Modeling recent climate variability in the Arctic Ocean without climatic surface salinity restoring

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The variability of sea ice and ocean is investigated for the period 1948-2000 from a coupled ice-ocean model of the Arctic Ocean and GIN Sea [*Neelov*, 1996; *Ryabchenko et al.*, 2001].

The model.

The coupled model includes a 3-D, z-coordinate ocean circulation model and a dynamic-thermodynamic sea ice model. The ocean circulation model is based on non-linear primitive equations of motion written in the hydrostatic and Boussinesq approximations, the equation of continuity, heat and salt transport equations, and the equation of state of seawater in the form suggested by UNESCO. The vertical mixing of the momentum, temperature, and salinity is treated using the 2.5-level turbulent closure scheme [*Mellor and Yamada*, 1982]. The sea ice model uses the dynamics and viscous-plastic ice rheology from [*Hibler*, 1979] and the thermodynamic energy balance from [*Parkinson and Washington*, 1979] with the following modifications: 1) snow at the ice surface is introduced as an additional variable with other albedo values and 2) all melt water is assumed to flow down from the ice/snow surface into the ocean that creates an additional negative buoyancy flux.

Simulations.

The coupled model was integrated on a rectangular grid with grid size of 80 km and 33 levels and forced by mean daily winds, cloudiness, air temperature from NCEP/NCAR reanalysis, the climatic annual transports, seasonal mean temperature and salinity at the oceanic open boundaries, and climatic monthly mean discharges of major rivers. The initialization of simulations for 1948-2000 was taken from the end of 300-year model spin-up with atmospheric forcing repeated for 1948. Restoring of temperature and salinity below 1500m to climatic values taken from PHC 2.1 archive was used both in the spin-up and simulations. Two simulations starting from the same initial conditions have been carried out: s*tandard run* (STD) without restoring of surface temperature and salinity and *run with 30-days surface salinity restoring* (SSR) to annual mean climatic values taken from PHC 2.1 archive.

Results

Standard run. The model results are in qualitative agreement with observed inter-annual changes in the summer ice extent in the Northern Hemisphere (Fig.1a). Ice thickness spatially integrated over the model domain (Fig.1b) decreases by 31% in the 1990's with regard to its value in the 1960-1970's. The data from submarine cruises show an average 42% reduction in the Arctic ice draft for the same periods [*Rothrock et al.,* 1999]. Likewise other models, from the period 1979-1988 to the period 1989-1996, the simulated ice thickness drops in the eastern and increases in the western Arctic Ocean (Fig.2). However, these ice thickness changes are about 2 times smaller than in the case of restoring temperature and salinity below the upper layer [*Zhang et al.*, 2000].

The model results confirm a significant warming and salinization of the Atlantic Water observed in the Arctic Ocean in the 1990s (Fig.3a,b; Fig.4). As follows from this and previous studies, freshening of the upper layer in most of the ocean and strong salinization over the

Eurasian Basin are due to eastward diversion of Siberian river waters because of change in wind patterns, and to transport of increased salinity waters from the Laptev Sea into the Eurasian Basin.

Comparison of STD and SSR runs. The surface salinity restoring leads to a decrease in basin-averaged sea ice thickness and summer ice extent, 0.1-0.2 °C decrease in basin-average surface layer (40m) temperature and 0.7-1.0 psu increase in basin-average surface layer (40m) salinity throughout the period 1948-2000 (Fig.1). SSR predicts about 0.5 Sv smaller inflow and about 0.7-0.8 Sv smaller outflow through the Fram Strait so that the total water transport (outflow from the Arctic Ocean) decreases by 0.2-0.3 Sv (Fig.5). These changes in water transport between the Arctic Ocean and GIN Sea are likely to be due to significant decrease in temperature in the upper ocean (0-400m) and its increase in the deep layer (500-1000m) in the western part of the Arctic Ocean (Fig.6). SSR also gives an increase in salinity almost everywhere with much more rise in the surface layers (Fig.7). Thus, climate restoring weakens the density stratification in the Arctic Ocean, especially in its western part (Fig.8), that eventually depresses Arctic water outflow through the Fram Strait.

Other sequence of events occurs in the GIN Sea. Here climatic restoring leads to significant temperature decrease (more than 1°C in the Greenland Sea) and salinity increase (up to 1.5 psu in the Greenland Sea) in the upper 40m layer (Fig.9). As a result, surface circulation in this region is weakened that is clearly seen from weakening in sea level gradients (Fig.10). Thus, climatic sea surface salinity restoring affects the communication between the Arctic Ocean and the Greenland Sea in a two-way manner. Inside the Arctic Ocean, the restoring weakens the density stratification, which decreases the water mass transport and the outflow of Arctic water. On the other hand, the restoring also changes density structure of the GIN Sea, thus changing (decreasing) the amount of Atlantic water inflow and therefore the amount of Arctic water outflow. As a result, the core of Atlantic water in the Arctic Ocean is shifted down about 200m (See Fig.3b, 3c and Fig.6).

Thus, introducing surface salinity restoring has a significant impact on salinity and thermal states in the oceanic upper and intermediate layers, changes density structure, ocean circulation, sea ice thickness and extent. These distortions are most significant in the intermediate layers and it is expected that the model with climatic salinity restoring would give even greater distortions of ocean response to changing atmospheric forcing if a much longer integration is performed.

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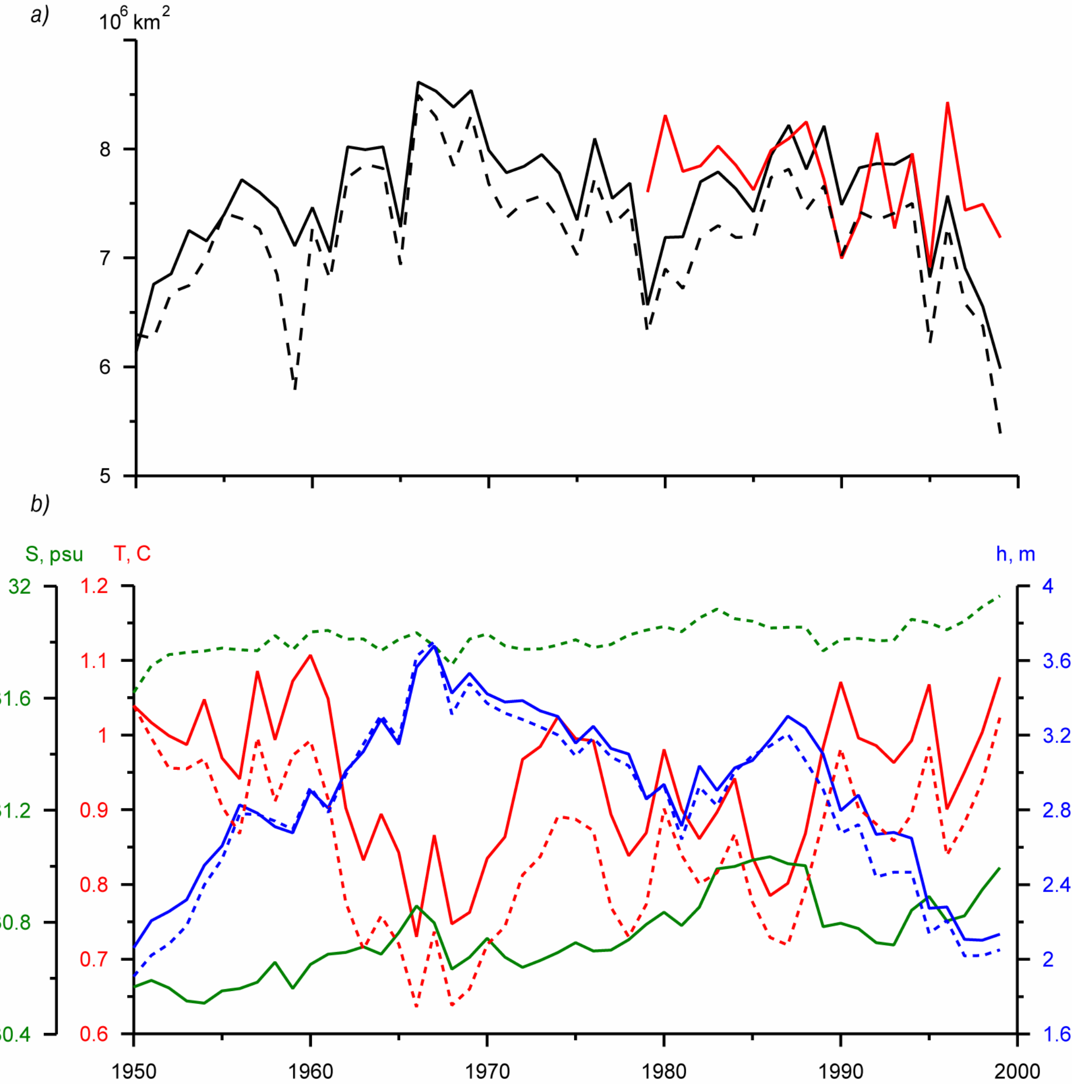


Fig.1. Time series of sea ice extent in the Arctic Ocean in September (*a)*, annual mean ice thickness averaged over the Arctic Ocean (*b*, blue curves), temperature (*b*, red curves) and salinity (*b*, green curves) averaged over the Arctic ocean for the upper 40m in the period 1948-2000. Solid and dashed curves are results relatively from STD and SSR. Red curve in (*a*) is [*NORSEX*, 2001] satellite-derived sea ice extent in the Northern Hemisphere in September.

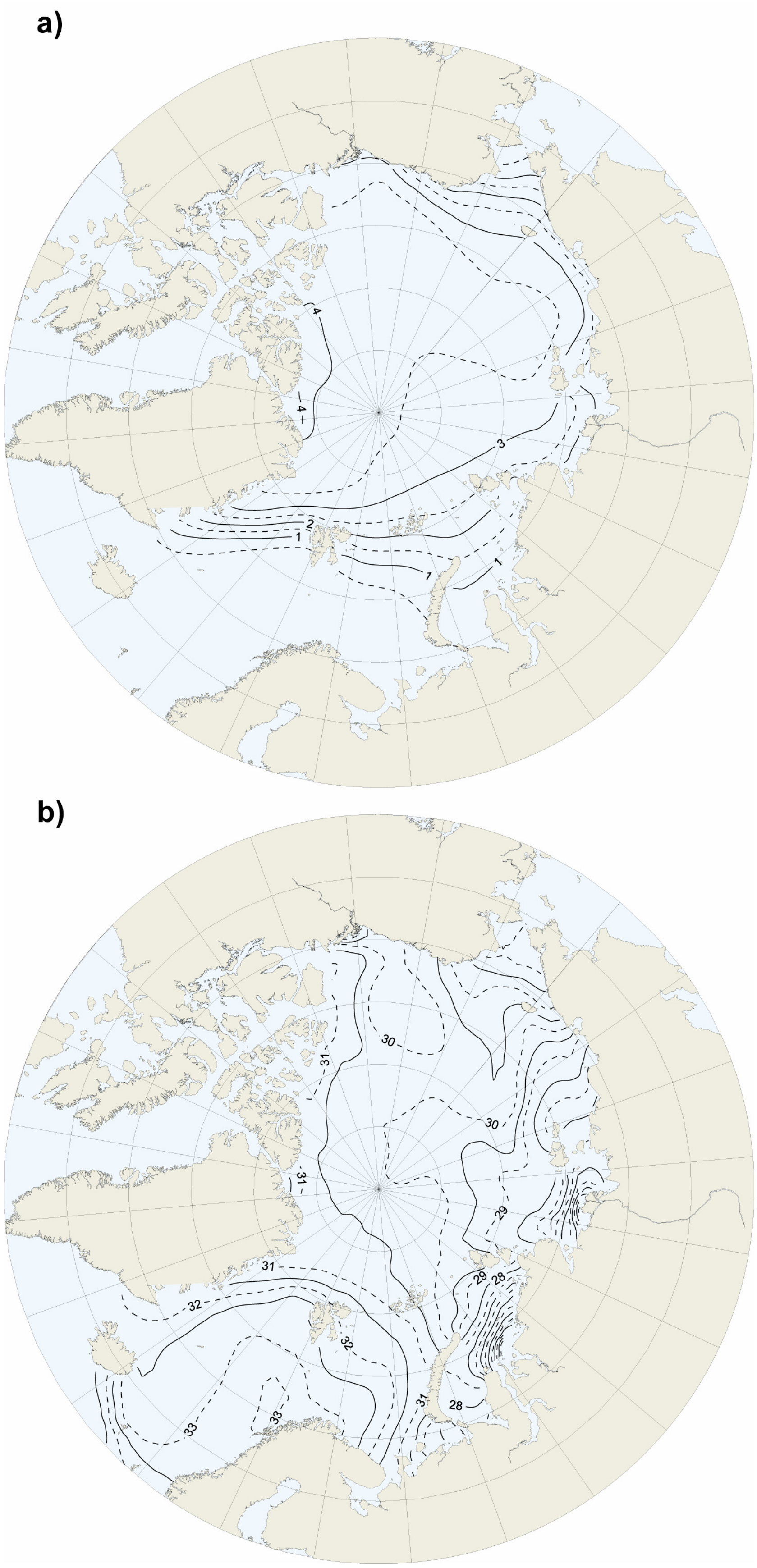
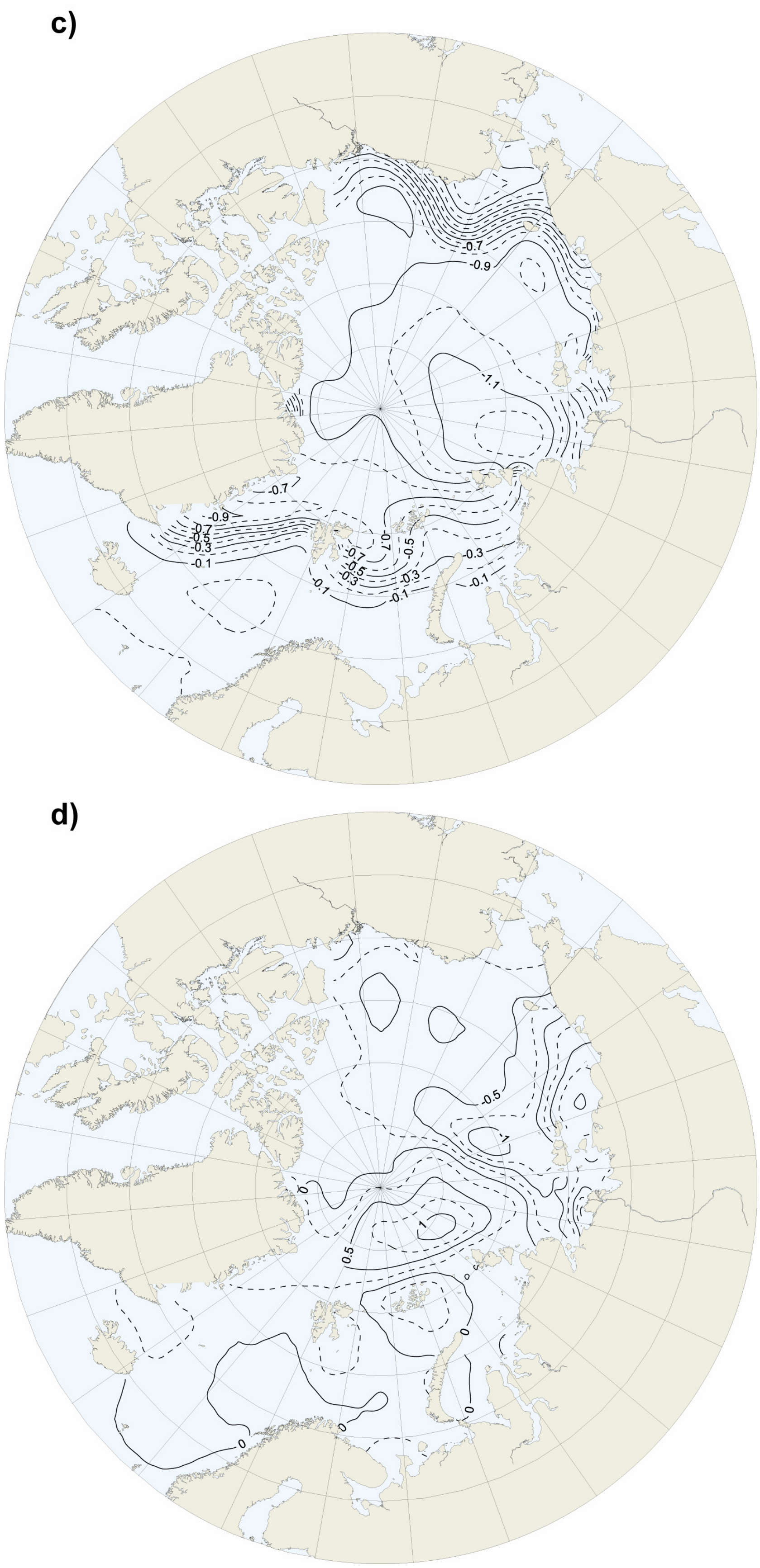


Fig.2. Ten-year (1979-1988) mean sea ice thickness in m (*a*) and salinity in psu averaged over the upper 40-meter layer (*b*) and their anomalies (relatively *c* and *d*) for the period 1989-1996 with regard to1979-1988 means.



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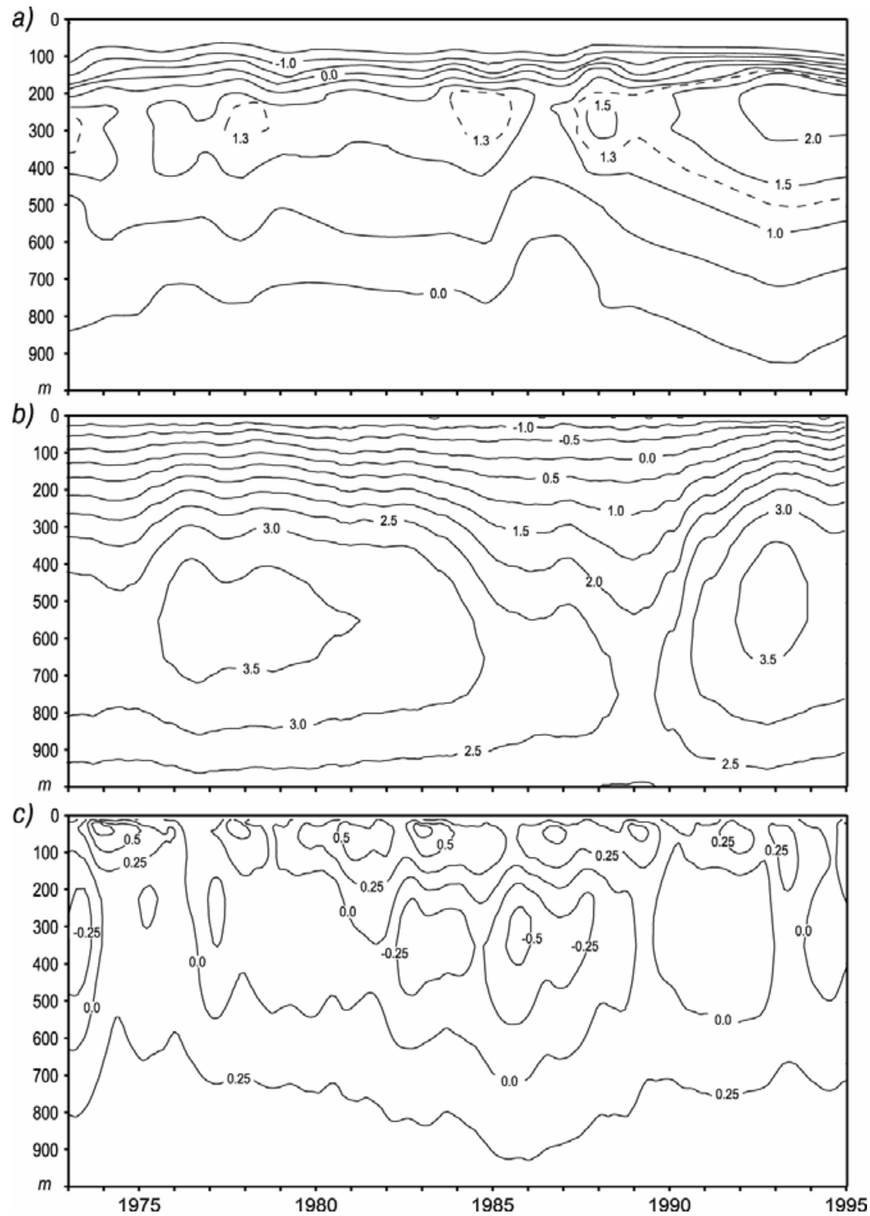

Fig.3. Time-depth plots in the upper 1000m of temperature (°C) for the period 1973-1995 near the location 79˚46′N, 118˚28′E: (*a*) observations [*Alekseev et al*., 1998], (*b*) model results from STD, and (c) the difference between SSR and STD results.

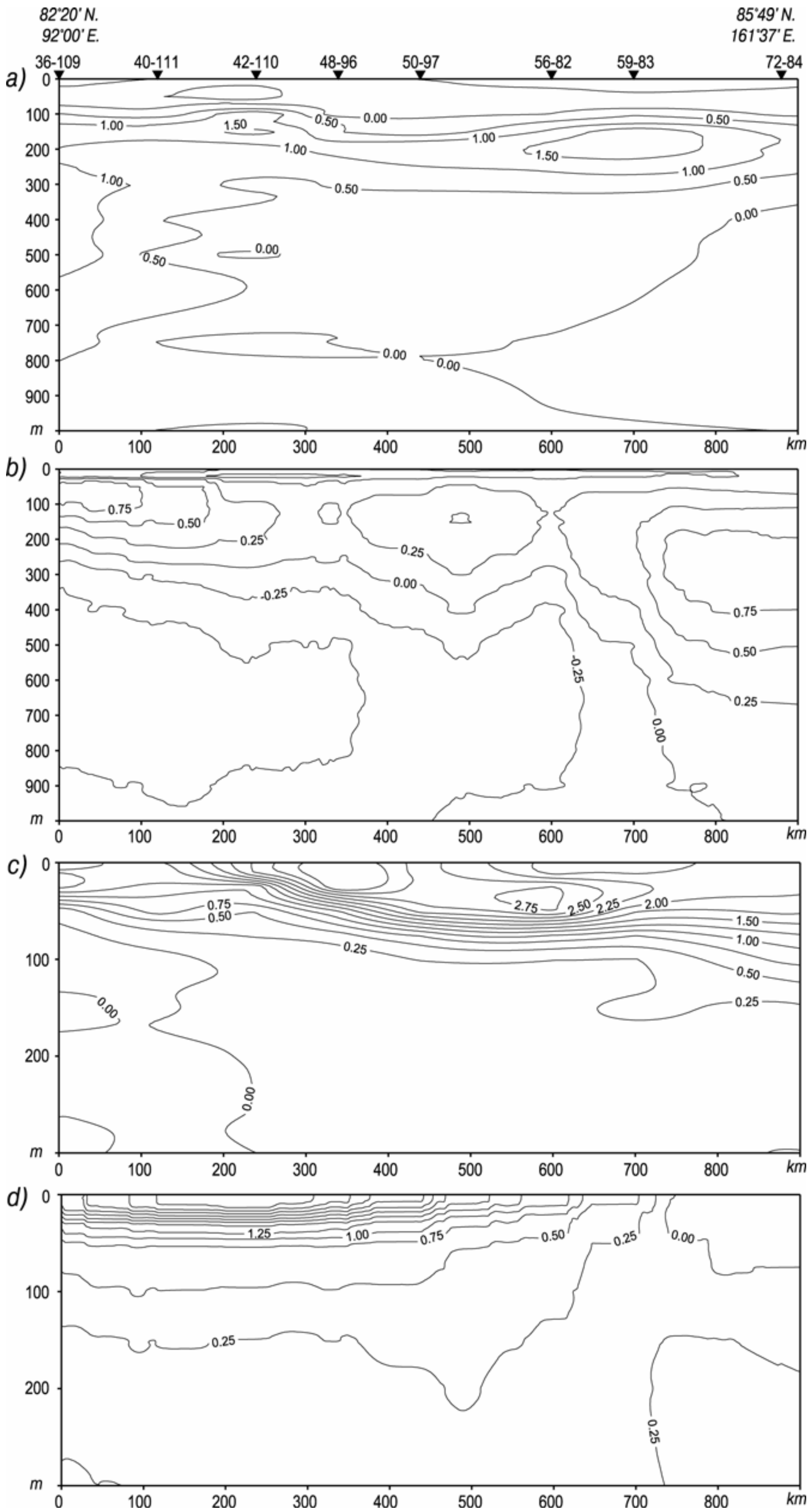

Fig.4. Changes in temperature (°C) in the upper 1000m (*a*,*b*) and in salinity (psu) in the upper 200m (*c*,*d*) in 1996 with regard to 1974 at a vertical section that begins at Cape Arkticheskii and goes to north-east: (*a*,*c*) are from data of 8 pair stations; (*b*,*d*) are from the standard model run. Locations of stations are given in (*e*), their numbers, at the top of (*a*).

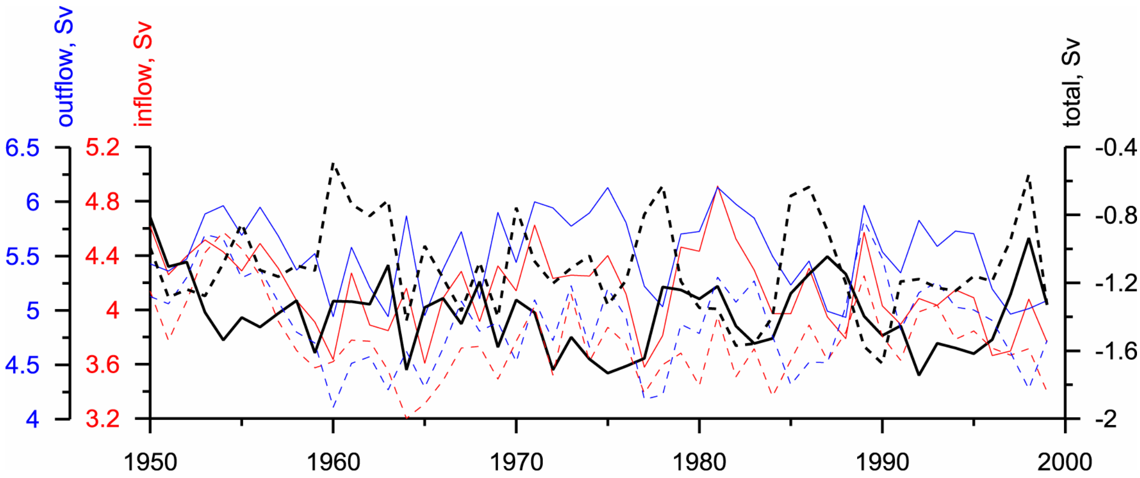

Fig.5. Time series of annual mean volume transport through the Fram Strait. Inflows (positive values), outflows (negative values) and totals are given respectively as red, blue and black curves. Solid and dashed curves correspond to STD and SSR.

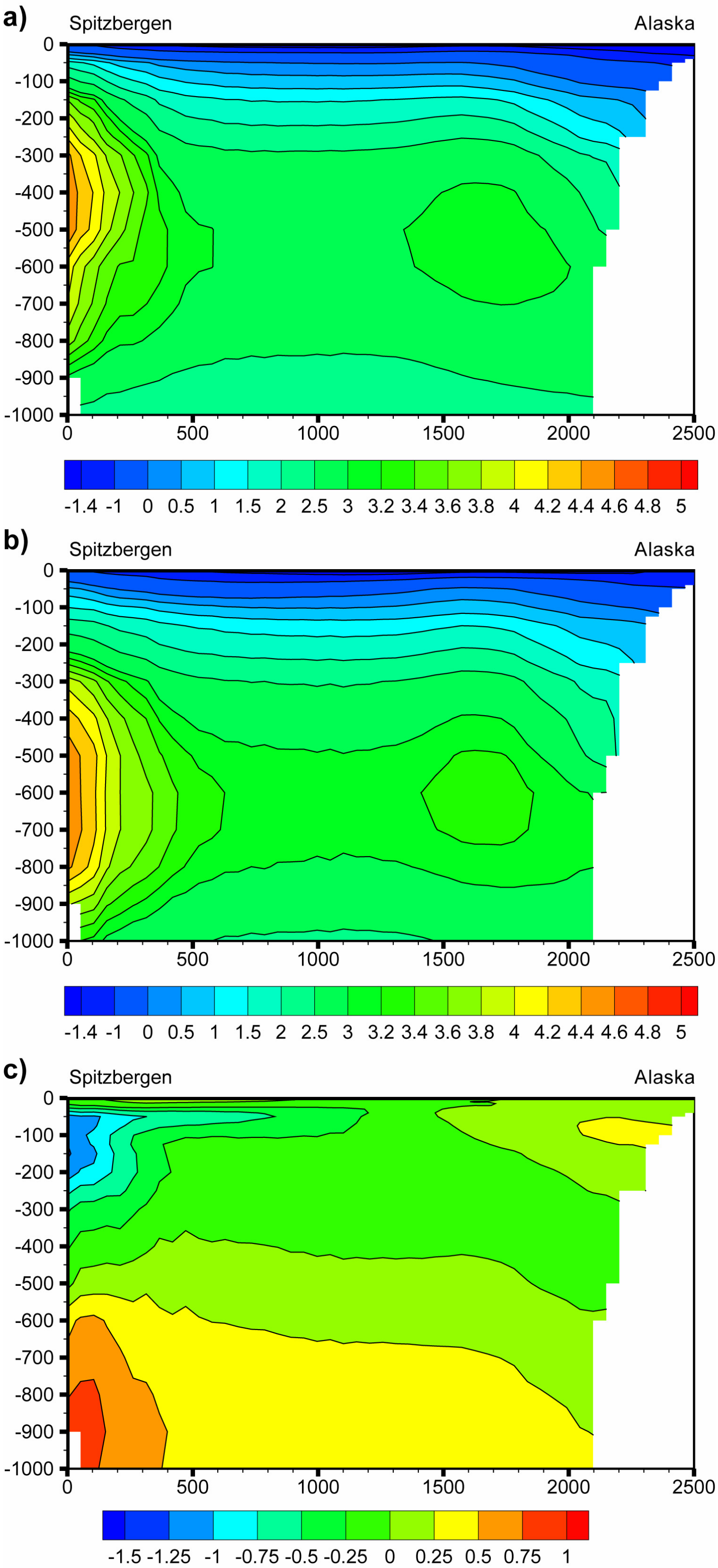

Fig.6. Ten-year (1990-1999) mean temperature (°C) at a section that crosses the Arctic Ocean and connects Spitzbergen and Alaska. (*a*) STD results; (*b*) SSR results; (*c*) SSR results minus STD ones.

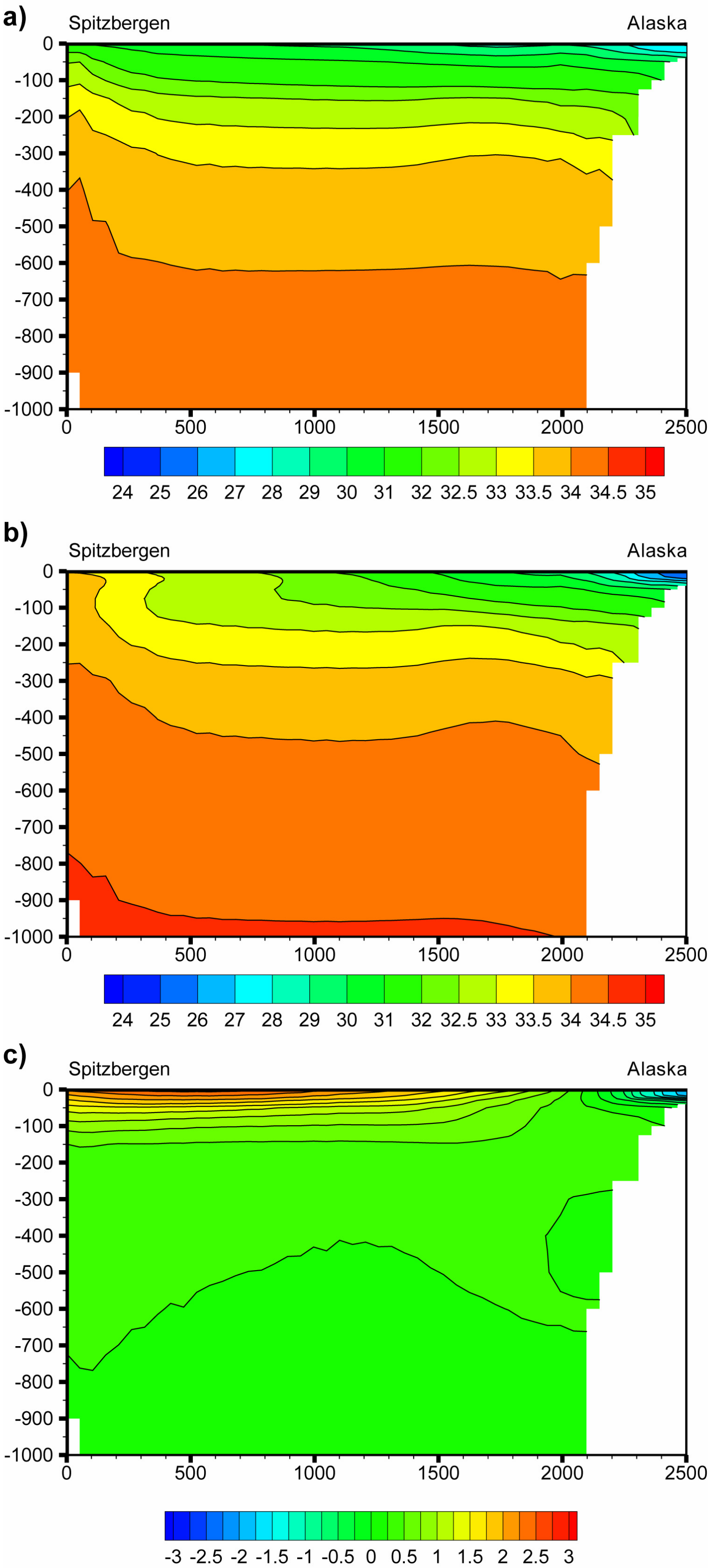

Fig.7. The same as Fig.6 but for salinity (psu).

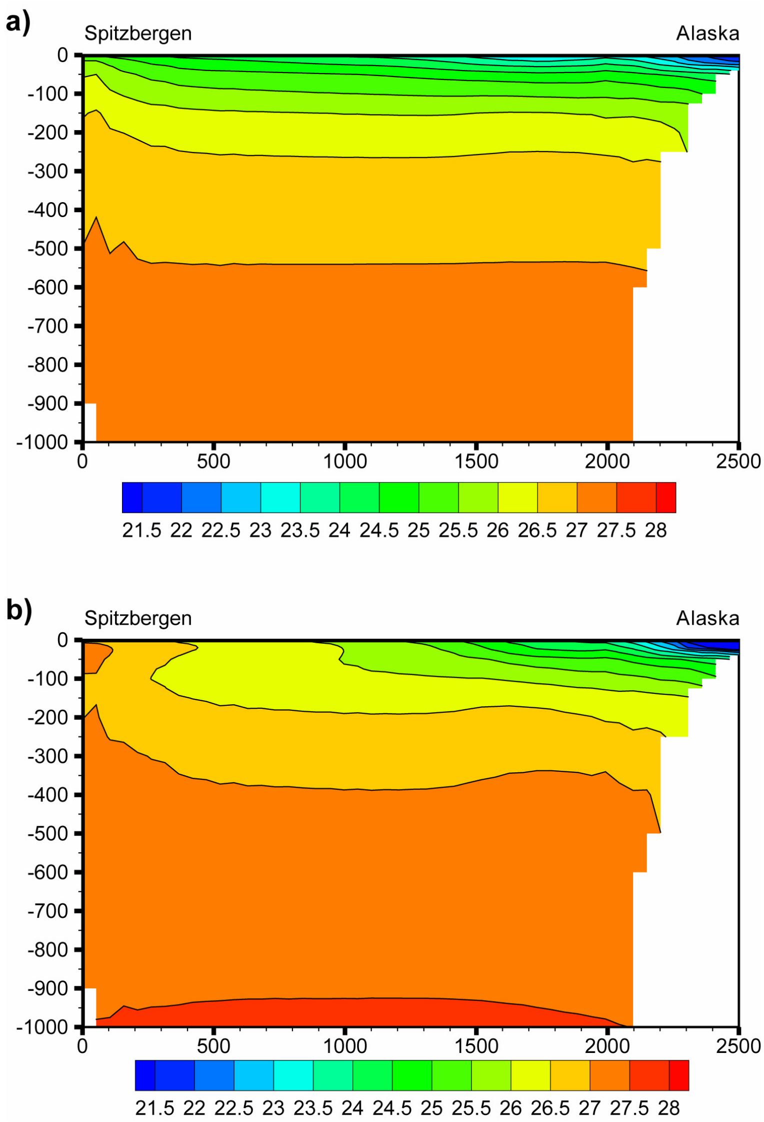

Fig.8. The same as Fig.6 but for density (σ_t).

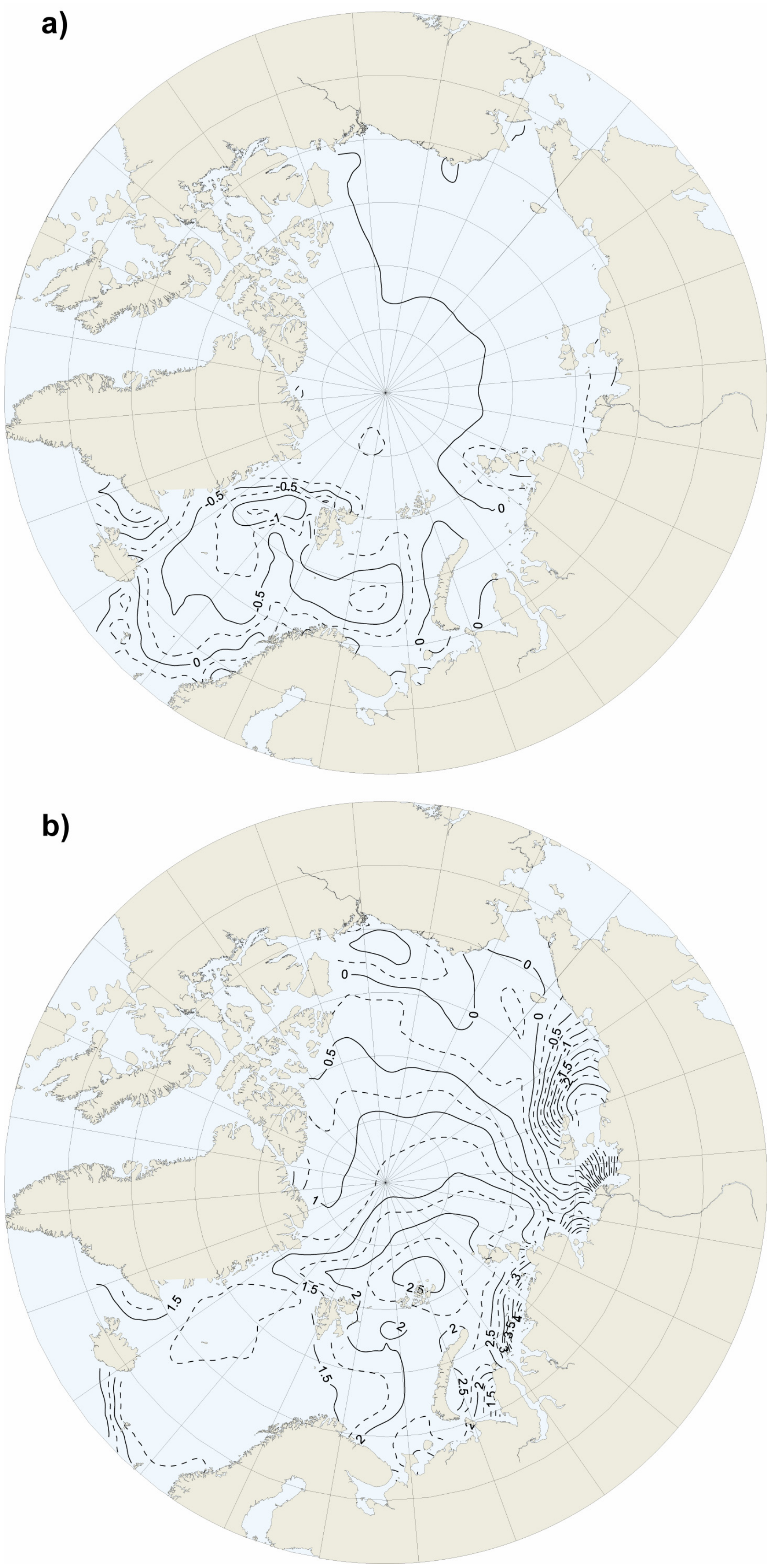

Fig.9. Ten-year (1990-1999) mean differences in the 40-meter upper temperature (*a*, °C) and salinity (*b*, psu) between two runs: SSR results minus Std ones.

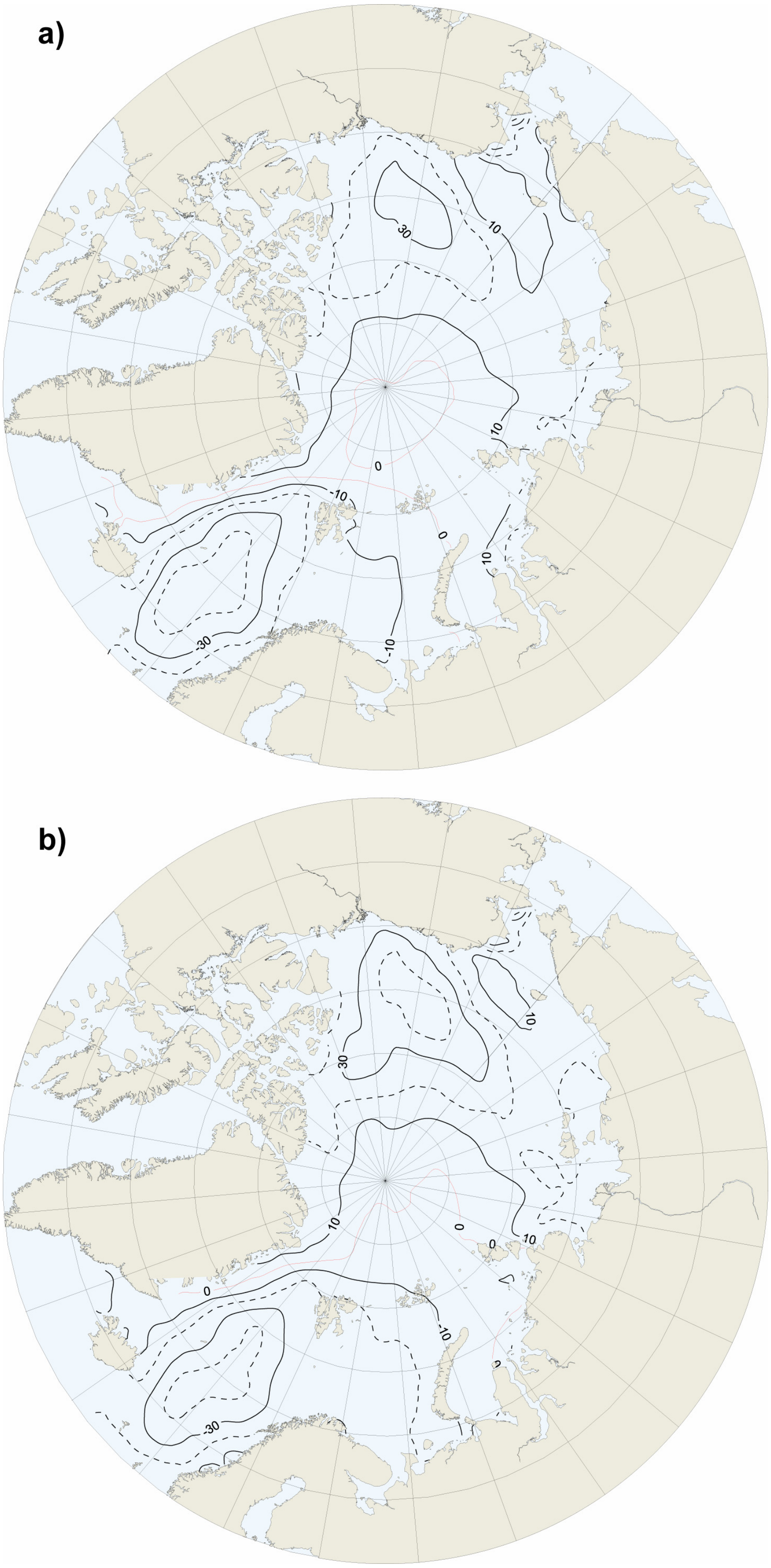

Fig.10. Ten-year (1990-1999) mean sea level (cm) in the basin: (*a*) Std results; (*b*) SSR results; (*c*) SSR results minus Std ones.