

Changes in the freshwater balance of the Arctic during global warming *analysis of the current state of research*

Introduction

The modern Arctic is becoming warmer and more humid, the Arctic Ocean is increasingly free of ice in summer, and the thickness of ice decreases. In 2012, the absolute minimum of the September sea ice area was recorded, and in 2016 the lowest winter maximum of the area. The beginning of ice formation is shifted to a later date, the melting of snow and ice begins all earlier, the duration of the occurrence of snow cover is reduced. Extrapolation of observations of sea ice and air temperature indicates a possible release Arctic from the ice in the summer 2030–2040s. It is believed that the anthropogenic CO₂ increase in the atmosphere is the main cause of modern warming which lead to feedbacks in the Arctic, increasing Arctic warming. The main influence is attributed to the decrease albedo. At the same time, the observed increase in the water vapor content in the atmosphere of the Arctic increases the influx of downward long-wave radiation to the surface of snow and ice, slowing down the winter buildup of ice and accelerating the summer melting of snow and ice. The source of the increase in the water vapor content in the arctic atmosphere is the atmospheric branch of the hydrological cycle, including moisture transport from low latitudes and inflow from the ocean surface.

The assessment of the AMAP,¹ noted that the freshwater content in the Arctic Ocean has increased in recent years compared with the average for 1980–2000 by 8,000 cubic kilometers, or by more than 11%. If this volume left the Arctic Ocean, it would affect circulation in the North Atlantic. However, earlier Polyakov² shown that during the twentieth century the Arctic basin became more and more salty with the loss of fresh water of 239–270 km³ per decade. In the perennial series of freshwater content, two periods stand out in the 1920s – 1930s and in recent decades, when the Arctic basin was more saline, despite an increase in the inflow of river water and precipitation, and two periods at the beginning of the century and in the 1940–70s when he was more freshened. The authors explain this discrepancy by the increased removal of ice and fresh water under the influence of the wind. They also note that changes in the influx of Atlantic water did not have a noticeable effect on changes in water masses in the upper layer. The freshwater budget of the Arctic Ocean is formed with the participation of the global hydrological cycle and with it responds to global climate change. Atmospheric moisture transport from low latitudes, river runoff from the surrounding land and reverse sea transport of fresh water are the main components of the freshwater budget of the Arctic Ocean. Freshwater entering the Arctic with the polar branch of the global hydrological cycle accumulates in the upper layer of the ocean and prevents it from mixing with the underlying waters. This circumstance, together with the strong cooling of the layer during the winter period, ensures the preservation of drifting ice on its surface currently. Water from the upper layer is carried in the liquid and solid (sea ice) phases to the North Atlantic. This process controls the spread of the desalinated water and sea ice on the surface of the North Atlantic and constitutes the main link in the formation of the Arctic impact on the global climate.

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Fresh water entering the Arctic Ocean undergoes multiple “water-ice” phase transformations that will change the dynamic and thermodynamic properties of the upper ocean layer and the residence time of incoming fresh water and thereby affect the formation of freshwater outflow. These processes constitute a kind of internal arctic hydrological cycle, acting together with the external cycle, which constitute the processes of fresh water influx into the Arctic Ocean and further to the North Atlantic. Most model and empirical calculations give an estimate close to the equal contribution of both components in the resulting freshwater flow from the Arctic Ocean. To estimate the content of fresh water, it should be calculated relative to some a priori given salinity. Aagaard & Carmack³ suggested a salinity of 34.80 psu as such reference salinity. This choice has a deep physical meaning, since this value is close to the critical value of salinity (approximately 34.80 psu),⁴ which separates the modes of deep and shallow convection in the central part of the Greenland Sea where water structure below the upper layer is close to the structure in the Arctic Basin. When the salinity of water in the upper layer is close to the critical value, the low-temperature compressibility of seawater operates, ensuring the convection plumes fall to great depths³. From this point of view, after removal of an excess fresh water from upper layer with a salinity of less than 34.80 psu will become possible deep convective mixing and, therefore, ice-free regime in the Arctic Ocean.

To calculate the excess fresh water in the upper layer from the surface to the depth of isochaline⁵ 34.80 used data from 8 winter-spring surveys of the Arctic Ocean by the Soviet expeditions “North” in 1955–1979. The average for 1955–1979 distribution of freshwater content (FWC) in layer above the the 34.80 isohalin show a maximum in the Beaufort sea gyre and a gradual decrease towards the Barents Sea and the Fram Strait. The maximum value of the FWC is formed by the joint contribution of strong desalination in the upper 30–50 meter layer and the influx of Pacific waters, the influence of which is noticeable here to a great depth. The layer in which the fresh water content was estimated has a thickness of from 120 m in the Atlantic part of the Arctic basin to 800 m above the Canadian Basin. The distribution of FWC in the vertical is also non-uniform in these parts of the Arctic Ocean: in the near-Atlantic part, its main part (60%) is in the upper 50 m layer, and above the Canadian hollow in this layer is only 40% of the total fresh water. In general, the greatest amount of fresh water is concentrated in this area under the influence

of anticyclonic circulation, and desalination here penetrates to a depth of 800 m, which is apparently due to its descent in the center of the anticyclonic circulation.^{6,7}

In connection with significant fluctuations from year to year of salinity and, accordingly, the content of fresh water in the upper layer of the Arctic Ocean, the question arises about their cause. The time series of components of the external inflows of fresh water into the Arctic Ocean^{8,9} show a certain increase in precipitation and runoff of rivers in the Arctic Ocean in the first half of the 1960s. However, correlations of these changes with fluctuations in salinity in various regions of the Arctic Ocean and the North Seas are weak.¹⁰

Calculations of freshwater budget components show⁵ that the bulk of fresh water enters the Arctic Ocean in summer. The total inflow during the summer period is estimated from 6,000 to 10,000 km³, which is much more than the average inflow over the year.⁵ The discrepancy is eliminated during the winter by converting a significant portion of fresh water into sea ice. However, changes in the conditions of summer melting and winter ice formation can lead to an imbalance in the freeze-melting cycle and, accordingly, to desalination or salinization of the upper layer in some years. In the winter period (from October to May), the bulk of fresh water from summer melting freezes out, mainly due to the formation of young ice, which for the most part is compressed during intensive movements of drifting ice. Measurements of the growth of perennial ices in winter, together with estimates of salinization of the upper layer, show that the freezing of fresh water is more associated with the growth of young ice than with the increase in the thickness of old ice.

The most striking result of the increase in freshwater outflow from the Arctic Ocean was a strong desalination in the upper layer of the North Atlantic in 1963–1973, called the great salinity anomaly.¹¹ All researchers who have examined this phenomenon point to the origins of the anomaly in the Arctic Ocean.^{12,13} The first manifestation of the anomaly in the 1960s was found in a decrease in the salinity of water in the upper water layer north of Iceland¹⁴ in the summer of 1963. The greatest decrease in salinity on the horizon of 50 m was noted here in 1969.¹⁵ At the same time, according to the data of Drinkwater,¹⁶ the lowest values of salinity and water temperature were noted off the west coast of Greenland in the Fylla Bank area in the area of the West Greenland Current. This circumstance indicates the almost simultaneous development of desalination in both regions and the two routes of fresh water from the Arctic to the North Atlantic: through the Fram and Danish Straits in the east and through the Baffin Sea and Davis Strait in the west. The source of the anomalous desalination of the upper layer of the Arctic Ocean in the 1960s could be a strong summer melting of ice and snow in the Arctic Ocean and on the surface of the Arctic land. In the summer of 1957–1962 in the Arctic unusually high air temperatures were observed, especially in the region of Western Greenland, the Baffin Sea and the adjacent part of the Canadian Archipelago, where the greatest amount of snow and ice accumulates in winter.¹⁷ Large positive air temperature anomalies here contributed to intensive summer thawing and freshwater flow into the Arctic Ocean, the Canadian Straits, the Baffin Sea and Hudson Bay.

Concerning the causes and contribution of various factors to the increase in summer warming, research results are differed. Dufour¹⁸ considers that the summer atmospheric moisture inflow from low latitudes dominates in the seasonal cycle and find the weakening of the mean annual inflow in 1979–2013. Bengtsson¹⁹ showed that precipitation and horizontal moisture transfer to the Arctic (north of 60°N.) is maximum in August and September, and evaporation in

June and July. Serreze²⁰ found the largest increase in moisture content in the atmosphere of the Arctic in the summer and early autumn. Dufour¹⁸ sees this as an argument against increasing the influx of water vapor into the Arctic from outside with climate warming in favor of increasing the role of evaporation. Sejas²¹ believes that less warming compared to winter in summer is associated with the opposite nature of feedback between shortwave and longwave radiation with cloudiness and albedo and with the influx of heat into the ocean. In autumn and winter, the ocean gives off summer heat, which, together with positive feedback of long-wave radiation and cloudiness, increases warming. The recent publications are noted that the Arctic freshwater content has increased significantly over the last two decades, with potential future implications for the Atlantic meridional overturning circulation downstream.²² The liquid freshwater content significantly increased also in the Beaufort Gyre in the 2000s during an anticyclonic wind regime and remained at a high level despite a transition to a more cyclonic state²³ in the early 2010s. Since the high-latitude freshwater plays a crucial role in establishing and regulating global thermohaline circulation, the long-term variations of the freshwater content should be considered when assessing climate change and variability.²

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Conflicts of interest

The author declares that there is no conflict of interest.

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