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Review

THE ARCTIC OCEAN IN THE GLOBAL CLIMATE SYSTEM

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Abstract: The oceanic portion of the Arctic climate system has a strong influence on global climate change. This is because, first, the Arctic Ocean can change its capacity for redistribution of solar heat in consequence of the changes of thermohaline structure of the upper layer and the sea ice area on its surface, second; the vertical oceanic circulation in high latitudes is very sensitive to changes of the fresh water balance on the ocean surface that can cause a profound effect on the production of the new deep water and on the global vertical ocean circulation. The increase of fresh water discharge into the Arctic Ocean can be one manifestation of global warming. An estimation for 1938–93 showed increase of discharge of main arctic rivers, rise of precipitation on the arctic river basins and decrease of snow depth on the Arctic Ocean sea ice. Data of regular oceanographic observations indicate decrease of upper layer salinity in the Siberian Arctic seas during 1950–1990. These climatic signals correlate with data on interannual variations of the arctic sea ice area. The strongest variations of the sea ice area occurred in the Atlantic Arctic. Freshening of the Arctic Ocean upper layer appears also in the Greenland Sea, where decrease of salinity and reduction of the frequency of deep winter convection events was found. Oceanographic data for 1950–1990s show that the salinity of the upper layer required for deep convection is attained due to permanent inflow of transformed Atlantic water into the Greenland Sea Gyre. This water arrives to the Arctic Ocean, where it constitutes the main salt source. The Atlantic water inflow in the North European Basin and the Arctic Ocean is prone to appreciable interannual variations that are assessed from oceanographic observations in the Faeroe-Shetland Channel for 1902–1990. Distribution and characteristics of the transformed Atlantic water in the Arctic Ocean vary from year to year. According to Russian oceanographic data there was water temperature and salinity reduction from 1950s to 1970s in the Arctic Ocean that was more detectable in the Eurasian Subbasin. These data make it possible to trace the intrusion of the transformed Atlantic water and to detect traces of cold intermediate and deep water formation in the St. Anna trough, near eastern Severnaya Zemla shelf and in the eastern part of the Barents Sea.

1. Introduction

The Arctic represents an important and in some aspects a key part of the global climate system. According to global models of joint ocean-atmosphere circulation, anthropogenic changes of climate should be especially dramatic there. At the same time the climate variations are very strong in the Arctic because of the decisive role of interrelationship of the polar part of the global climate system with its other parts in Arctic climate formation. In its turn the Arctic climate influences the global climate . The oceanic component of this interrelationship has especially strong effects on the global climate changes. The reason is that the structure and circulation of water masses in the

Arctic Ocean that can be changed under the influence of variations in fresh water, salt and heat exchanges with non-Arctic regions of the global system. The most active components in this relation are the upper layer of the Arctic Ocean and the drifting sea ice. The basic processes which unite the Arctic climate system and connect with the global system are fresh water, heat and salt transfers. These involve significant changes of parameters and properties of the active upper layer of the Arctic Ocean. These changes are exhibited by transitions from open ocean surface to ice cover by movement of its boundary, and increase or decrease of the active layer thickness. These changes affect not only the climate system albedo but also the ocean's ability to redistribute of heat in the climate system. Such redistribution increases the mean annual temperature in the atmosphere-ocean-land system as compared with the atmosphere-land system by value θ that is proportional to interseasonal heat redistribution by ocean (Q) and the area of ocean (α). From the energy balance equation the relation between these values should be written in the following form (ALEKSEEV, 1994a):

$$\theta = \frac{\alpha Q}{2}\left(\frac{1}{4\delta_1 T_{01}^3} - \frac{1}{4\delta_2 T_{02}^3}\right),$$

where δ_1 and δ_2 are the integral longwave transparency of atmosphere in summer and winter, respectively; T_{01} and T_{02} are summer and winter air temperatures in the system without and ocean. Changes of values α and Q due to increase or decrease of the Arctic sea ice area and changes of the active layer structure result in variations of the mean annual air temperature in high and moderate latitudes.

Another important consequence of exchange between the Arctic and other oceans is that more saline waters moving from lower latitudes are involved in production of new deep and bottom waters in the Arctic Ocean and adjacent North Atlantic. Mixing of saline water with freshened Arctic water in the Greenland and Labrador Sea gyres forms unstable thermohaline structure of water masses which can be mixed up to the bottom under winter cooling influence (NANSEN, 1906; ALEKSEEV *et al.*, 1994). Strengthening of freshened water and ice runoff suppresses the process of anomaly deep convection in polar gyres (AAGAARD and CARMACK, 1989). On contrast, the saline water penetrating into the polar gyres and Arctic Ocean intensifies vertical mixing, deep and bottom water formation and thereby the large-scale vertical ocean circulation and oceanic heat transfer to high latitudes.

Another source of deep and bottom water formation is presumed to be cooling and salting of surface Arctic waters followed by mixing with more saline underlying water in certain regions above the Arctic sea shelves (QUADFASEL *et al.*, 1988). Both sources depend significantly on the ratio between influx and outflow of fresh water and sea ice floes, on the large-scale oceanic circulation and atmosphere circulation oscillations. Finally, these sources are the most sensitive and vulnerable elements in a chain of global climate formation processes.

2. Data Sets

The Arctic Ocean studies started by F. NANSEN at the end of the last century were considerably extended in the 1950–1980s by Soviet Arctic research programs. They included oceanographic and meteorological observations from the ice drifting stations *North Pole*, aircraft oceanographic surveys of the Arctic Ocean, complex expeditions with the use of ice drifting stations, research vessels and flying laboratories. During the 1950–1980s observations were conducted 80 annual drifts of *North Pole* stations and more than 10 aircraft oceanographic surveys of the Arctic Ocean. In the 1960–1990s, summer oceanographic surveys of Siberian shelf Arctic Seas were carried out. In 1976–1993 the seasonal oceanographic surveys in the Norwegian and Greenland Seas were performed. These works provided a unique oceanographic collection comprising data from more than 40000 stations in the Arctic Basin and Siberian shelf Seas, more then 70000 stations in the Norwegian and Greenland Seas and about 40000 in the Barents Sea.

In 1993–1995 the oceanographic investigations in the Arctic Seas of the Siberian shelf were continued in the framework of joint international projects with Norwegian, German and American researchers. On 1st January 1994 the ten-year Arctic Climate

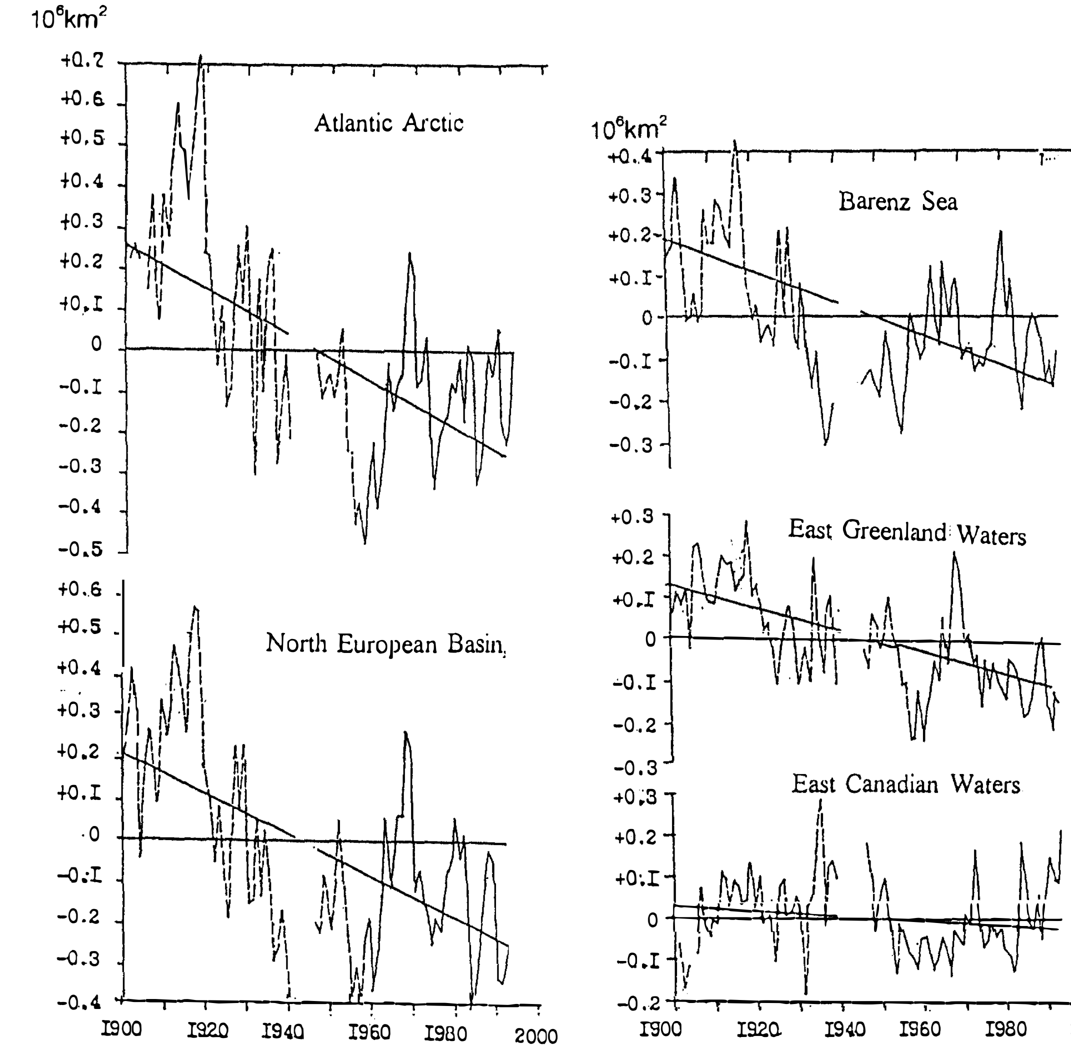

Fig. 1. Anomalies of mean annual sea ice area in the Atlantic Arctic, the North European Basin, the Barents Sea, East Greenland and East Canadian Waters. The broken line is the 5-year running mean.

System International Program (ACSYS) was started (WCRP-72, WCRP-85). One of the goals of the Program is field studies in the Arctic Ocean. Another important aim of ACSYS is to establish a historical oceanographic data base for studies of interannual variability and for numerical modelling of Arctic Ocean water masses and ice dynamics.

3. Results and Discussion

The area of Arctic sea ice clearly shows that the conditions of the Arctic part of the climate system and its changes serve as an integral indicator of climate variations in the North Polar region. Estimates of this parameter were obtained using the historical data of observations of sea ice in the Northern Hemisphere started in 1900 (Fig. 1). Data up to the early 1960s were obtained by visual observations from aircraft, vessels and coastal stations providing reconstructions of annual mean sea ice area values for separate regions. The representative estimates of interannual changes of the Arctic sea ice area can be obtained on the base of data on ice of Nordic seas whose proportion account for as much as 80% of the Arctic ice area interannual variations. What the data in Fig.1 have in common is that the sea ice cover in the subatlantic Arctic tends to be reduced. The sea ice area in the Siberian Arctic remained steady in summer time up to the end of the 1980s. It was reduced in size only in early 1990s (Fig. 2).

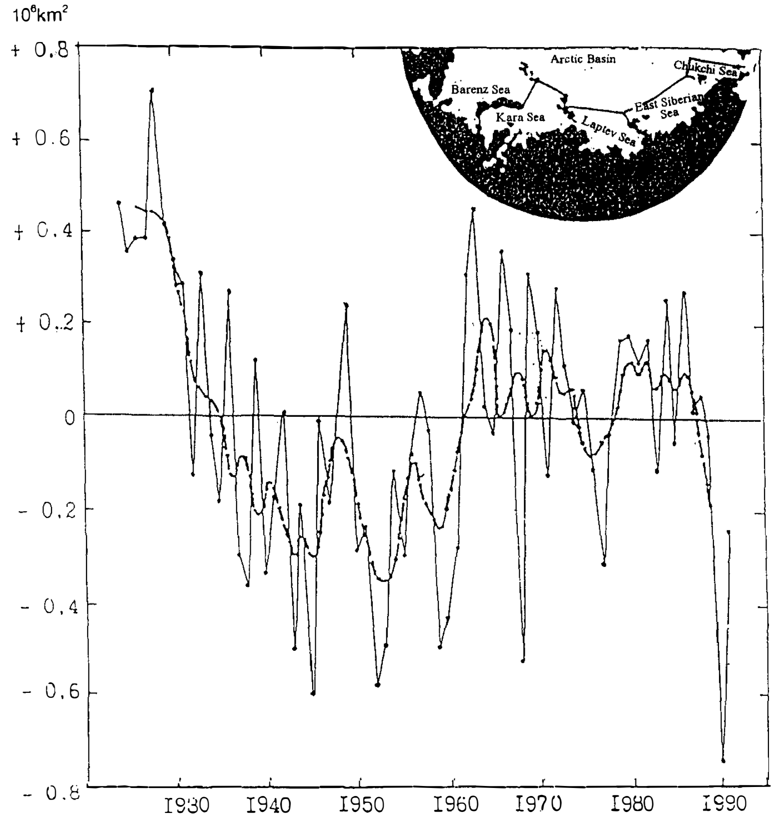

Fig. 2. Sea ice area anomalies in the Siberian Arctic waters during second half of August. Upper right chart is a location map for the Siberian Arctic waters. The broken line is the 5-year running mean.

The Arctic sea ice area and its large-scale changes are connected with a distribution of Arctic Water at the surface of the Arctic Ocean and the North Atlantic (Dickson *et al.*, 1988). The Arctic Water forms there a 30–70 m freshened layer. The limits of such a fresh "lake" and the distribution of drifting ice in the Northern Hemisphere coincide and exhibit joint variation (Zakharov, 1981). One of the reasons for these changes is the river runoff into the Arctic Ocean from the surrounding land (Mysak *et al.*, 1990) which jointly with precipitation's makes the upper layer fresher. Multi-year observations of Siberian river runoff (Ivanov, 1995) showed steady increase (Fig. 3) which was especially prominent in winter. At the same time the amounts of precipitation at the Arctic Ocean surface in winter tend to be decreased (Fig. 4) and that in Siberian river basins to

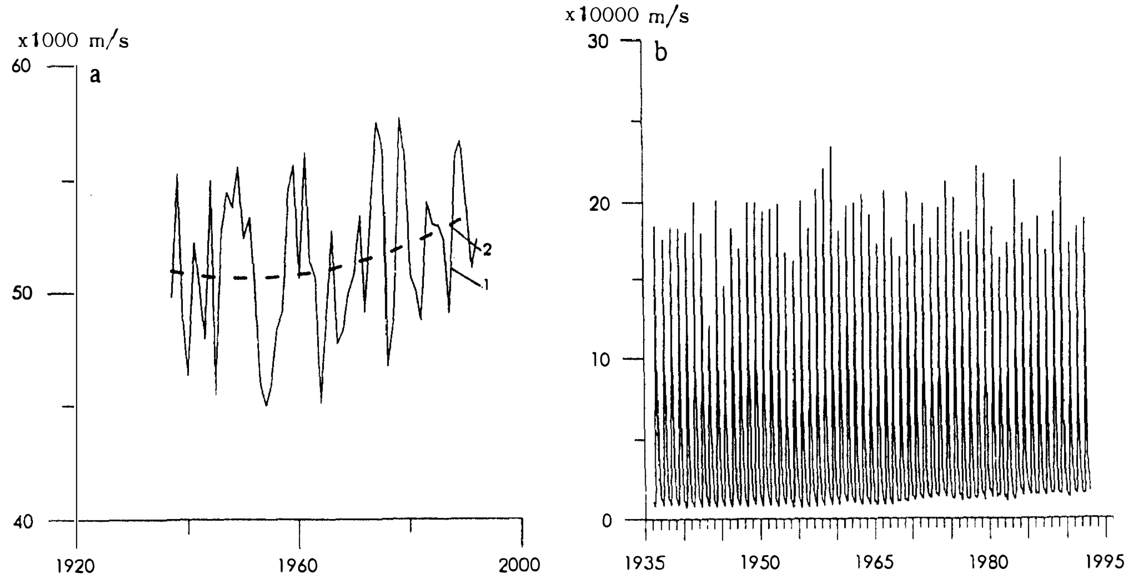

Fig. 3. Mean annual value of the five Siberian rivers runoff in 1937–1992 years. The broken line is the second order polynomial fitting.

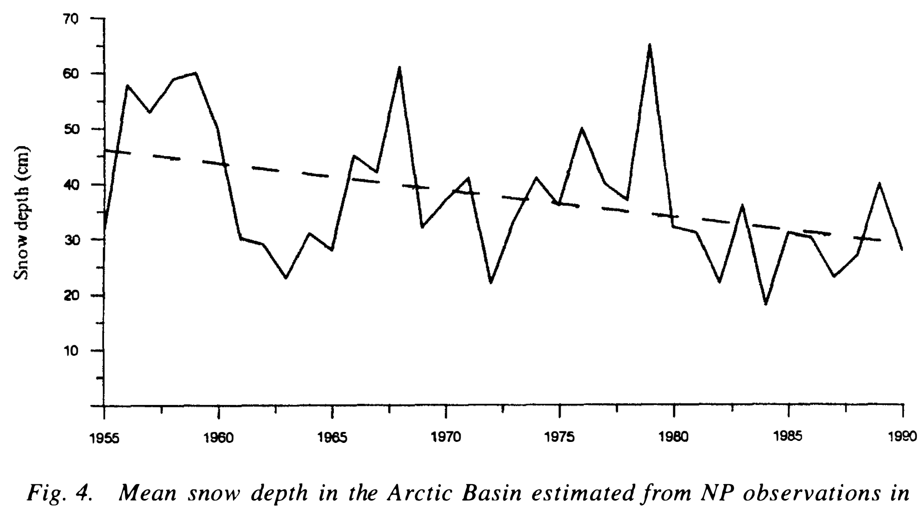

Fig. 4. Mean snow depth in the Arctic Basin estimated from NP observations in May 1955–1991 years (Alekseev et al., 1996). The broken line is the linear fitting.

be increased. Additional local sources of fresh water for the upper layer are due to the processes of snow and ice summer melting, which freshens the highest two-meter layer.

A great excess of fresh water in the Arctic Ocean upper layer which is induced by the runoff, especially in summer, as well as by precipitation and snow and ice summer melting, is eliminated by winter ice formation. This produces the greater part of the heat from the Arctic Ocean surface into the atmosphere in winter (ALEKSEEV, 1994a). This conclusion is based on the comparison of estimates for heat fluxes at the Arctic Basin

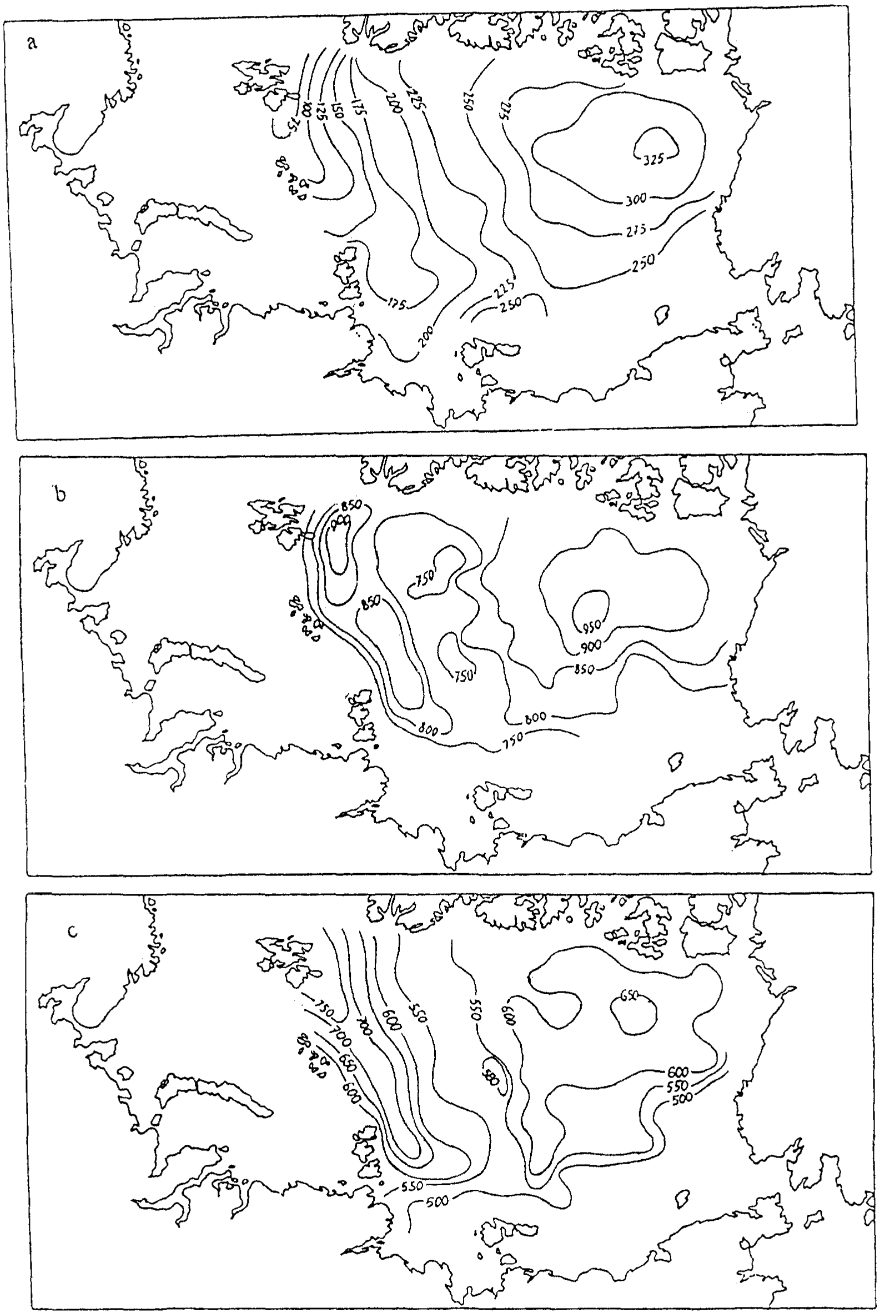

Fig. 5. Depth of upper (a) and lower (b) boundaries and thickness (c) of the Atlantic water layer in the Arctic Ocean.

surface according to meteorological observation data and calculations of saline balance constituents in the upper layer.

The multi-year trends in variations of the Arctic Ocean upper layer parameters are characterised by noticeable summer warming in the Siberian Arctic Seas which is accompanied by a salinity decrease (ALEKSEEV, 1994b). According to aircraft oceanographic surveys, a decrease of salinity of the 150-m upper layer averaging 0.1% was observed in the Arctic Basin between the middle 1950s and middle 1970s.

Freshened Arctic Water from the Arctic Ocean upper layer as well as the sea ice continuously enters through Fram Strait to the Greenland Sea and further to the North Atlantic. For maintaining the salt balance in that layer an outer source represented by the Atlantic Water influx into Arctic Ocean through Fram Strait and the Barents Sea is necessary. In addition, the Atlantic Water actively participates in the formation of deep

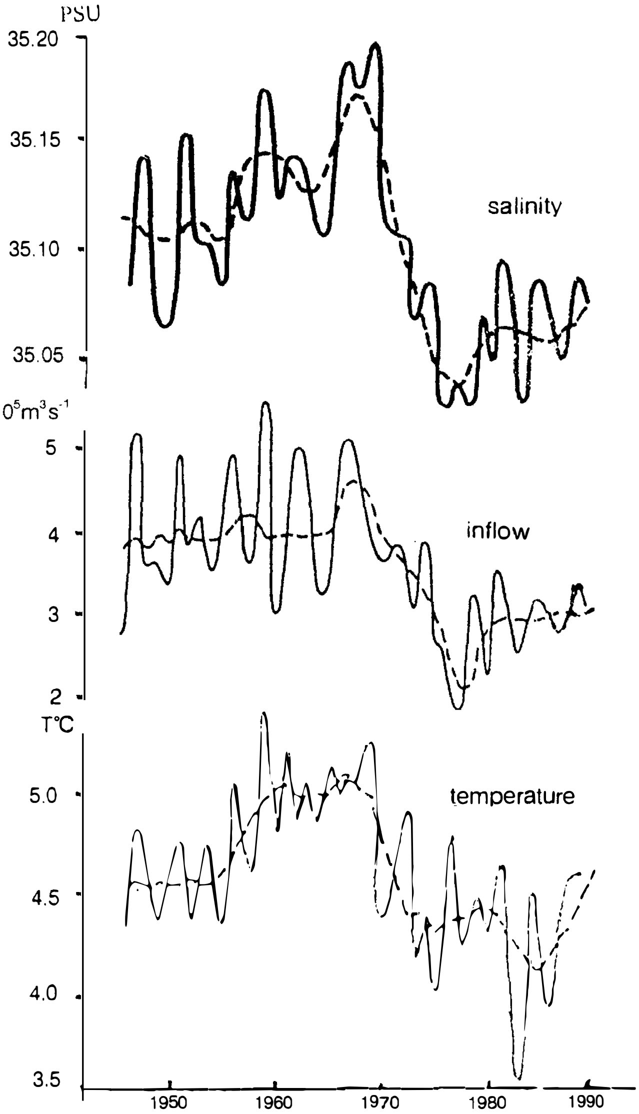

Fig. 6. Mean annual values of salinity inflow and water temperature in the 0 – 400 m layer in the Faeroe-Shetland Channel. The broken line is the 5-year running mean.

and bottom waters of the Arctic Basin. The mean multi-year parameters of distribution of this water in the Arctic Ocean are shown in Fig. 5.

The Atlantic Water influx undergoes significant interannual variations which may be seen from the estimates of water influx, temperature and salinity according to observation data in the Faeroe-Shetland Channel (Fig. 6). Water of Atlantic origin starts to affect the processes of.water mass formation for the Arctic Ocean in the Greenland Sea (NANSEN, 1906; AAGAARD and CARMACK, 1989). Here Atlantic water is entrained into the gyre and mixed with the Arctic water mass. As a result the water column becomes unstably stratified . The latter is then mixed from the surface to the bottom under the influence of winter cooling (ALEKSEEV *et al.*, 1994). In this case deep and bottom waters are produced; part of them enters into the Arctic Basin (NANSEN, 1906; CARMACK and AAGAARD, 1973).

A problem connected with the presence of Atlantic water in the Arctic Ocean is to determine mechanisms and places of its entrainment into the upper and lower layers. F. NANSEN and other investigators (TIMOFEEV, 1960; NIKIFOROV and SHPAIKHER, 1980) maintained that this water participates in surface water production on the Arctic shelf. The Atlantic water is entrained into the deep layer mainly when the water enters in the Arctic Ocean from Fram Strait (AAGAARD *et al.*, 1987). Much of the deep water entering the Arctic Basin from the Greenland Sea has relatively low temperature (approx. –1°C) and salinity's (approx. 34.91 PSU). As both water masses moves toward east along with Atlantic Water they are transformed by the system of ridges filling the deep basins. Then they are flow out through Fram Strait (NANSEN, 1906; TIMOFEEV, 1960; ANDERSON, 1991), with the volume of deep water increasing and their temperature and salinity rising at the exit. A schematic sketch of Atlantic water participation in formation of the Arctic Basin water masses is shown in ALEKSEEV (1994a).

Recently, much attention has been paid to the role of winter vertical mixing processes on the boundary between the Arctic Basin and Arctic Seas, not only in generation of the upper layer but also in entrainment of the Atlantic Water into deep and bottom layers in the regions with deep water canyons and troughs in the northern parts of the seas. Here the Atlantic Water penetrates far into the shelf region. During winter it can penetrates into low layer together with cooled surface water that flows downslope. Examples of distributions of water temperature and salinity observed in winter on the Kara and Laptev Sea shelf are shown in (GOLOVIN, 1993; BULATOV and KOCHETOV, 1995). In spite of observations which indicate cold deep water production on the Arctic Sea shelves, the scales and contribution of these processes in water mass creation and transformation in the Arctic Ocean are yet to be elucidated.

4. Conclusions

The influence of the Arctic Ocean on global climate is connected first of all with processes involving formation of a freshened upper layer, surface sea ice and deep water masses. These processes include fresh water influx by river runoff and precipitation, ice melting and formation and inflow of Atlantic Water which influences Arctic Ocean water mass formation.

Interannual dynamics of drifting sea ice at the surface of the Arctic Ocean and neighboring oceans is characterised by gradual decrease of their area which is clearly expressed in the subatlantic Arctic. The influx of fresh water with Siberian river runoff continuously increases and the snow thickness at the ice surface in the Arctic Basin decreases. Winter ice production plays an important role in the Arctic Ocean upper layer heat balance formation. That converts the excess fresh water into ice which is discharged from the Arctic Ocean. The temperature in the upper layer of the Arctic Seas on the Siberian shelf rose and the salinity decreased. The salinity decrease was noted also in the Arctic Basin upper layer within the period 1950–1970s. Water of Atlantic origin plays a role in water mass formation by means of winter convection processes in the Greenland Sea and Arctic Ocean.

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