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Review

Arctic Sea Ice Loss Enhances the Oceanic Contribution to Climate Change

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Abstract: Since the mid-1990s, there has been a marked decrease in the sea ice extent (SIE) in the Arctic Ocean. After reaching an absolute minimum in September 2012, the seasonal variations in the SIE have settled at a new level, which is almost one-quarter lower than the average climatic norm of 1979–2022. Increased melting and accelerated ice export from marginal seas ensure an increase in the open water area, which affects the lower atmosphere and the surface layer of the ocean. Scientists are cautiously predicting a transition to a seasonally ice-free Arctic Ocean as early as the middle of this century, which is about 50 years earlier than was predicted just a few years ago. Such predictions are based on the fact that the decrease in sea ice extent and ice thinning that occurred at the beginning of this century, initially caused by an increase in air temperature, triggered an increase in the thermal and dynamic contribution of the ocean to the further reduction in the ice cover. This paper reviews published evidence of such changes and discusses possible mechanisms behind the observed regional anomalies of the Arctic Sea ice cover parameters in the last decade.

Keywords: Arctic Ocean; climate change; ocean currents; convection; water masses; sea ice; feedbacks

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1. Introduction

An increasing interest of the international community in the Arctic is understandable and has a number of reasons. Among them, the two main ones are rapid climatic changes, in which the Arctic plays a significant role [1,2], and the urgent need to meet the growing socioeconomic potential of the region. Long and extensive continental shelves, which surround the Arctic Ocean's deep interior, are among the greatest, but at the same time underexplored, natural stock of the mineral resources (https://www.iisd.org/articles/deep-dive/arctic-warming accessed on 20 January 2023). During annual opening for a prolonged time interval, Arctic seas provide the shortest shipping route between Europe and Asia [3]. Taking this into account, the Arctic may be considered an important geographical region where scientific, economic, and environmental interests are interconnected. Particular importance is attached to research work; without the systematic conduct of research, it is impossible to reliably assess the ongoing changes in the natural environment and to provide a reasonable forecast of their development in the future (https://cordis.europa.eu/project/id/265863 accessed on 20 January 2023).

Since the mid-1990s, there has been a marked decrease in sea ice cover in the Arctic Ocean (AO) [4]. After reaching the absolute minimum in September 2012, the seasonal variations in the ice cover extent have settled at a new level, which is 20 ± 9% lower than the average climatic norm of 1979–2022 (Figure 1).

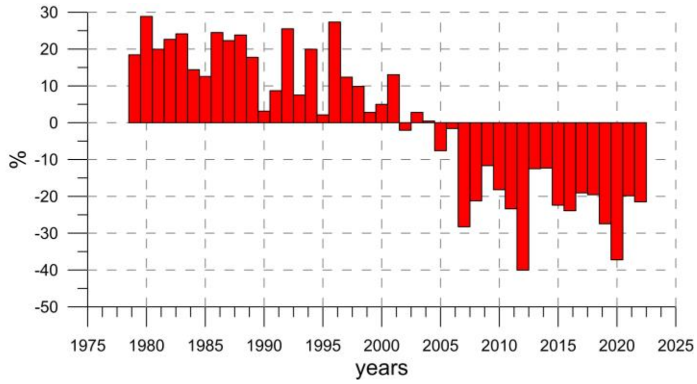


Figure 1. Anomaly of the minimum Arctic Sea ice extent (area where ice concentration exceeds 15%) in September (%) relative to the average for the period of satellite observations (1979–2022), based on the data from [5]. The data for 2022 were taken from the website: http://nsidc.org/arcticseaicenews/ accessed on 20 January 2023.

It should be emphasized that despite the indicated stabilization of the total ice cover area at the peak of the seasonal minimum, there is a significant nonuniformity of its decrease in different sectors of the AO [6]. For instance, at the beginning of September 2020, the ice cover boundary in the eastern Atlantic sector of the AO (0–120° E) shifted north of 85° N for the first time during the satellite monitoring period (since 1979) (https://seaice.uni-bremen.de/databrowser/ accessed on 20 January 2023), and almost complete ice-free conditions in the Siberian shelf marginal seas occurred significantly earlier than the average climatic dates (https://www.statista.com/statistics/1184167/laptev-sea-ice-extent/ accessed on 20 January 2023). One year later, in September 2021, the ice edge for the seas of the Siberian shelf was close to 80° N, and some areas, such as the Chukchi Sea, were adjacent to the coast (https://www.adn.com/alaska-news/weather/2021/11/19/november-ice-extent-in-chukchi-sea-is-well-above-average-of-past-30-years/ accessed on 20 January 2023). Increased melting and accelerated ice export from the marginal seas and the deep AO interior lead to an increase in the area of open water, which controls the energy balance in the ocean–ice–atmosphere system, the hydrological regime of the upper ocean, and biological productivity.

Scientists cautiously predict a transition to seasonally ice-free AO substantially earlier than was predicted by climate models a few years ago (https://www.nationalgeographic.com/science/article/arctic-summer-sea-ice-could-be-gone-by-2035 accessed on 20 January 2023). A model study [7] suggested a possible reason for the accelerated summer shrinkage of the Arctic Sea ice: the through thawing of melt ponds—puddles of meltwater that form on the ice's upper surface in the summer season under the influence of solar radiation. Melt puddles have always formed at the upper surface of Arctic Sea ice in the summer season. However, under the conditions of thick multiyear ice, which prevailed in the AO until the mid-2000s, their influence on ice melt was practically negligible because there was no through thawing as a rule [8,9]. A significant decrease in the mean sea ice thickness in the AO [10,11] and the transition to seasonal ice cover around a substantial part of the AO in the 2000s [12–14] resulted in the fact that, even with an unchanged total melt pond area, the number of cases of through thawing has increased, which, in turn, has accelerated the fragmentation of the ice cover. The described mechanism can be considered one of the manifestations of the general trend, which can be defined as an intensification of the feedback in the ocean–ice–atmosphere system. It is of principal importance that the reduction in the sea ice volume (http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/ accessed on 20 January 2023) due to decreases in ice area and thickness served as a trigger mechanism that provided intensification of the feedbacks, which were either not manifested at all or were ineffective when thick consolidated ice cover prevailed. Generally speaking, a reduced volume of sea ice requires less heat consumption for melting, thus allowing the same amount of heat to melt an additional amount of ice. It should be underlined that the gradual decrease in the Arctic Sea ice volume during the second part of the 20th century was primarily preconditioned by an increase in surface air temperature (SAT) in the Arctic [15]. The accelerated shrinkage of the Arctic Sea ice cover after the 1990s was additionally enhanced by increases in SAT and sea surface temperature (SST) in lower latitudes, which were translated to the Arctic by meridional air flows and ocean currents [16,17]. Under the present conditions of reduced sea ice volume, excess advective heat from the lower latitudes is spent on heating the ocean–ice–atmosphere system in the North Polar region. This process resulted in an increase in the temperature of the lower troposphere, which was estimated in [18] as 3.5 °C during the time interval of 1979–2020.

This paper reviews the facts known from observations and reports in recent publications, pointing to changes in energy fluxes in the polar ocean–ice–atmosphere system and discussing possible mechanisms behind the observed regional anomalies in the Arctic Sea ice cover parameters in the last decade.

2. Major Feedbacks in the Ocean–Ice–Atmosphere System in the Arctic

As applied to the surface of the partially ice-covered ocean, the so-called "albedo mechanism", related to the multiple difference between the reflectivity (albedo) of ice and water, is considered to be among the most effective [19,20]. The emergence of zones of open water in solid ice massifs, due to seasonal ice breaking and melting, ensures the effective absorption of shortwave solar radiation in the ice-free areas and the heating of the water surface. Additional lateral and bottom ice melting in relatively warm water promotes the further expansion of ice-free water surface and the increase in solar radiation absorption, thus providing positive feedback [21,22]. It should be emphasized that the albedo mechanism works only in the summer season when the thermal balance of the ocean surface is positive (the ocean uptakes atmospheric heat). In the winter season, due to the large difference between the water and ice surface temperatures, the presence of open water leads to the opposite effect: rapid formation of new ice on the open water surface due to intensive heat loss to the atmosphere, i.e., to negative feedback [23].

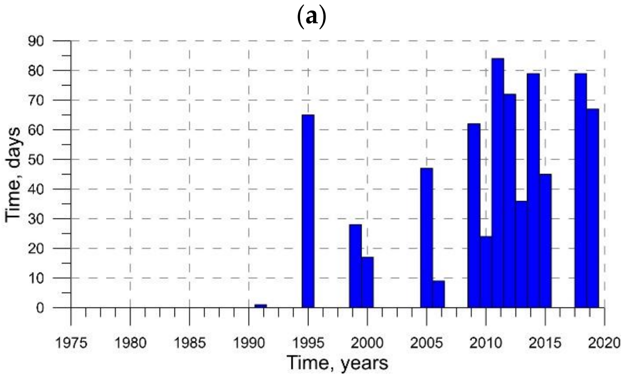
The thermodynamic effect of the albedo mechanism can be enhanced by dynamic forcing. The wind impact of the atmosphere on the ice cover results in mechanical distraction (fragmentation) and motion (drift). In conditions with solid and thick ice cover, both processes have no significant effect on seasonal changes in sea ice [24]. With a decrease in the cohesion and an expansion in the ice-free zones, the situation may change. An increase in the fetch contributes to an increase in the height of wind waves, penetration of swell waves to a greater distance into the zone of solid ice cover, and an increase in the area of fragmentation [25]. Additionally, with thin ice, the drift velocity increases. Examples of such changes were demonstrated by the drift of the Tara yacht in 2006–2007 [26] and the MOSAiC expedition aboard the Polarstern [27]. Both vessels roughly followed the historical drift of the Fram, which lasted about three years (1893–1896). The Tara's drift to the Fram Strait took half as long. Although the Polarstern was frozen in the ice some 1100 km closer to the Fram Strait (due to the impossibility of finding a suitable ice field to set up camp), the ship almost reached the Svalbard Archipelago in nine months in free drift.

A favorable combination of thermodynamic and dynamic forcing is probably capable of significantly accelerating summer ice retreat under conditions of reduced ice cover in the AO. The effect of the albedo mechanism increases as a result of the greater fragmentation of thinner ice and an increase in the total ice floe's perimeter, which leads to the intensification of lateral melting [22]. Accelerated summer ice removal in the Siberian shelf seas due to the faster export of relatively thin seasonal ice into the central Arctic Ocean leads to an extended open-water period, an increase in the heat content of the upper layer, and its deepening due to enhanced vertical turbulent and tidal mixing [28]. In the summer season, thermodynamic and dynamic forcing act in concert in the direction of a further reduction in the ice cover and an increase in the surface air temperature. A possible connection between thermodynamic and dynamic forcing in sequential seasons was formulated in [29]. Further on, it was shown that some of the scenarios predicted in that paper started to emerge in the eastern Atlantic sector of the AO in the second half of the 2010s [30]. Another new phenomenon is "atlantification" [31], which can be interpreted as specific ocean-related positive feedback due to the enhanced impact of warm and salty Atlantic-origin water on the thinner and less consolidated sea ice [32].

3. Seasonal Memory in the Ice Cover Properties

A hypothetical connection between the albedo mechanism and processes in other seasons is described in [29]. The large area of open water formed under some external forcing (e.g., global increase in air temperature) in summer enhances the action of the albedo mechanism, which contributes to accelerated ice melt and greater heat accumulation in the upper water layer in the summer season. The presence of excess heat in the upper ocean slows down the winter ice build-up, resulting in thinner ice at the beginning of the next melt season. The thinner ice breaks up faster in the following summer, resulting in a larger area and longer open-water period. Then, the whole loop repeats but with a reduced initial ice volume. The described scheme is rather idealized as it does not take into account the timing of reaching the ice thickness seasonal limit, the possible contribution of ocean heat beneath the upper ocean layer, ocean currents, or ice drift. The ice thickness limit is the thickness that can be reached during a single winter season [24]. While ice thickens, its rate of growth decreases (negative feedback). The time interval of rapid ice growth in the AO is usually shorter than the duration of the winter season [33]. Accordingly, the delay in the onset of ice formation due to the presence of excess heat in the upper ocean layer at the end of the summer season becomes significant only if it is long enough to reduce the time required for ice to reach its maximum seasonal thickness. Until the mid-2010s, there was no documented (observation-based) evidence that such a situation developed in any region of the AO. However, an analysis of the results of ensemble calculations on climate models [34] showed a statistically significant memory of excessive summer heating in the ice cover parameters, exceeding the typical red noise spectrum, in which a significant correlation is lost at a scale of about three months [12].

The increase in duration of the ice-free season, along with an increase in the sea surface temperature (SST) in the Laptev Sea after 2007 (Figure 2), created the basic preconditions for an increase in the heat content of the upper mixed layer (UML). This anticipation was confirmed by a comparative analysis of the UML parameters and the energy exchange between the ocean and the atmosphere in the central part of the Laptev Sea in contrasting ice conditions in 2003, 2005 and 2013, 2015 [35]. With the onset of autumn cooling, the rate of heat loss from the upper mixed layer of water is primarily determined by the prevailing atmospheric circulation and related weather conditions controlling the intensity of turbulent heat exchange between the ocean and the atmosphere (in the absence of incoming shortwave solar radiation) [35].



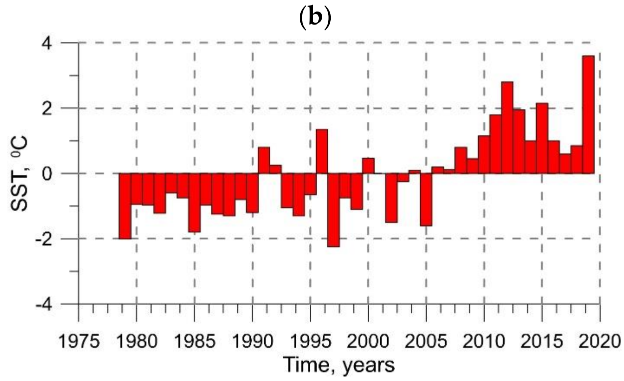


Figure 2. (**a**) Time series of the duration of the period of open water (ice concentration less than 15%) in the Laptev Sea (**a**), based on data from [5]; (**b**) SST anomaly in August–September on the Laptev Sea shelf, based on ERA5 atmospheric reanalysis data.

With typical average heat transfer from the ocean to the atmosphere being in the 100–200 W/m^2 range [36], it took less than 1 day for the temperature of the UML to reach the freezing point in 2003 and 2005, 3 to 6 days in 2013, and 16 to 32 days in 2015. The latter meant a noticeable delay in the onset of ice formation in 2015, which was recorded on satellite images. For the average winter surface air temperature in the Laptev Sea of −30 °C, an empirical formula [37] gives the first-year ice thickness after 180 days of ice growth as equal to 182 cm. Decreasing the time interval by 16–32 days leads to an 8–17 cm decrease in the first-year ice thickness. Despite this value being small, satellite measurements make it possible to detect [38]. In addition, at shorter time intervals, with a later start of freezing, the relative thinning of ice can be more significant, which, taking into account the dynamic effects described in the previous section, can affect the ice cover cohesion in the middle of the winter. It should be noted that in 2018 and 2019, the delay in the start of ice formation in the Laptev Sea was more than one month (https://seaice.uni-bremen.de/databrowser accessed on 20 January 2022). Taking this into account, the anomalously early ice retreat in the Laptev Sea (in early July) in 2020 (Figure 3) can be considered as additional evidence of increased positive feedback between the ocean and ice cover parameters on a seasonal scale.

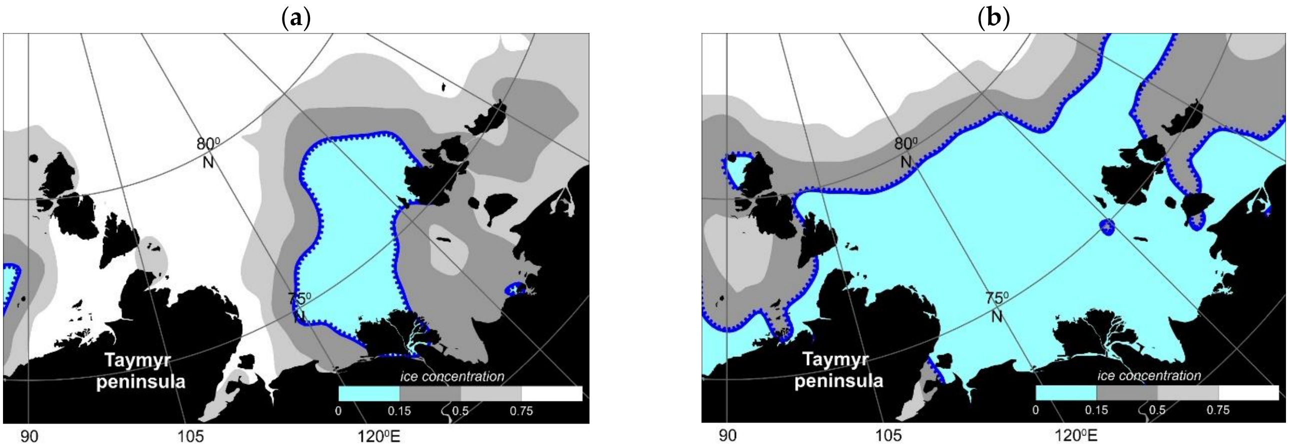


Figure 3. Sea ice extent (white) and open water (blue) in the Laptev Sea on July 15 in 2005 (**a**) and in 2020 (**b**), based on data from [5].

4. Atlantification of the AO

In the study [34] cited above, it was demonstrated that the highest correlation between the summer temperature of the UML and the ice cover properties in the subsequent winter season is geographically attached to the areas of Atlantic and Pacific water inflow into the AO. On this basis, it can be assumed that the vertical structure of water masses below the UML is a significant factor determining the seasonal memory in the characteristics of the ice cover. In most of the Arctic Ocean, warm and saline water (AW) inflowing to the AO from the Atlantic Ocean are embedded within the depth range of 150–900 m [39,40] and, therefore, are isolated from the UML by a strongly stratified structural zone (known as halocline/pycnocline) that impedes vertical mixing [41]. There are two exceptions: the western part of the Nansen Basin (between Svalbard and Franz Josef Land) and the southwestern part of the Barents Sea, where the upper AW boundary reaches the ocean surface [42,43]. The rate of cooling and spreading of the upper AW part as it moves in these areas directly depends on the state of the ice cover [41,44]. The decreases in the area and thickness of the sea ice in the AO in the 1990s–2010s led to a decrease in the volume of meltwater mixing with the AW, which caused increases in the temperature and salinity of the UML. Due to the predominant contribution of salinity to water density at low temperatures [45], such changes resulted in the weakening of the vertical density stratification at the lower boundary of the UML [44].

Under the conditions of weakened density stratification, the preconditions for deeper mixing along the AW transport trajectories in the Nansen Basin and in the Barents Sea arose [42,44]. The consequences of these changes were clearly manifested in the western part of the Nansen Basin in the second half of the 2010s through an abnormally low ice concentration in the winter season, which were explained by the action of the positive feedback initiated by the increasing depth of the winter thermal convection [44] (Figure 4). When convection reaches the AW layer, warm and salty water rises to the ocean surface and blocks ice formation [46]. Being cooled at the surface due to intense heat transfer from the ocean to the atmosphere, this water sinks deeper than its initial position, which causes a new portion of warm and salty water from the underlying AW layer to rise to the ocean surface. Through this mechanism, positive feedback, which maintains open water in the winter season in areas with weakened vertical density stratification, is realized. The described positive feedback mechanism, the essence of which consists of intensifying the influence of the heat of the Atlantic-origin waters entering the AO on the ice cover, has been defined as atlantification [32]. It should be emphasized that both phenomena of atlantification and seasonal memory, described in the previous section, are initially caused by the reduction in the sea ice cover, making it a necessary precondition. In the presence of solid thick ice, the strong density stratification at the lower boundary of the UML prevents deep penetration of convection and no effectively working feedback is formed [46].

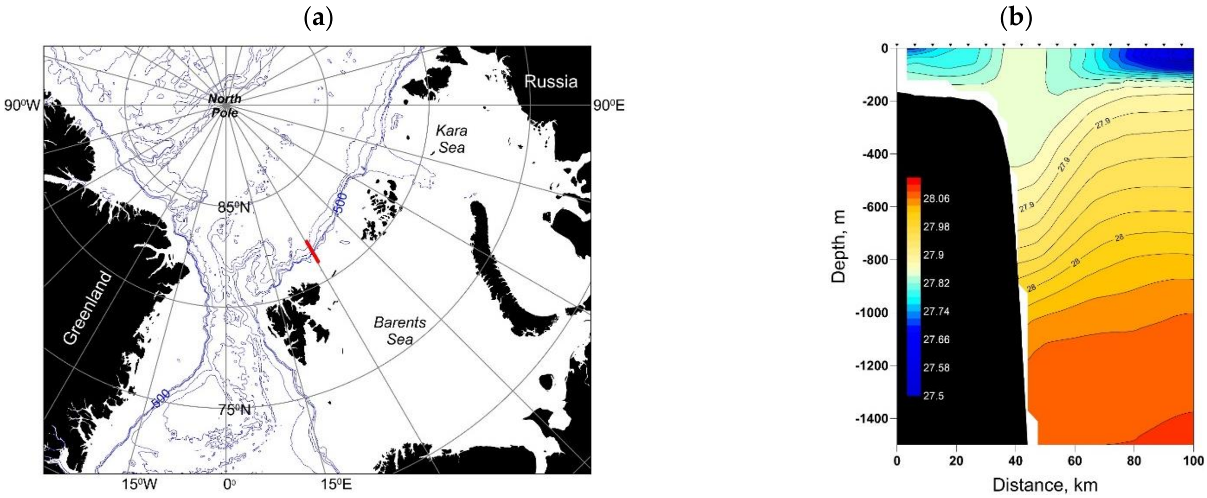


Figure 4. (**a**) Bathymetry map of the Arctic Ocean (blue lines). Location of cross-front section (red); (**b**) vertical distribution of the anomaly of potential density, kg/m^3 (color), on 31 December 2016. Black triangles on the top show location of grid points (based on the data from GLORYS12V1 reanalysis (https://doi.org/10.48670/moi-00021 (accessed on 16 February 2023).

The results of recent studies have shown that atlantification (as defined above) has also begun to manifest at the far edge of the eastern Atlantic sector of the AO, in the eastern part of the Nansen Basin. According to [47], in 2015–2018, the upper AW boundary in the Laptev Sea rose to a depth of 80 m against the typical 150 m in this area, which created favorable conditions for the entrainment of warm and salty waters in the UML and ice melt from below in the winter season, which was not previously observed.

5. Discussion and Conclusions

It is generally acknowledged that various feedbacks in the ocean–ice–atmosphere system play a significant role in the climate system. With respect to the Arctic, positive feedback is considered to be a major contributor to polar amplification, which ensures the accelerated increase in surface air temperature in the Arctic against the background of its slower growth at lower latitudes [19,48]. In addition to the well-known feedback relevant for high latitudes described in the scientific literature (namely albedo mechanism, lapse rate, meridional heat transfer in the atmosphere and ocean, cloud cover and water vapor, soot on snow, etc.), this paper discusses two additional feedback mechanisms that potentially increase the importance of the oceanic contribution to the present climate change: seasonal memory in the characteristics of the ice cover and atlantification. The specific feature of these feedbacks is that their effect became efficient only after a significant reduction in the Arctic Sea ice area, caused by another reason—global air temperature rise.

The phenomenon of seasonal memory in the sea ice parameters has been known for quite a long time [39]. However, under the ice regime typical of the second half of the 20th century, the correlation between the ice cover parameters in successive seasons was noted only for the marginal seas in some years with anomalous ice cover extent. The transition to a qualitatively different ice regime, characterized by the prevalence of seasonal ice, created the prerequisites for the formation of a stable seasonal memory in the ice cover parameters in the eastern Atlantic sector of the AO after 2007. The mechanism of seasonal memory formation is the accumulation of excessive heat in the UML under the conditions of prolonged existence of open water in the summer season. When this heat is sufficient to significantly delay the onset of freezing, it leads to a decrease in ice thickness and an accompanying decrease in ice concentration in the subsequent winter season through dynamic atmospheric forcing. In case of a significant delay at the beginning of ice formation (more than one month), one can expect a shift in the timing of opening in spring and complete ice disappearance in summer at earlier dates, i.e., the realization of positive feedback on a seasonal scale, which was hypothetically suggested in [29]. In such context, the anomalously early ice retreat in the Laptev Sea (in mid-July) in 2020 can be explained by this phenomenon.

The term "atlantification" (in a broad sense) means an increase in the influence of the heat of Atlantic-origin water entering the AO on the ice cover [32]. The main conductor of atlantification in the eastern Atlantic sector of the AO is winter thermal convection, which provides effective vertical heat exchange between the AW layer and the UML. The reason for the increased intensity of winter convection is a monotonous decrease in the ice volume in the summer season during the last three decades (http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/ accessed on 20 January 2023). A decrease in the volume of water formed during summer ice melt leads to an increase in the salt stock of the UML, weakening vertical density stratification and creating favorable prerequisites for deeper convective mixing in the subsequent autumn–winter season [46]. The unbalanced heat inflow to the ocean surface from the AW layer slows the ice build-up and contributes to its melting [43]. Cooling and spreading in the upper part of the AW layer slows down, which ensures a farther to the east penetration of warm and salty water near the ocean surface and additional ice melting along the AW pathway. Due to this positive feedback, there is a possibility of atlantification spreading to the eastern part of the Nansen basin, which has been discussed in recently published articles (e.g., [47]).

The feedbacks considered in this paper contribute to the further reduction in Arctic Sea ice, which in turn leads to their additional amplification. However, this may not be the case all around the AO. In the eastern Atlantic sector of the AO, both mechanisms act in concert, amplifying the final result [46]. The more intensive and prolonged summer warming of the UML due to the decreased sea ice extent and increased duration of the ice-free season may, at some stage, lead to a situation when the AW entering the AO merges with the warmed UML (i.e., the seasonal thermocline will noticeably weaken or even change its sign). A consequence of this transition could be a sharp increase in the depth of winter convective mixing along the AW pathways, which could theoretically lead to a situation observed under 20th-century climatic conditions in the Norwegian Sea and in the western Barents Sea: a year-round ice-free regime maintained by intense heat transfer from the ocean to the atmosphere. In the Pacific sector of the AO, no visible signs of atlantification or seasonal memory in the ice properties have been detected so far [35]. A possible explanation for these regional differences is yet to be studied in detail. Theoretically, the increased duration of the heat accumulation period invoked two competitive trends. On the one hand, a longer open water season leads to the forward shift of freezing onset (positive feedback); on the other hand, a wider area of open water ensures an enhanced ice formation after the water temperature has reached the freezing point (negative feedback).

We anticipate that the regional prevalence of one of these trends basically determines the present differences between seasonal variations in the ice properties in different sectors of the AO. This hypothesis was generally supported in a model study [49], where the authors concluded that negative feedback driven by the increasing sea ice retreat in summer, and the consequent increase in thermodynamic ice growth during winter dominates in the Arctic marginal seas from the Laptev Sea to the Beaufort Sea, while in the Barents and Kara Seas, positive feedback appears to be stronger.

The climate scenarios [50] predict that the warming of the Arctic observed today will intensify over the coming decades, causing changes in different environments, with consequences both inside and outside the Arctic. Positive feedback can be expected to play an important role in this, providing polar amplification in the current context in which the Arctic climate system is in an unstable transition state. The general expectation is that along with the reduction in the AO sea ice volume and the increasing duration of the open water season, the influence of oceanic processes on the ice cover and the lower troposphere will increase. Purposeful model experiments, supported by new observations, might be the right way to judge whether this expectation is correct and to formulate reliable projections of the state of the Arctic Sea ice properties in the specific Arctic regions in the coming years.

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