and Marine Research (Gerdes et al., 2003; Karcher et al., 2003; Kauker et al., 2003). The model has been driven with daily atmospheric data from the NCEP/NCAR reanalysis for the period 1948 to 2004, In addition to a moderate restoring of sea surface salinity to PHC climatology (Steele et al., 2001) runoff from the major rivers has been simulated by annual cycles of negative salt-fluxes at the river-mouths. Initial conditions for temperature and salinity are taken from the PHC climatology as well. For the initialization of $\delta^{18}O$ distribution a linear relation with salinity derived from observational data has been applied (D. Bauch, pers.comm.). Inflow values for $\delta^{18}O$ vary for the different rivers from -15 ‰ in Scandinavia to -22 ‰ for the easternmost rivers. For inflowing Atlantic Water at the southern boundary a $\delta^{18}O$ value of 1 ‰ has been applied. The simulation of ^{99}Tc starts in 1970 and is based on an input near Sellafield and La Hague according to documented releases (J. Gwynn, pers.comm, Karcher et al., 2004). Initial condition for ^{99}Tc is zero in the entire domain. The release function is characterized by two maxima centered in 1978 and 1995, respectively.

Variability freshwater dispersion from rivers
The large scale patterns of river water derived $\delta^{18}O$ in the simulation exhibits substantial changes over the 5 decades. The basic pattern consists of low $\delta^{18}O$ values near the river mouths and in the Kara and Laptev Sea where the largest rivers enter the Arctic. From here they feed into the Transpolar Drift (TPD) and move towards the Fram Strait (Figure 1a). This principal structure is

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superposed with large variability in width, location and $\delta^{18}O$ concentration of the TPD on seasonal and longer timescales. This behavior poses an obstacle for the interpretation of observational results, which in the Arctic typically cover space and time only very patchy. An even larger deviation from the canonical picture of river water flow in the Arctic Ocean occurs in the early 1990s, when river water almost entirely moves eastward along the shelves instead of crossing the Eurasian basin with the TPD according to our model simulation (Figure 1b). This deviation of river water flow had already been hypothesized from observations of a retreating cold halocline in the eastern Eurasian Basin (Steele and Boyd, 1998). Measurements of $\delta^{18}O$ on short sections in this basin confirmed this interpretation by showing low river water concentrations in 1996 as compared to 1991 (Schlosser et al., 2002). The simulation reveals that the changes commence in 1989 when the Arctic Oscillation (AO) index switches to record high values for a period of about 6 years. The surface concentration of simulated $\delta^{18}O$ follows the changes of the wind field and the river water is carried eastward in the period 1989.-1994, leaving a significantly saltier surface in the Eurasian Basin. In the recent decade the situation has partially returned to the earlier conditions due to a release of the river water from the east Siberian shelves to the central Arctic and a re-establishing of the TPD (not shown). This is consistent with observations of a partial recovery of the cold halocline (Boyd et al., 2002).
Further investigations of simulated $\delta^{18}O$ will elucidate the relation of river water pathway variability and atmospheric forcing. Special attention will be devoted to the potential of the shelves or single basins to buffer river water runoff before release and to the conditions for the partitioning of river water outflow between the Canadian Archipelago and Fram Strait.

Tracing of Atlantic derived water

The simulated spreading of the two ^{99}Tc release maxima can serve to study the movement and mixing of Atlantic derived water in the Arctic Ocean. The ^{99}Tc tracer is advected into the Arctic with the two major branches of Atlantic Water via Fram Strait and the Barents Sea. In the Barents Sea the Atlantic derived water is know to be separated into different density classes which feed into the central basins. The light surface water recirculates to Fram Strait with the TPD on timescales of a decade. The dense fraction which leaves the shelf through the deep St.Anna Trough circulates cyclonically as mid-depth Atlantic Water layer along the rim of the deep Arctic basins (Figure 2). This pathway, which had been deduced from observations (Rudels et al., 1994) is also the main transit path for the Barents Sea Branch Water in the model simulation, as visualized by the ^{99}Tc tracer dispersion. For the early maximum which has started in the Irish Sea in 1978 we find advective times of about 7 years from the entrance of the Barents Sea to the Laptev Sea slope and about 18 years to the Chuckchi Plateau in the Canadian Basin. For the short route along the Lomonosov Ridge about 16 years are needed to leave the Arctic again through Fram Strait. These advective timescales for the Barents Sea Branch Water compare well with transit times calculated from tritium/He ratio, temperature and salinity from observations (Smethie et al., 2000).

As a next step we will perform multi-tracer simulations including anthropogenic radionuclides, $\delta^{18}O$ and Barium. These shall serve to distinguish the Atlantic water, river water and Pacific water components of water leaving the Arctic to the North Atlantic. Combining these simulations with observations can then help to determine the causes for the variability of the composition and pathways of outflow water at the surface and at overflow depth.

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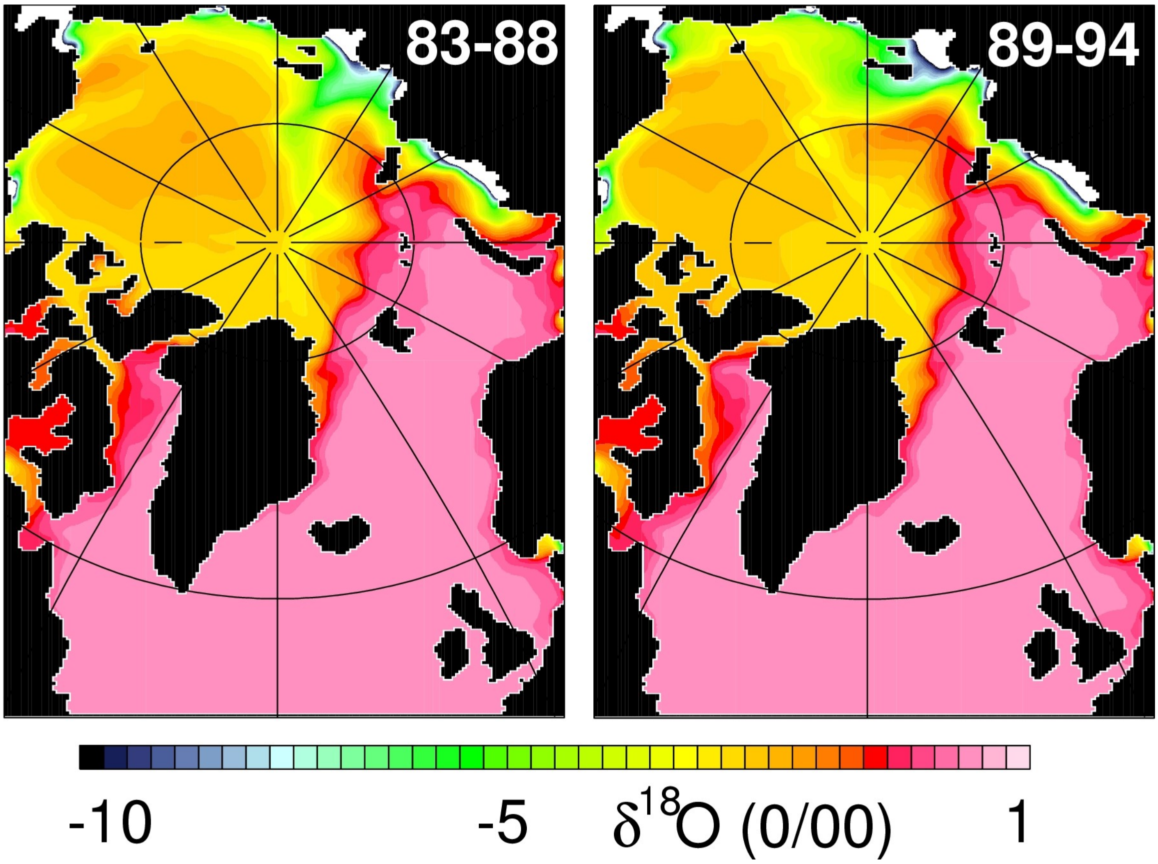

Figure 1: Mean surface concentration of $\delta^{18}O$ as simulated by NAOSIM for the periods a) 1983-88 and b) 1989-94. The shift of the river pathways from the TPD (a) to the eastern Siberian shelves (b) as a consequence of the high AO state in the early 1990s is a prominent feature.

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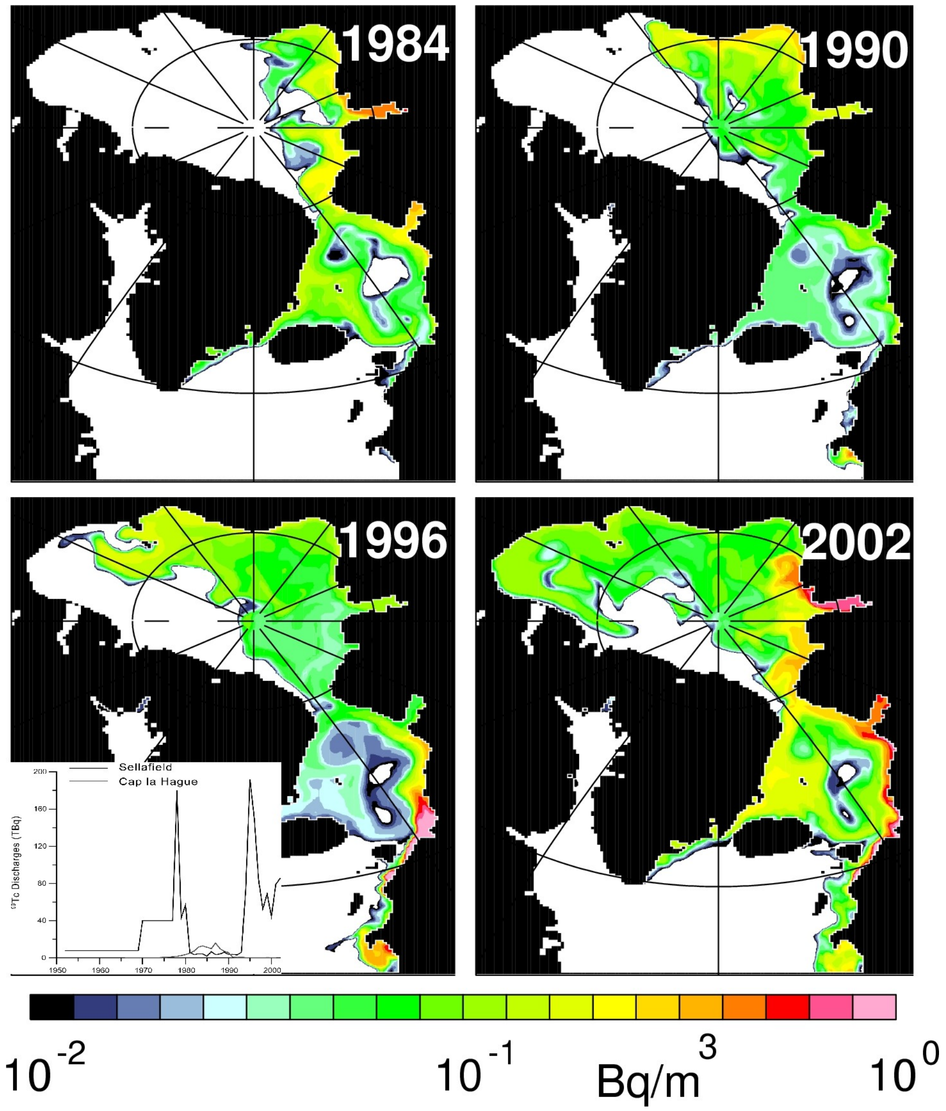

Figure 2: The concentration of ^{99}Tc in the Atlantic Water layer (here at about 350m depth) in successive years shows its propagation into the central Arctic basins. The insert on the lower left visualizes the input function for the radionuclide at Sellafield (Irish Sea) and La Hague (English Channel).