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ЯВЛЕНИЕ АРКТИЧЕСКОГО УСИЛЕНИЯ И ЕГО ДВИЖУЩИЕ МЕХАНИЗМЫ

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Представлен научный обзор одной из важнейших особенностей глобальной климатической системы — арктического усиления: более высокая скорость изменения приземной температуры воздуха в Арктическом регионе по сравнению с Северным полушарием или глобальным средним. Арктическое усиление является региональным проявлением более общего явления — полярного усиления. Однако антарктическое усиление значительно слабее арктического. Основными механизмами, определяющими арктическое усиление, являются различные климатические обратные связи, работающие по-разному в разных широтах, и перенос тепла к полюсу, вызванный атмосферной и океанической циркуляцией. Современные научные результаты в основном продемонстрировали относительную роль различных климатических обратных связей в формировании арктического усиления. От более важных к менее важным — это обратная связь вертикального градиента температуры, обратная связь Планка и альбедо поверхности. Однако некоторые другие возможные механизмы остаются малоизученными. В частности, вклад изменяющегося во времени меридионального переноса тепла довольно неясен. Более того, меридиональная адвекция тепла атмосферой и океаном может играть существенную роль в наблюдаемых изменениях интенсивности арктического усиления на разных временных масштабах.

Ключевые слова: арктическое усиление, положительные и отрицательные климатические обратные связи, атмосферный и океанический перенос тепла, климатическая система, морской лёд, долгосрочные колебания.

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THE ARCTIC AMPLIFICATION PHENOMENON AND ITS DRIVING MECHANISMS

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This paper presents a research synthesis of one of the essential features of the global climate system — Arctic amplification: a higher rate of change of surface air temperature in the Arctic region compared to that of the Northern Hemisphere or global average. Arctic amplification is a regional manifestation of the more common phenomenon — Polar amplification. However, Antarctic amplification is significantly weaker than the Arctic one. The major mechanisms defining the Arctic amplification are various climate feedbacks, operating differently at different latitudes, and a poleward heat transport induced by the atmospheric and oceanic circulation. The state-of-the-art scientific results have mostly demonstrated a relative role of different climate feedbacks in forming the Arctic amplification. From the more important to the less important ones, these are the lapse rate, Planck and surface albedo feedbacks. However, several other possible mechanisms are remained poorly studied. In particular, the contribution from the time varying meridional heat transport is quite unclear. Moreover, meridional advection of heat by the atmosphere and ocean can play a significant role in the observed variations of the intensity of the Arctic amplification at different time scales.

Key words: Arctic amplification, positive and negative climate feedbacks, atmospheric and oceanic heat transport, climate system, sea ice, long-term variations.

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1. Introduction

The Polar amplification is a manifestation of the differences in functioning of the climate system in polar and extra-polar latitudes. Instrumental and paleoclimatic records, as well as climate model projections confirm the existence of this phenomenon for a wide range of temporal and spatial scales [1]. The formal definition of Polar amplification is based on the argument of Swedish scientist S. Arrhenius [2] who stated that changes in the concentration of carbon dioxide in the atmosphere could alter the Earth's surface temperature and that the temperature change would be especially strong in polar latitudes. Presently, the Polar amplification is understood as a phenomenon characterized by higher amplitudes of long-term surface air temperature (SAT) variations at high latitudes compared to the global average. For instance, nowadays, the rate of the surface air temperature increase in the Arctic is about twice higher than the global average rate.

The Polar amplification is relevant for both the Arctic and Antarctic. However, it is significantly weaker in the Antarctic than in the Arctic. This review focuses on the issues of the Arctic amplification (AA).

Now, the existence of this phenomenon is generally accepted by the scientific community, whereas some time ago it has been a subject of discussion. For example, Polyakov et al. [3] computed the trend over the 127-year record of surface air temperature in 1875–2001 and found no significant enhancement of warming at the high latitudes. As a consequence, authors concluded that there is no Arctic amplification of global warming and that pronounced low-frequency variability in the Arctic explains high-latitude amplified signals.

Arctic amplification has manifested itself in the distant past. Thus, historical proxy records revealed enhancement of both positive and negative tendencies in the global temperature in the Arctic region [4]. Moreover, during earlier geologic periods, such as the Cretaceous (65 million years ago), the Arctic amplification was a common feature of the climate system, including time periods when the continental configurations differed from those today [4].

The current Arctic amplification is illustrated by fig. 1 showing the spatial and seasonal pattern of present-day warming [5] (see Inset). Two features are evident in this figure: the global warming is enhanced in the Arctic, and this enhancement is most pronounced in winter being significantly weaker during summer. The general enhancement of the global warming in the Northern Hemisphere (NH) compared to the Southern one also should be noted.

Global climate models predict that the Arctic amplification will continue in the future. Thus, 31 CMIP5 model projections driven by the forcing scenario RCP8.5 (Representative Concentration Pathway 8.5) show very strong Arctic amplification to the end of the 21st century when the warming in the Arctic scaled in degrees Celsius may be three times higher than the global average [6].

The preindustrial records of the phenomenon showed that natural physical mechanisms are key drivers of the Arctic amplification. However, in the present climate, the increasing anthropogenic forcings sum with the natural ones and must be adequately accounted for.

The polar amplification is extremely important for the climate system, and study of this phenomenon is included in the number of the international research programs. For instance, among the Coupled Model Intercomparison Project Phase 6 (CMIP6) implemented Model Intercomparison Projects (MIPs), there is the special Polar Amplification Model Intercomparison Project (PAMIP) [7].

Several metrics are used at present for the quantitative estimate of the Arctic amplification [8]. The first metric has been suggested by Bekryaev et al. [9] who proposed to express the Arctic amplification as the coefficient in a regression relationship linking the annual temperature anomalies over the Arctic and Northern Hemisphere.

Table 1

Existing Arctic amplification (AA) metrics [8], (ΔT are temperature anomalies, A and NH indicate correspondingly Arctic and Northern Hemisphere)

AA metric definition	Mathematical expression	Reference
Coefficient of linear regression between the Arctic and the NH SAT anomalies	$\Delta T_A = a\Delta T_{NH} + b$	[9]
Ratio of the inter-annual SAT anomalies variability in the Arctic to inter-annual SAT anomalies variability in the NH	$\frac{\sigma_A}{\sigma_{NH}}$	[10]
Difference between SAT anomalies in the Arctic and Northern Hemisphere	$\Delta T_A - \Delta T_{NH}$	[11]
Ratio of absolute value of 30-year linear trend of SAT anomalies in the Arctic to absolute value of 30-year linear trend of SAT anomalies in the NH	$\frac{\lvert \Delta T_{Atrend} \rvert}{\lvert \Delta T_{NHtrend} \rvert}$	[12]

The second metric has been introduced by Kobashi et al. [10] as the ratio between inter-annual SAT anomalies variability in the Greenland and Northern Hemisphere. However, this metric can be easily extended to the whole Arctic region. The third metric has been proposed by Francis and Vavrus [11] as the difference between 1000 hPa air temperature anomalies in the Arctic and mid-latitudes, as the authors aimed at capturing the signals of the mid-latitude dynamics. To be consistent, their metric needs to be re-computed using the mean temperature of the whole Northern Hemisphere as the reference. Finally, the fourth metric has been suggested by Johannessen et al. [12]. They defined an index for the Arctic amplification assessment as the ratio between absolute values of the slopes of 30-yr running linear SAT trends in the Arctic (65–90°N) and Northern Hemisphere. For analysis and comparison of different metrics, the second and third metrics were re-formulated in [8]. Table 1 summarizes available metrics of the Arctic amplification. Monthly mean climatologies at every grid point are used as references to find the temperature anomalies.

2. Physical mechanisms responsible for Arctic amplification

2.1. The scope of mechanisms involved

Dynamics in polar regions is extremely complex being defined by numerous interactions among the atmosphere, land surfaces, ocean and sea ice [13]. Nowadays, there is no full understanding of the physical processes that drive polar regions climate, which is additionally complicated by a high sensitivity of these regions to external forcings and significant internal variability [14–17]. It is difficult to establish a large network of in-situ observational sites in the polar regions because of the severe weather conditions and the quasi-permanent sea ice cover. As the consequence, we have limited observational records affecting the quality of climate models, which show large biases in these regions [18] and opportunities to advance our scientific understanding [19, 14].

Nowadays, two different types of mechanisms are considered as the main drivers of Arctic amplification. They are various climate feedbacks operating differently at different latitudes and teleconnections inducing heat and moisture exchange between polar regions and lower latitudes, including tropics. The climate feedback is positive when a response to the initial perturbation amplifies its effect, and the closed loop is formed with a constant enhancement of the first forcing. The climate feedback is negative when a response to the initial perturbation dampens its effect, and the closed loop is formed with a constant dampening of the first forcing. The notion of climate feedback itself implies the amplification; therefore, the causes of polar amplification are widely attributed to the feedbacks in the climate system. A perfect example is the positive surface albedo feedback which is an essential mechanism for the Arctic amplification; however, new studies and modelling results have argued that some other feedbacks should be considered as more important. The detailed referenced discussion of the main feedbacks involved in the Arctic amplification is given in the next section. After that, the role of oceanic and atmospheric advective processes is examined.

2.2. Climate feedbacks

Being important element of the Earth system, climate feedbacks play a less stabilizing role in the polar regions than in the tropics: i. e., feedback parameters are less negative for negative feedbacks and/or more positive for positive feedbacks in polar regions, compared to tropics [13, 20–23]. This causes larger temperature variations in the polar regions compared to the rest of the Earth.

As we mentioned earlier, for the climate changes projected for the 21st century, the polar amplification is much stronger in the Arctic than in the Antarctic. In the Arctic, the large amplification mostly results from (1) a relatively large and positive lapse rate feedback because of the different vertical distributions of temperature in the higher and lower latitudes, (2) a relatively weak negative Planck feedback due to the different surface temperature in the colder and warmer regions, and (3) a large positive surface albedo feedback when Arctic sea ice melting is accelerated with the presence of water on its surface [13]. Thus, in addition to the recently prevailing trend of the dominant role of surface albedo feedback in the Arctic amplification [24], temperature feedbacks are now considered equally or even more important in driving the Arctic amplification.

Other feedbacks, although considered to be less important, also affect polar amplification. Figure 2 (see Inset) summarizes the most important radiative and non-radiative feedbacks in the polar regions [13].

Table 2 summarizes the feedbacks involved in the Arctic amplification, together with their principal time scales. According to Goosse et al. [13], radiative feedbacks are studied quite good, and, therefore, they provide clear insights into processes controlling high latitude climate change. In contrast, we have not achieved consensus on the relative importance of non-radiative feedbacks and on how to quantify them.

Table 2

Summary of radiative and non-radiative feedbacks involved in the Arctic amplification, together with their principle time scales

Radiative feedbacks	
More important (According to [13])	**Less important (According to [13])**
Lapse rate feedback (+) Annual, most pronounced in winter. Negative in the tropics	Water vapour feedback (+) Annual, positive everywhere, but stronger in the tropics
Planck feedback (–) Annual, negative everywhere, but weaker in the Arctic	Cloud feedback (+) Annual, but active only in non-summer months
Surface albedo feedback (+) Annual, most pronounced in summer	Cloud feedback (–) Annual, relevant both for the Arctic and lower latitudes
Non-radiative feedbacks	
More important (According to the time scale length)	**Less important (According to the time scale length)**
Ice growth–thickness (–) Annual, but the mechanism is expressed seasonally	Surface mass balance–elevation (+) Mostly active in Greenland Ice Sheet, significant on longer time scales than annual

Among the three most important radiative feedbacks, the first two ones are the different processes of the temperature feedback. In a warmer climate and in the Arctic region, the lower troposphere has more pronounced stable stratification conditions which gives rise to a larger warming of the lower atmosphere compared to the upper troposphere, leading to a smaller increase in outgoing longwave radiation than under vertically uniform warming, and thus to further warming [20, 21]. In contrast, the vertical distribution of temperature in the tropics leads to the negative lapse rate feedback because of the strong turbulent mixing in the boundary layer. The way how this feedback operates at low and high latitudes contributes to the Arctic amplification. However, the leading role of the lapse rate feedback was obtained based on modelling studies; therefore, these results should be considered with caution. Indeed, climate models have a coarse resolution and fail to accurately represent subgrid processes, including the sea ice dynamics. The Planck feedback is negative everywhere; however, at lower temperatures in the Arctic a one-degree surface warming leads, according to the Stefan–Boltzmann law, to lesser increase in the outgoing longwave radiation than the same warming in the low latitudes, especially in the tropics. As a result, it gives higher warming rate in the Arctic than in the lower latitudes [25–28]. Again, the difference of this feedback magnitudes at various latitudes leads to the Arctic amplification.

The surface albedo feedback is also very important, especially in the present conditions when sea ice in the Arctic retreats dramatically. Climate warming causes enhanced melting of sea ice leading to exposure of new areas of open water with much lower albedo resulting in increase of absorption of solar shortwave radiation. It, in turn, causes further sea ice melting. These processes form the positive feedback loop which amplifies warming. Additional contribution to this feedback is provided by melt ponds formed by the melting snow on the sea ice surface [20, 29–31]. The surface albedo feedback is limited mostly by the polar regions.

Under the global warming, the concentration of water vapour in the atmosphere increases amplifying the greenhouse effect and inducing further warming [32, 33]. This positive water vapour feedback is stronger in the tropics, where at higher mean temperatures variations in water vapour content can be larger than in the polar regions. At high latitudes, however, this feedback still plays a non-negligible role in air temperature response to external forcing [20, 22, 34].

Clouds influence the heat balance of the Earth, and the sign of any cloud feedback depends on the balance of shortwave cooling and longwave heating by the clouds. Cloud feedbacks are the most uncertain of all the radiative feedbacks as the cloud radiative effect depends on a number of factors that, themselves, can be modified by the initial perturbation [27, 35–37]. Two polar-specific cloud feedbacks deserve to be mentioned: the cloud sea-ice feedback [38–41] and the cloud optical depth feedback [42, 36, 43]. When sea ice melts and new areas of the open water are exposed to direct interaction with the atmosphere, the increased sea surface turbulent heat fluxes increase the humidity in the lower atmosphere and the fraction of the low-level clouds. During the polar night, increased amount of the low clouds makes the downwelling longwave radiation higher which leads to a deceleration of sea ice formation and thus contributing to a positive feedback. The cloud optical depth feedback operates both at mid- and high- latitudes. Cloud liquid particles are smaller than cloud ice particles, and are therefore more efficient at reflecting solar radiation back to space. As the climate warms, the total amount of water in the mixed phase clouds increases, which increases the amount of the reflected solar radiation (i. e., increase the cloud albedo), acting as a negative feedback

[42]. Further, the fraction of cloud water droplets also increases, enhancing the cloud optical depth feedback [13]. Generally, a warmer Arctic is accompanied by the increased amount of clouds, and the effects from cloud forcings vary from warming the surface to cooling the surface depending on the season [44]. An interesting peculiarity about clouds is that they can dampen the positive surface albedo feedback: when sea ice melts and its albedo changes, formation of clouds has a certain compensation effect. The mechanism of damping has two ways to work. The first one is characterized by the high cloud fraction over the area with melted ice. The second is due to the enhanced evaporation induced by the sea ice melt which leads to the additional cloud formation [45].

For the Arctic region, two non-radiative feedbacks of a relatively low importance are specified. The basal sea ice growth rate is largely driven by heat conduction through the ice, which is an inverse function of the sea ice thickness: a thin ice grows faster than a thick one [46]. At the same time, sea ice melt rate is nearly independent from the ice thickness. This leads to a negative ice growth-thickness feedback. When a positive radiative perturbation is applied to the sea ice surface energy balance, leading to ice thinning during the warm season, ice growth rate in winter enhances, adjusting the seasonal variations in ice thickness to a new equilibrium with new growth and melting rates [47].

Variations in the area of the ice land sheets generally, but not exclusively, play role on longer time scales. In the positive surface mass balance-elevation feedback, increased air temperature leads to ice melting, which lowers the surface elevation of the ice sheet, exposing the ice to warmer air at lower levels and, thus, facilitating further melt of the glaciers [48, 49]. In the Northern Hemisphere, this positive feedback is particularly relevant for the Greenland Ice Sheet where surface elevation is substantial.

The radiative and non-radiative feedbacks affect atmospheric and oceanic circulation patterns because a climate response to perturbations also gives rise to variations in a redistribution of the heat between different latitudes. It has been demonstrated in a number of studies that a more intensive poleward atmospheric energy transport, that adds to warming of polar regions, results from a warming in the tropics under the greenhouse gas forcing [50–54]. This indicates a coupling between the radiative feedbacks and the atmospheric heat transport [53, 55, 56]. Moreover, the atmospheric processes at lower latitudes, in turn, are also affected by the changes in polar regions [57]. A generally accepted understanding, whether the response of the system has a direct impact on the original perturbation itself such that a closed feedback loop can be identified, has not been achieved. This is an area of highly debated research. In addition, the role of variations in the oceanic meridional heat advection is thought to be essential in shaping the polar climate with a response to a global warming increasing the poleward heat transport into the Arctic [58–60] and decreasing the poleward heat transport towards the Antarctic continent [61, 58]. Again, it is not possible to state confidently if these changes can be represented in terms of a closed feedback loop (e. g., sea ice thinning enhancing ocean heat transport into the Arctic) [60] or they should be referred to as important drivers of the observed polar climate change.

2.3. Atmospheric and oceanic circulation and heat transport

2.3.1. Coupling of the processes

Atmospheric and oceanic meridional heat transports to the Arctic can operate separately and be coupled, and may be essential for understanding the processes behind the Arctic amplification. For instance, a transport of warm Atlantic water (AW) into the Arctic eventually affects the regional atmospheric circulation patterns via the heat release to the atmosphere, while the atmospheric winds govern the intensity of oceanic circulation. In this section, we discuss the most important mechanisms of the ocean-atmosphere coupling, which affect the Arctic amplification.

The ocean transports heat to the Arctic mostly through the Atlantic domain; the Pacific domain is of secondary importance. The AW significantly changes its characteristics, on the way to the Arctic, while being transported northwards across the Nordic Seas: through mixing with the surrounding fresher and colder polar water and through the ocean-atmosphere exchange. The modified AW enters the Arctic Ocean through the Fram Strait and further spreads under the sea surface as a layer of warmer and more saline water [62]. AW forms the major heat supply to the Arctic Ocean. The branch of the AW, entering the shallow Barents Sea loses nearly all its heat via an intense ocean-atmosphere exchange and further conveys little oceanic heat to the neighbouring regions [63, 64]. The annually averaged AW volume transport by the West Spitsbergen Current via the Fram Strait is around 3 Sv [65], whereas annually averaged heat transport ranges between 26 and 50 TW (1 TW = 1012 W) [66].

Ocean circulation is sensitive to variations of the atmospheric wind stress and its curl [67, 68]. The cyclonic gyre over the Nordic Seas responds to anomalous wind stress curl, as well as to the intensity of the wind stress itself along the coastline [69]. As a result, the strength of the AW flow varies in time [70, 71]. Variation in the local atmospheric pressure over the northern Barents Sea redistributes heat, coming with the Norwegian Current, between the Barents Sea and the Fram Strait [72].

The AW temperature (warm/cold AW pattern) in the northern Fram Strait is found to inversely depend on the intensity of the Greenland Sea Gyre circulation, in particular its barotropic component [73], than on the temperature of the incoming AW through the Ferrero-Shetland Strait. For example, although the AW temperature is found to be at maximum during 2007, the net heat transported toward the Arctic Ocean through the Fram Strait was not as high at that period [66]. The latter is due to the wind-induced Ekman divergence, which, through changing the sea surface height anomalies in the Greenland Sea Gyre, intensifies the recirculation of the AW in the Nordic Seas, thus reducing the heat transport to the Arctic Ocean [73].

In summary, the Nordic Seas are not a passive conductor of the Atlantic heat to the Arctic, but can significantly modify the heat flux governed by regional ocean-atmospheric feedbacks.

2.3.2. The fate of the oceanic heat inflow in the Arctic

Until recently, the warm AW advected into the Eurasian Basin (EB) of the Arctic Ocean has been considered a relatively unimportant contributor to the sea ice reduction during the last few decades [74–77]. The main reasoning was an effective separation of a significantly fresher upper mixed layer (UML) from the warm and saline AW by a strong pycnocline. However, a few recent studies discovered an episodic exceptionally strong mixing through the pycnocline in the western Nansen Basin, north and northeast of Svalbard [78, 79]. With the on-going warming of the Arctic, AW in the Nansen Basin can reach the UML, particularly in winter, due to cooling and haline convection associated with the contraction of the areas, permanently covered with the sea ice and with a slowly growing thick ice, replaced by a more intensive young sea ice formation [80, 81]. The observed shoaling of the AW is another favourable factor for a more intensive heat supply to the UML [81]. Observations of 2013–2015 by means of oceanographic moorings and drifting Ice-Tethered Profiler buoys showed that, similar to the western EB, the eastern EB presently is also in a transition to a stronger mixing conditions [82, 83]. This eastward progression of the western EB conditions is called the “atlantification” of the Arctic Ocean [81]. The main processes responsible for the “atlantification” are summarized in fig. 3 (see Inset). The progress of the “atlantification” eastwards is a result of a positive ocean-ice feedback, when an additional heat, advected to the UML and below, induces a higher vertical mixing through the pycnocline, a reduction of the ice cover and a further intensification of the vertical heat flux to the UML through mixing.

The additional heat, entering the UML, is finally released to the atmosphere, thus increasing the role of the oceanic heat flux through the Fram Strait in the Arctic amplification.

The similar progressive warming is also found in the Canadian sector of the Arctic. The typical heat content in the halocline of the Beaufort Gyre per unit area, which was around 2×10^8 J m^{-2} before the 2000s, in 2014–2017 reached beyond 4×10^8 J m^{-2}. The maximal values are observed at the central area of the Beaufort Gyre [84]. Fig. 4 shows the observed progress of this rapid warming (see Inset).

On the basis of reanalysis products, Timmermans et al. [85] have shown that the cumulative net summertime (July to September) heat input to the northern Chuckchi Sea (this is the region of net positive subduction [86]) increased from around 100 to around 500 MJm^{-2} over the three decades between 1987 and 2017. The authors relate this increase to the loss of sea ice area, which allowed more solar absorption by the surface ocean.

The doubling of the Beaufort Gyre halocline heat content over the past three decades is attributed to a warming of the Chukchi Sea source waters that ventilate the subsurface layer [85]. Therefore, the local ice-albedo feedback is not confined to the upper ocean heat budget but also leads to heat accumulation in the ocean interior. If this subsurface heat can be efficiently translated to the UML, the warming of the Beaufort Gyre directly affects the sea ice retreat and further intensifies the albedo feedback contributing to the Arctic amplification.

2.3.3 The atmospheric meridional heat transport and its link to the ocean dynamics

The purely atmospheric heat transport is thought to be also of high importance in forming the Arctic amplification. For example, some authors estimate over 50 % of the winter warming observed over the most of the Arctic Ocean since the end of the 19th century is to be linked to the atmospheric sensible and latent heat transport by storm systems, originating over Atlantic and Pacific Oceans with the dominant role of the Atlantic “gate” [87, 88]. The advection of the sensible and latent heat to the Arctic through the Atlantic “gate” is observed in the lower troposphere (with the maximum around 1000 hPa) mainly during the winter season. The heat fluxes influence the Arctic winter temperature from the Norwegian and the East Siberian seas to the North Pole [88]. In particular, the analysis of the winter temperature anomalies of 2015–2016 suggested the leading role of the heat transport through the Atlantic “gate” [89, 90], mainly being an integral effect of the heat intrusions with cyclones [91, 92]. The results are also confirmed by the calculations based on reanalysis data [93–96, 88]. It is important to emphasize that atmospheric heat transport is linked with the climate feedbacks which was already mentioned before. Thus, the warming in the tropics leading to the increase in the atmospheric heat transport is more important in the Arctic warming than a response to the changes in the meridional temperature gradient. This is also relevant for the consequent surface warming in the Arctic due to higher downward longwave radiation [97]. Both the dry-static energy and latent heat contribute to the Arctic warming; however, their role might be different in that the dry-static energy dominates the net heat transport, whereas the warming effect is more pronounced due to the latent heat component via the greenhouse effect [98].

When studying the Arctic amplification, it is essential also to consider the atmospheric and oceanic dynamics in the regions that are more sensitive to the temperature variations, such as the Barents and the Kara Seas. Here, Arctic warming is the strongest, and in these regions, the sea ice cover is the most significantly affected by the on-going warming and regional feedbacks [99–102]. For instance, a stronger oceanic heat flux leads to a reduction of sea ice, an increase of the sensible and latent heat fluxes from the ocean and an anomalous heating of the lower troposphere. The latter changes the regional atmospheric circulation patterns creating conditions for the intensification of cyclonic vorticity, which further increase the oceanic heat advection in the region [103, 104, 100, 105].

The Arctic Ocean Oscillation (AOO) index, introduced in [106], is defined on the basis of a wind-driven simulated sea-surface height field across the Arctic and shows the intensity and sense (clockwise/anticyclonic or counterclockwise/cyclonic) of the Arctic Ocean wind-driven circulation. The AOO variations indicate that from 1948 to 1996 the anticyclonic circulation regimes (ACCRs) and cyclonic circulation regimes (CCRs) alternate with a typical periodicity of 10–15 years [107].

The conceptual hypothesis of the mechanisms governing the observed change of the regimes [108] implies the freshwater and heat exchanges between the Arctic and Nordic Seas to be a self-regulated system, including the ocean-atmosphere coupling (fig. 5, see Inset). A less intensive atmospheric heat advection to the Arctic results in a lower-than-normal Arctic atmospheric temperature, a higher-than-normal sea level pressure in the central Arctic and an increase of the negative atmospheric vorticity (ACCR). The stronger anticyclonic vorticity in the atmosphere leads to a freshwater accumulation in the Beaufort Gyre via the Ekman convergence and a reduction of the freshwater flux to the Nordic Seas. This increases sea surface salinity in the Nordic Seas and promotes an intensification of winter convection preconditioned by a weaker stability of the upper part of the water column. The deeper winter convection results in an additional heat release to the atmosphere from the lower ocean levels. This heat is advected by the mean atmospheric circulation or heat transport with cyclones to the Arctic, which increases the air temperature in the Arctic and reduces the anticyclonic circulation. This means the process reverses because of a transition from the ACCR to the CCR [108, 109]. The hypothesis was tested via an idealized multi-box model of the ocean-ice-atmosphere system [110–112].

However, since 1997, the ACCR dominates in the Arctic atmospheric circulation regimes, and a breakdown of the quasi-decadal variability has occurred, not behaving according to the predictions of the conceptual model presented above [108, 110–112]. The freshwater fluxes through Fram Strait do not show any large variations since 2002 [113, 114], which confirms the fixed regime pattern during the latest decade.

The Arctic Ocean–Nordic Seas were viewed in that conceptual model as a closed system; however, in recent decades, anomalously warm atmospheric temperatures have led to variations in the global climate, including a rapidly increasing melt of the Greenland Ice Sheet. Recent assessments of freshwater flux from Greenland show an exponentially growing increase of the freshwater release [115]. From 1992 to 2010, the freshwater flux to the ocean has increased by 36 %. Assuming all the Greenland Ice Cap freshwater flux entering the Nordic Seas, we receive a clearly longer ACCR compared to CCR in the multi-box model simulations. Doubling of the freshwater flux, not inconceivable in the future given present warming and Greenland melting trends [116, 117], might result in a clear dominance of the ACCRs persisting over two-three decades and separated by 3–4 years of the CCRs [107]. However, the latest model study suggests that the Greenland freshwater practically does not enter the Nordic Seas, and only a very diluted fractions of percent can enter the region from the south with the North Atlantic Current a decade after the water come into the ocean [118]. Other external forcings, such as a variation in the intensity of the Atlantic meridional overturning circulation or an increase of the mean temperature in the North Atlantic may be responsible for the observed variations of the regional climate system [119, 120].

3. Conclusion

Arctic amplification is caused by various mechanisms. Among them, two sets of mechanisms are considered the most important:

1) Interplay between magnitudes of climate feedbacks in the Arctic, from one hand, and tropics and mid-latitudes, from another hand.

2) External forcing for the Arctic, mostly heat transport via atmospheric and oceanic circulation.

However, more research is needed to make definitive statements. For example, regarding climate feedbacks, where the clarity seems to be the highest, we still do not have precise understanding about the role of clouds. Although this review has highlighted the emergence of other feedbacks driving the Arctic amplification, the albedo feedback stands out in this framework given present trends of sea ice melting in the Arctic.

As compared to the regional climate feedbacks, the role of atmospheric and oceanic circulation in the Arctic amplification is presently unclear. There are many papers where circulation patterns are considered as a result of Arctic amplification although they are highly debated [11, 57, 121, 122]. However, the circulation factor affecting the Arctic amplification and related atmospheric and oceanic advective processes have not been well studied.

One of the crucial unresolved questions is the relative importance of the atmospheric and oceanic meridional heat transports for the observed Arctic amplification, as well as the way they respond to external forcing. Even for better investigated atmospheric heat advection, different studies suggest different importance of this mechanism: from negligibly small [20] to of equal importance with the main radiative feedbacks [88]. Distinguishing causes and effects in the coupled variations of the meridional heat transports by the atmosphere and the ocean to polar latitudes requires further model experimentation frameworks.

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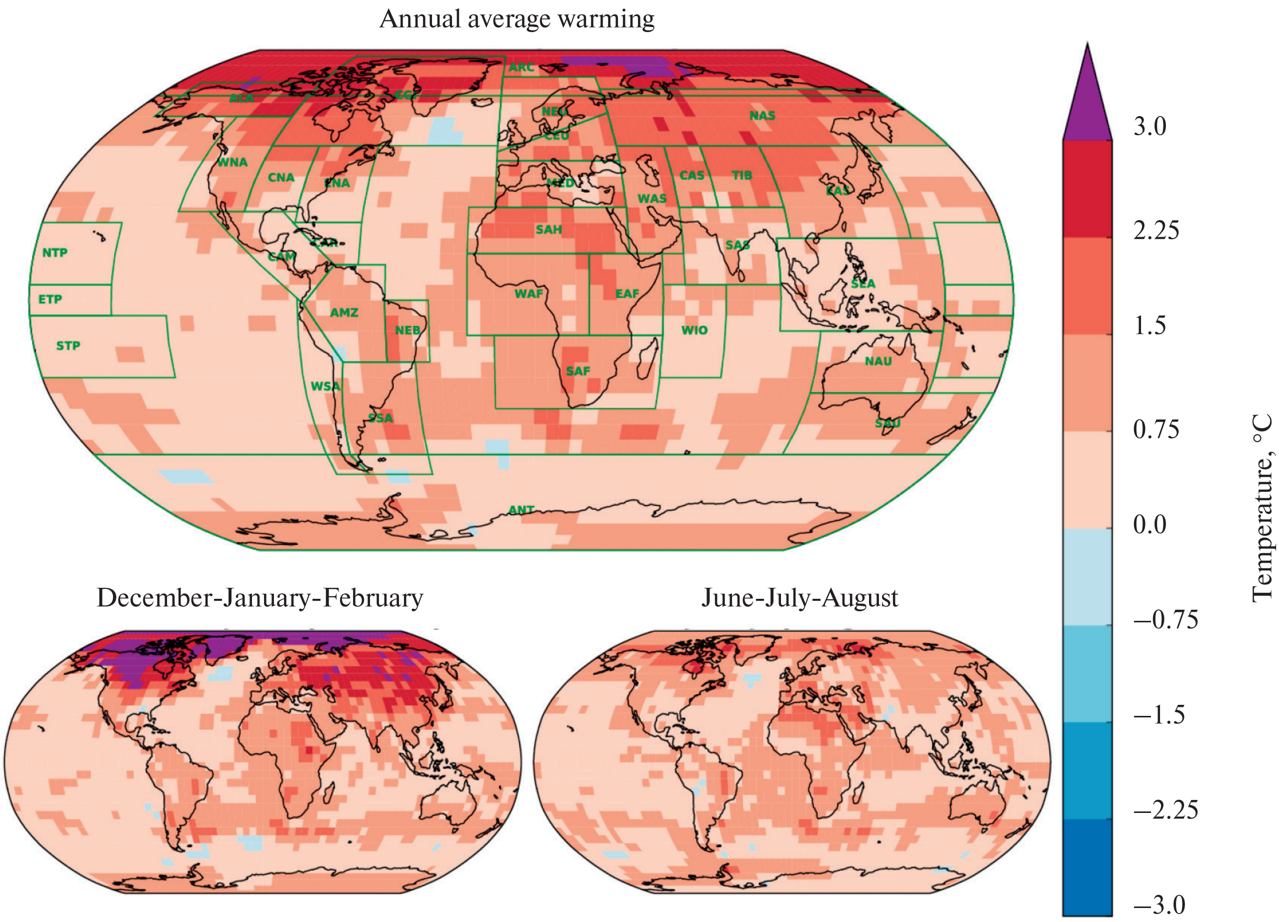

Fig. 1. Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January, and February (bottom left) and for June, July, and August (bottom right) (from fig. 1.3 in [5]).

К статье *Латонин М.М.*, *Башмачников И.Л.*, *Бобылёв Л.П.* Явление арктического усиления...
Latonin M.M., Bashmachnikov I.L., Bobylev L.P. The Arctic amplification phenomenon...

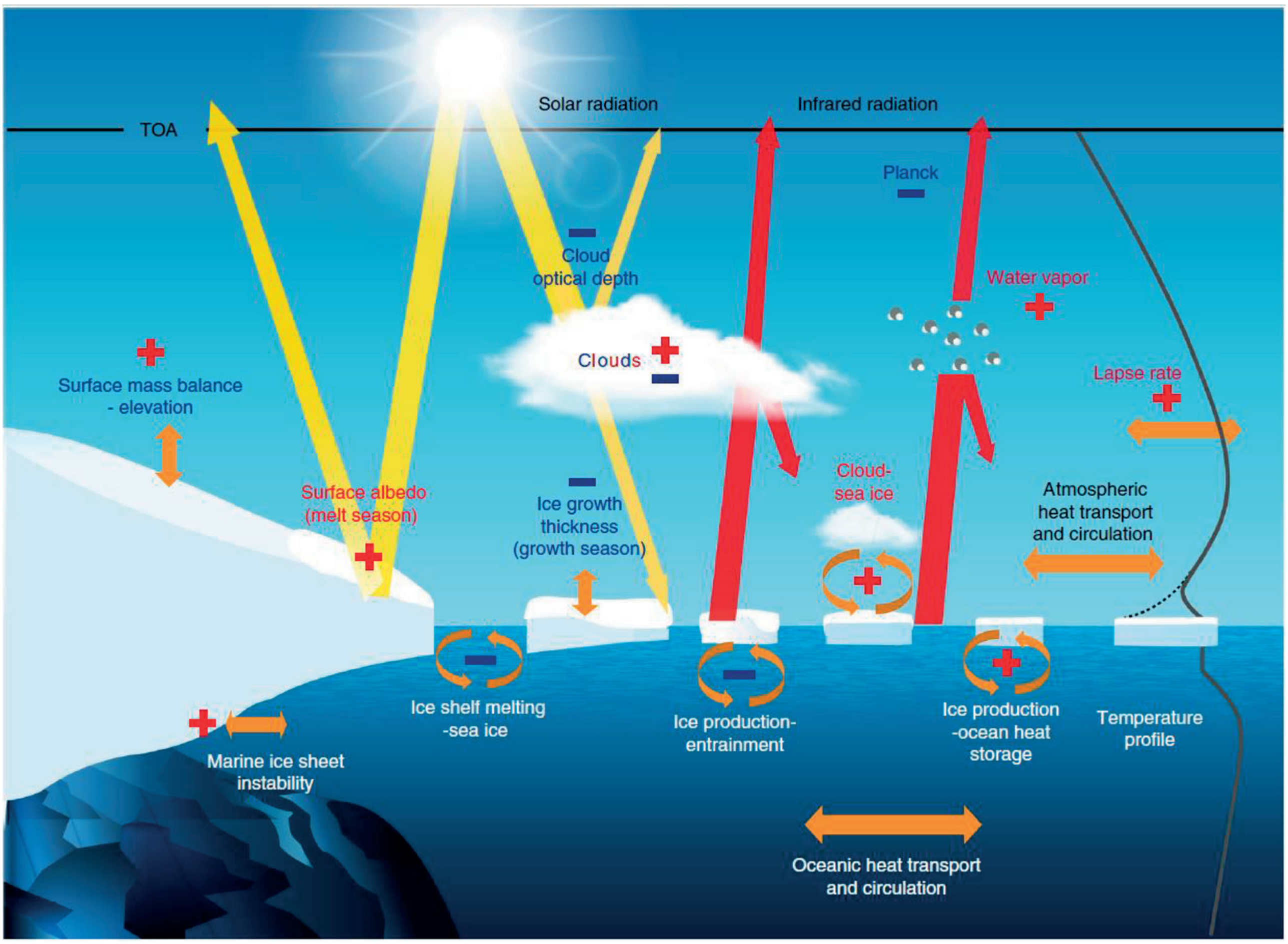

Fig. 2. A schematic of some important radiative and non-radiative feedbacks in polar regions involving the atmosphere, ocean, sea ice and ice sheets. TOA refers to the top of the atmosphere. Solar radiation (in yellow) and Infrared Radiation (in red) represent the shortwave (solar) and longwave (infrared) radiation exchanges. A red plus sign means that the feedback is positive; a negative blue sign corresponds to a negative feedback. Both signs are present for cloud feedbacks as both positive and negative feedbacks are occurring simultaneously, and the net effect is not known. The gray line on the right represents a simplified temperature profile in polar regions for the atmosphere and ocean, the dashed line corresponding to a strong surface inversion. Oceanic and atmospheric heat transport are mentioned but without signs as the processes involved are not restricted to polar regions, and it is not clear if they could be formally expressed using a closed feedback loop (from fig. 1 in [13])

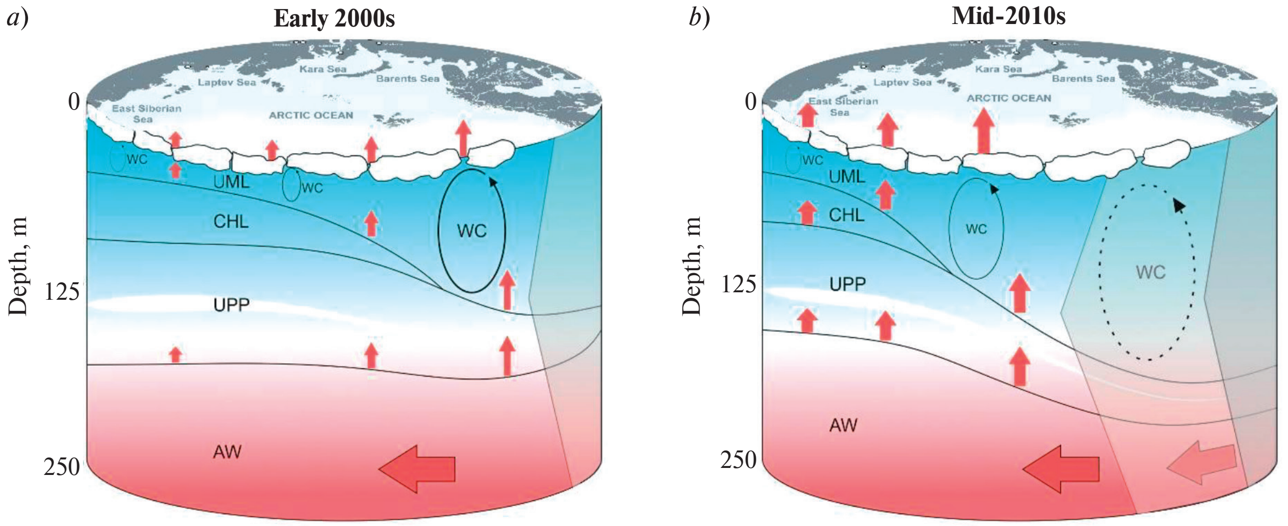

Fig. 3. Conceptual model of "atlantification" of the eastern Eurasian Basin (EB) along the continental margin during the recent years : the situation in the early 2000s (*a*) and the situation in the mid-2010s (*b*). The broad grey arrow extending from the right side schematically represents a suite of processes associated with the "atlantification": (1) a stronger influence of the Atlantic water (AW) on characteristics of the Upper mixed layer (UML) in the eastern EB (an increasing heat flux and/or vertical mixing), (2) reduction of the ice cover, resulting in (3) a higher heat and moisture flux to the atmosphere and (4) an increasing depth of the winter penetrative convection, further increasing the AW heat flux to the UML and the transformation of the permanent cold halocline layer (CHL) to the seasonal halocline over a larger area. UPP indicates the upper permanent pycnocline; WC is winter convection; the size of vertical red arrows schematically indicates the intensity of the upward heat flux and horizontal red arrows — the advective flux (picture is based on fig. 5 in [81]).

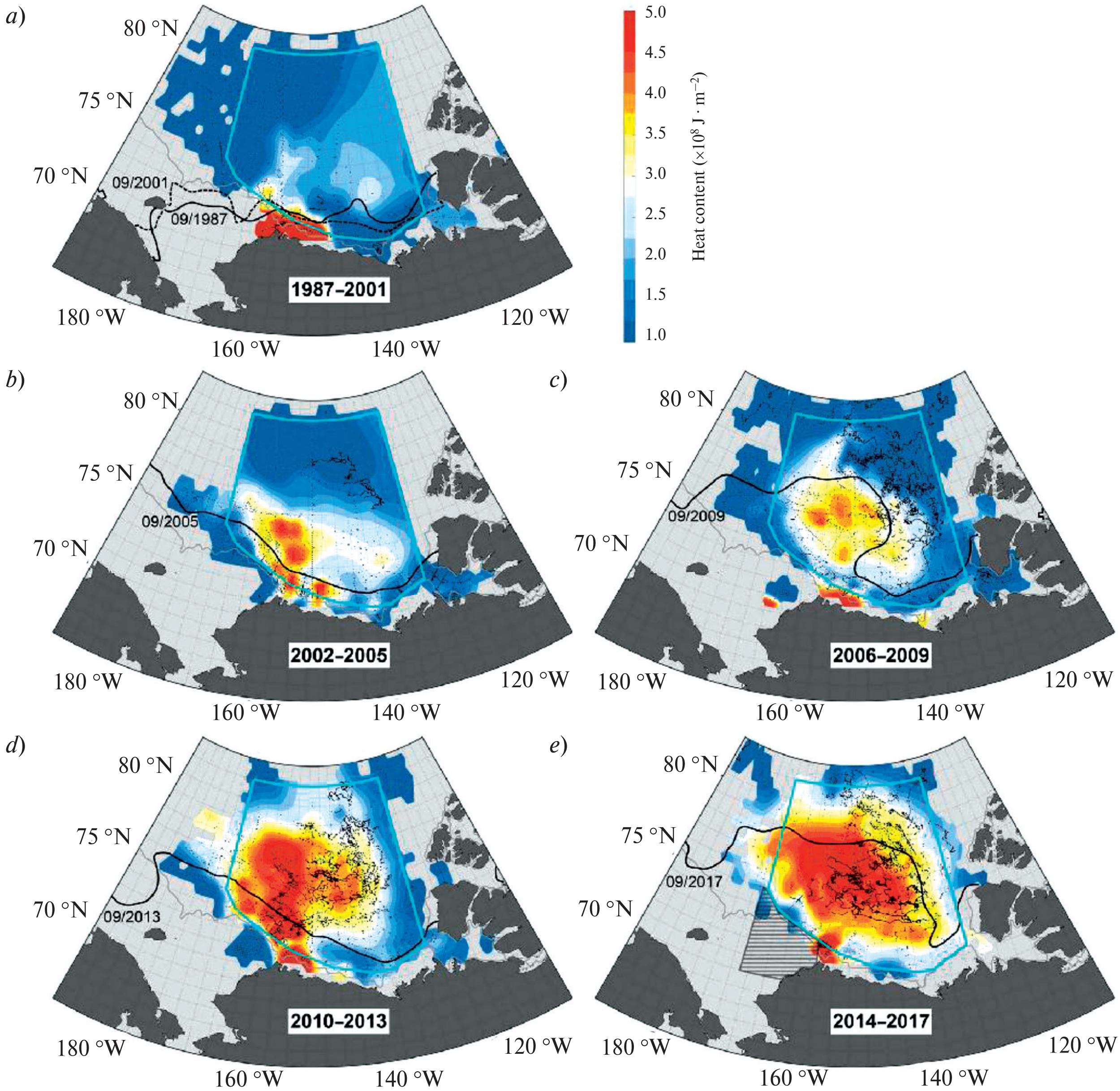

Fig. 4. Time variations of the spatial distribution of the heat content (J m^{-2}) in the upper Beaufort Gyre: (*a*) 1987–2001, (*b*) 2002–2005, (*c*) 2006–2009, (*d*) 2010–2013, and (*e*) 2014–2017. The heat content is referred to the seawater freezing temperature and integrated between the isohalines S = 31 and S = 33 over all seasons. The black dots indicate locations of the temperature profiles used. The cyan line delineates the Beaufort Gyre (BG) region. The hatched region in (*e*) is the northern Chukchi Sea region of the strongest water subduction. The grey contour marks the 100-m isobath, and black contours indicate the monthly-mean sea ice edge (15 % concentration) for September (from fig. 2 in [85])

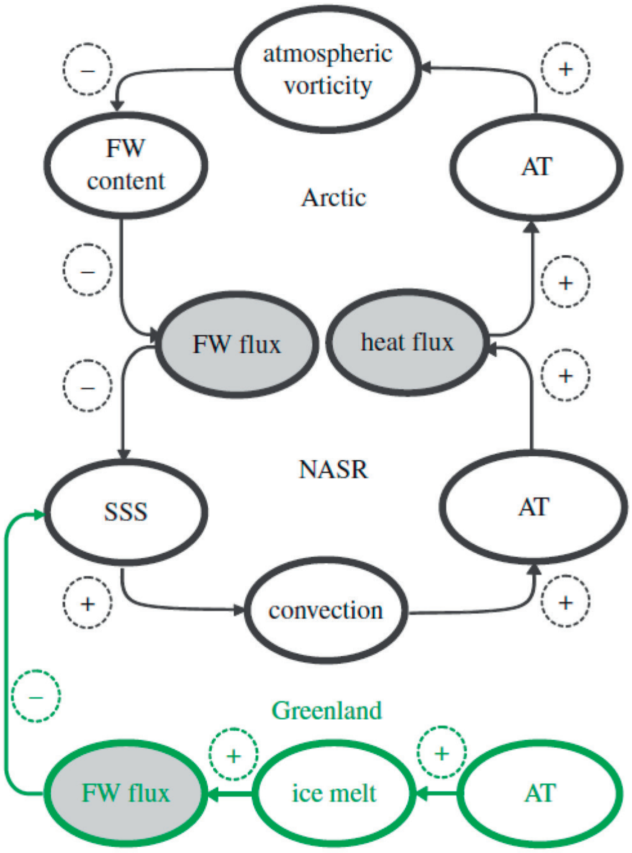

Fig. 5. A self-regulating decadal variability of the atmosphere–ice–ocean system in the Arctic — Nordic Seas (in the figure: North Atlantic Subpolar Region — NASR). A plus sign denotes mechanisms with positive feedbacks (i. e. an increase in the one cell causes an increase in the following one), a minus sign — negative feedbacks (i. e. an increase in the one cell causes a decrease in the following one). The idealized behaviour of the closed system under stable climate conditions is presented in black. An influence of the external forcing is shown in green. In this case, it is a freshwater flux from the Greenland Ice Cap. AT stands for air temperature, SSS — for sea surface salinity and FW — for freshwater (from fig. 6 in [107]).