Journal of
Marine Science and Engineering

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Influence of Sea Surface Temperature in the Tropics on the Antarctic Sea Ice during Global Warming

Genrikh Alekseev *, Anastasiia Vyazilova and Alexander Smirnov

Arctic and Antarctic Research Institute, 199397 St. Petersburg, Russia
* Correspondence: alexgv@aari.ru

Abstract: Sea ice extent in the Antarctica, unlike in the Arctic, did not show a decrease until 2016 under observed global warming. The aim of the study is to explain this climatic phenomenon based on the idea of joint dynamics of the Southern Ocean oceanic structures—the Antarctic polar front, the boundary of the maximum sea ice extent and atmospheric structures—Intratropical Convection Zone (ITCZ) and the Hadley circulation. ERA5 reanalysis and HadISST data were used as well as the sea ice database for the period 1979–2021. The effect of SST at low latitudes of the North Atlantic on the position of the Antarctic polar front and the maximum sea ice extent has been established. The SST in the same area of the North Atlantic has an opposite effect on the sea ice extent in the Arctic. The impact of the SST on the sea ice is mediated through the ITCZ and the Hadley circulation. The obtained results confirmed the key role of the SST at the low latitudes of the North Atlantic in the development of multidirectional trends in changes in the Arctic and the Antarctic ice cover in 1979–2016.

Keywords: climate change; sea ice; Antarctic; tropic SST; ITCZ; Hadley cell

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Citation: Alekseev, G.; Vyazilova, A.; Smirnov, A. Influence of Sea Surface Temperature in the Tropics on the Antarctic Sea Ice during Global Warming. *J. Mar. Sci. Eng.* **2022**, *10*, 1859. https://doi.org/10.3390/jmse10121859

Academic Editor: Michael H. Meylan

Received: 22 October 2022
Accepted: 23 November 2022
Published: 2 December 2022

1. Introduction

The Antarctic sea ice cover during the period of maximum growth is bounded in the north by the Antarctic Circumpolar Current and the Antarctic Polar Front (APF) and hence is influenced by the factors determining their position and intensity. The consistency between the maximum spreading of the Antarctic sea ice in September and the position of the frontal transition zone in the stratification of the upper 100 m layer is shown in [1]. The reason is the different stratification of the upper layer on both sides of the APF. To the south of it, the strongly stratified layer contributes to rapid cooling of water to the freezing point and ice formation. To the north, stratification in the upper layer is weak, resulting in deeper mixing that prevents rapid water cooling and ice formation.

It was shown earlier based on the analysis of the climatic position of the main oceanic and atmospheric circulation structures of the South Polar Area [2] that deviations from zonal symmetry in the spatial position of the Antarctic Circumpolar Current, the Antarctic Polar Front and the atmospheric pressure and temperature fields are close to each other and correspond to a shift of their center from the South Pole to the Antarctic Inaccessibility Pole.

The observational data, in addition to the general increase in the Antarctic sea ice extent in 1979–2014, show significant seasonal [3] and regional [4] differences in the magnitude and sign of the trends. The annual cycle and trends of the Antarctic sea ice extent from model experiments for 1850–2005 on 18 global models from CMIP5 differ significantly from those observed in the last 30 years [5]. Most models reproduce too small sea ice extent in February, and some of them show less than 2/3 of the observed September maximum. In contrast to satellite observation data, which indicate an increase in the ice cover extent, the average model value decreases every month in 1979–2005, which indicates, in the opinion of the authors of this article, that there are no processes in the models responsible for the growth of the ice cover extent in the last 30 years.

In both modeling and empirical studies, the causes influencing the sea ice spreading in the Antarctic are related to either atmospheric [6–10] or oceanic [11–15] influences. The influence of the positive phase of the Atlantic multidecadal oscillation on the sea ice redistribution between the Ross Sea and the Amundsen, Bellingshausen and Weddell Seas has been found in the assumption that the northern tropical Atlantic is important for projections of future climate changes in the Antarctic and can influence the global thermohaline circulation and ocean level changes [13].

A review of the publications shows the absence of a generally accepted explanation for the stability of the Antarctic sea ice cover during the current global warming and the inability of global climate models to reproduce this climatic phenomenon. The search for the causes of the observed changes in the sea ice cover is conducted either in the ocean or in the features of atmospheric circulation in the Southern Hemisphere. Our approach includes a joint analysis of oceanic and atmospheric data within the framework of the idea of interaction of oceanic and atmospheric modes and processes in the Southern Hemisphere climate system and in low latitudes of the Northern Hemisphere.

2. Materials and Methods

Data from the ERA5 [16] and HadISST [17] reanalysis and the sea ice database (http://www.aari.ru/datasets, access on 2 September 2022) were used in this work. The position of the Antarctic Polar front in September 1979–2021 was determined by using the mean monthly sea surface water temperature data of the ERA5 reanalysis and calculating the maximum meridional SST gradient at each longitude through 0.25° in the band 50–70° S, SST values with a step of 0.25° latitude. Fourier analysis was performed to estimate circular modes and asymmetry of the Antarctic polar front and ice edge position. Calculations of multidimensional mutual-correlation functions of the characteristics of the Antarctic polar front and SST in the low latitudes of the World Ocean were fulfilled to highlight the areas where water temperature affects the APF position, the sea ice edge and ice area. We calculated the assessments of the relations between the SST series and the characteristics of the APF position, ice edge and ice area, taking into account the lag between them.

The position of the temperature maximum of the monthly mean temperature in the tropics from 20° S to 20° N based on ERA5 reanalysis data from 1979 to 2021 was determined. The temperature maximum T_{max} was found at each meridian within this zone for each month "m" of each year "g", its latitude "F" at a given meridian "l" was recorded and then both values were averaged over the latitude "l":

$$Tmg = \langle Tmgl \rangle_l, Fmg = \langle Fmgl \rangle_l.$$

3. Results and Discussions

Figure 1 shows the APF position corresponding to the maximum (September 2014) and minimum (September 2017) sea ice extent (Figure 1a) and the mean multiyear position and maximum deviations from it (Figure 1b). The decomposition of the APF latitude into a Fourier series confirms the main contribution of the first circular mode, which center is located near the pole of relative inaccessibility on the Antarctic continent (Figure 1c). The coordinates of the APF circular mode center are shifted from the South Pole to the Pole of Relative Inaccessibility in accordance with the conclusion [2] about the influence of the Antarctic continent on the position of climatic zones in the Southern Hemisphere. The circular mode accounts for 69% in September and 70% in October of the variability of the APF position in these months between 1979–2017.

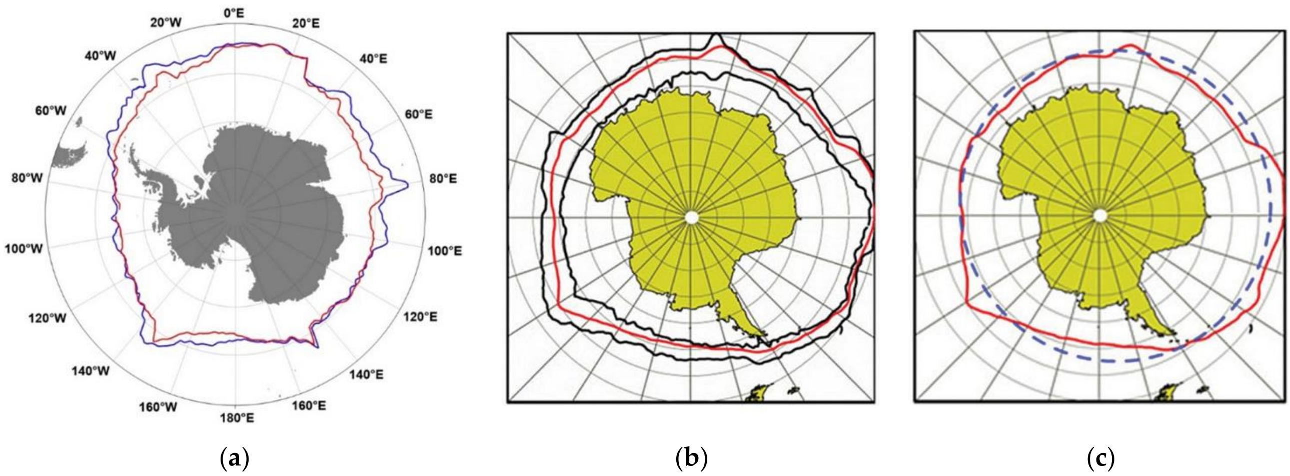

Figure 1. The position of the Antarctic Polar Front determined from the mean monthly sea surface temperature in September. (**a**) In 2014 (blue) and 2017 (red); (**b**) average position of the APF (red) and the maximum deviations from the average in 1979–2014; (**c**) average position and circular mode (dashed line) of the APF average position. Mode center coordinates—86.7° S, 30° E.

The mean APF latitude and maximum ice extent in September change with a correlation coefficient of −0.59 over 1979–2021 (Figure 2a). This means an increase in the ice extent with the shift of the APF to the north (the latitude of the APF decreases). Smoothing of the series by moving averaging over three years enhances the agreement between them (correlation coefficient −0.68, Figure 2b). The corresponding coefficients for 1979–2016 are −0.70 and −0.79. The distribution of ice in winter is also influenced by air temperature. The dependence between the sum of frost degree days and the maximum ice extent is maximal in August (correlation coefficient–0.51).

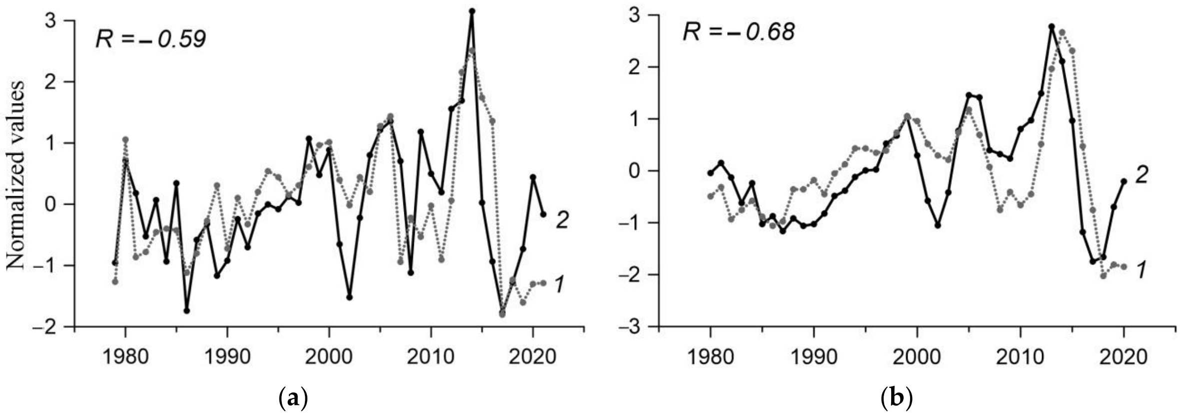

Figure 2. Normalized values of the mean latitude anomalies of the Antarctic Polar Front (1), used with the opposite sign, and the maximum sea ice extent (2) in September 1979–2021, (**a**) original data; (**b**) series smoothed by moving averaging over three years.

The changes in the position of APF and the ice extent indicate a gradual shift of the APF northward with a maximum in 2014 and an increase in ice extent from the beginning of observations until 2015. The APF shifted southward after 2015 and the ice extent decreased with the minimum in 2017. This year also marked by the absolute minimum of the sum of frost degree days at the water area usually occupied by winter sea ice. The changes in 2016–2017 were obviously caused by the powerful El Niño in 2015. Previous changes, characterized by a gradual increase in the Antarctic sea ice extent, accelerated after 1997, are opposite to the decrease in Arctic sea ice and therefore have attracted special attention.

Previously, we found a connection between the decrease of Arctic ice and warming in the low latitudes of the North Atlantic (5–25° N and 60–10° W) [18], which led to search for a similar connection for the Antarctic ice. The ocean surface temperature anomalies in this area of the North Atlantic were compared with the anomalies of the APF position and the maximum Antarctic ice extent in September. The greatest correspondence between them was found when the APF and ice extent anomalies lagged relative to the SST anomaly for two years. The correlation coefficients between the ocean surface temperature anomalies in October and the latitude of Antarctic Polar Front were −0.69 and −0.76 after smoothing for the period 1979–2015 (Figure 3). This means a shift of the APF to the north (the latitude of the APF decreases) with an increase in SST.

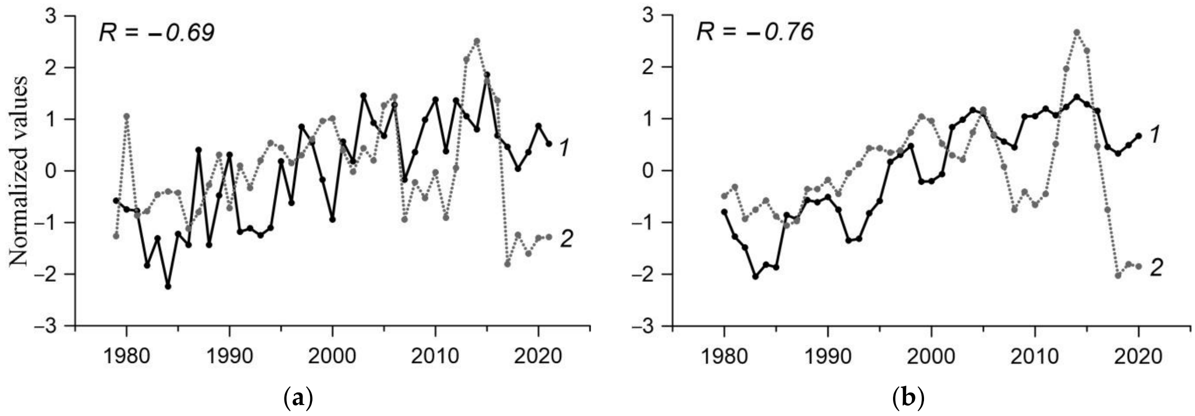

Figure 3. Normalized sea surface temperature anomalies in the region of 5–25° N, 60–10° W in October in 1979–2021 (1) and the latitude of the Antarctic Polar Front (2) with the opposite sign. (**a**) original data; (**b**) series smoothed by moving averaging over three years; R is the correlation coefficient between (1) and (2) for 1979–2015.

The results showed that the SST anomalies in the tropical region of the North Atlantic cause the opposite trends of the ice extent in the Arctic and in the Antarctic. The mechanism of such influence of the SST anomalies includes presumably displacement of the global climatic structures as the Intertropical Convection Zone (ITCZ) in the atmosphere and the surface air temperature (SAT) maximum (T_{max}), which position is supposed to reflect the ITCZ position, followed by the Antarctic Polar Front and the edge of maximum ice distribution in the Southern Ocean. The SAT maximum is located to the north of the equator in summer and moves closer to the equator in winter, dipping south of the equator at some longitudes. These seasonal displacements are a consequence of the tilt of the Earth's axis rotation to the ecliptic plane. Are these movements only seasonal, or do they also experience long-term changes? To answer this question, we determined the position of the temperature maximum of the average monthly SAT in 20° S up to the 20° N zone for 1979 to 2021 from reanalysis ERA5.

The maximum temperature increases in all months most of all in September–October, and the average latitude of T_{max} slightly shifts towards the equator in winter (summer in the Southern Hemisphere) and in July–October (Table 1).

Table 1. Trends of maximal surface air temperature (T_{max}, °C/year) and mean latitude of T_{max} (Lat, grad/year). In lower line—mean latitude T_{max}. All values for 1979–2021. Bold numbers are 90% significant values.

Month	1	2	3	4	5	6	7	8	9	10	11	12
T_{max}	**0.016**	**0.017**	**0.019**	**0.017**	**0.017**	**0.018**	**0.019**	**0.019**	**0.021**	**0.02**	**0.019**	**0.018**
Lat	0.016	0.006	0.004	0.012	**0.03**	**0.011**	**−0.024**	**−0.017**	−0.014	−0.013	0.01	**0.03**
Mean Lat, ° N	−2.84	−2.3	−0.69	2.59	7.15	10.29	11.38	11.76	10.47	7.01	2.72	−1.09

The shift of T_{max} towards the equator in winter of the Southern Hemisphere is accompanied by a shift in the APF (Figure 4a) and an increase of the maximum Antarctic sea ice extent (Figure 4b). The correlation coefficient for 1979–2016 between the T_{max} latitudes and APF is 0.58 and between the T_{max} latitude and the maximum Antarctic sea ice area in September is −0.60, with APF and sea ice extent lagged by 2 years. The correlation coefficient between series smoothed by averaging over three years is −0.70 for both series. A positive correlation reflects the shift of T_{max} and APF to the equator, and a negative correlation between the latitude of T_{max} and the Antarctic sea ice extent corresponds to an increase in the Antarctic sea ice extent with a decrease in the latitude of T_{max}.

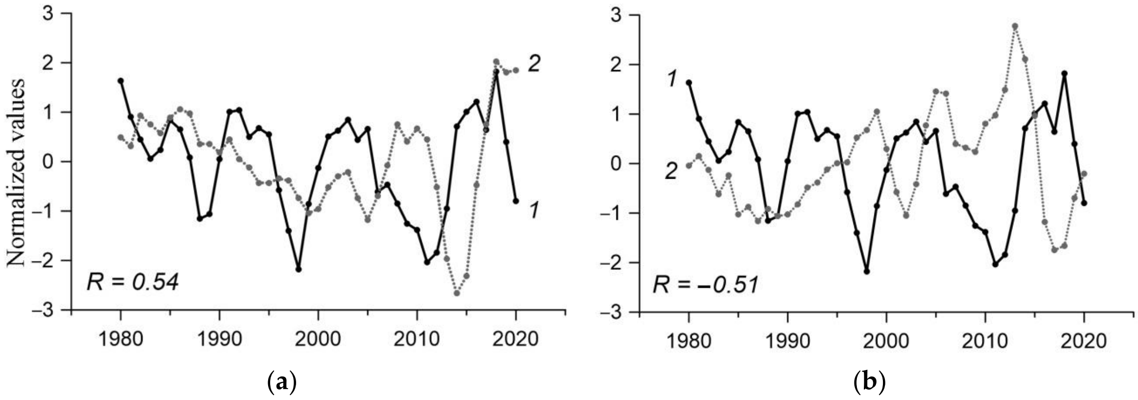

Figure 4. (**a**) Normalized anomalies of T_{max} mean latitude (1) and mean latitude of the Antarctic Polar Front (2) in September for 1979–2021, smoothed by moving averaging over three years. (**b**) The same for the maximum Antarctic sea ice extent in September (2). R is the correlation coefficient between (1) and (2). Changes in T_{max} latitudes are ahead of the APF latitudes changes by 2 years.

The shift of T_{max} towards the equator and the sea ice in the Arctic show a positive, but less close correlation (Figure 5a). At the same time, a strong correlation exists between the tropical SST and the Arctic sea ice (Figure 5b). This fact points to a different mechanism of the low latitudes influence on the Arctic sea ice. This mechanism includes the interaction of oceanic and atmospheric (NAO) circulation in the North Atlantic, which develops under the influence of SST anomalies in the tropics [18–20].

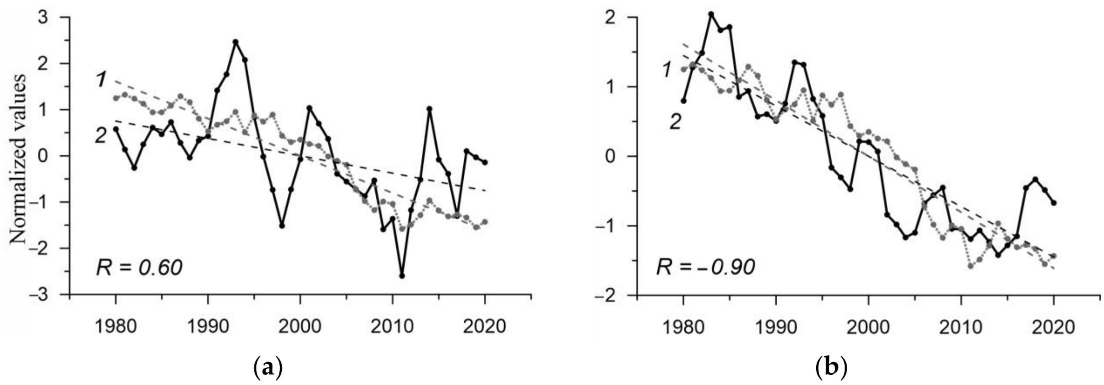

Figure 5. (**a**) Normalized anomalies of T_{max} mean latitude in August (1) and the Arctic sea ice extent in September (2) 1979–2021; (**b**) SST in the region of 5–25° N, 60–10° W in October (1) and the Arctic sea ice extent in September (2) for 1979–2021, smoothed by moving averaging over three years. R is the correlation coefficient between smoothed (1) and (2). Changes of T_{max} latitudes are ahead of the ice extent changes by 2 years, changes in SST are ahead of the ice extent changes by 3 years. Sign of the SST values is reversed.

The shift of T_{max} towards the equator corresponds to the opposite trends in the evolution of the ice cover in the Antarctic and the Arctic. However, it is unclear whether such ITCZ shifts occur. The structure and dynamics of ITCZ has been studied in many works, for example [21–23]. Nguyen et al., 2013, in particular, noted that the ITCZ intensity is maximal in the winter hemisphere. The correspondence between T_{max} (Figure 6) and ITCZ [24–26] can be confirmed by maps of their average position in January and July.

Figure 6. The average position of T_{max} in January and July according to the ERA5 reanalysis (1 × 1°) for the period 1979–2021, smoothed by moving averaging over 31 window.

It follows from Figure 6 that the position of the ITCZ is different by the opinion of different authors and the position of T_{max} approximately corresponds to the position of the ITCZ. Therefore, it can be assumed that the increase in T_{max} and the shift towards the equator in the Antarctic in winter–spring are accompanied by the intensification of ITCZ and SE trade winds. This leads to an increase in the transport of warm waters from the Southern Hemisphere, a shift of the APF towards the equator and an increase in the maximum area of Antarctic sea ice.

4. Conclusions

The mean position and the largest deviations from the mean position of the Antarctic Polar Front (APF) corresponding to the maximum sea ice extent in September 1979–2017 were found. The circular mode of the APF accounts for 69% of the interannual variability in the average latitude of the APF in this month. The center of the circular APF mode is shifted from the South Pole towards the Pole of Relative Inaccessibility, which confirms the influence of the Antarctic continent on the formation of the position of climatic zones in the Southern Hemisphere. The Antarctic Polar Front limits the possible expansion of sea ice to the north. As a result, the average latitude of the APF and the maximum sea ice cover in September changed consistently with a correlation coefficient of –0.70 throughout 1979–2016.

The APF gradually shifted to the north and at the same time, the maximum ice extent increased from the beginning of observations in 1979 to 2015. After that, there was a shift of the APF to the south and a decrease in the ice extent, with a minimum in 2017 as a result of the powerful El Niño in 2015.

A close relationship has been established between SST in the area of 5–25° N, 60–10° W of the North Atlantic, the position of the APF and the maximum extent of Antarctic sea ice in September, with APF and ice extent lagged by two years. The correlation coefficients between them are −0.74 and 0.57, respectively. After smoothing the series with a window of three years, the coefficients increase and, respectively, become equal to –0.86 and 0.74.

The increase in SST is a manifestation of the general increase in temperature in the tropical zone. Another consequence of warming in the tropics is an increase in the maximum surface air temperature (SAT) and a shift in the position of the temperature maximum. A negative relationship has been found between changes in the mean latitude of the SAT maximum and the maximum extent of Antarctic sea ice in all months of the year. The closest relationship occurs in September, with a two-year lag in ice extent change. The increase in T_{max} and the shift towards the equator in the Antarctic in winter–spring are accompanied by the intensification of ITCZ and SE trade winds. This leads to an increase in the transport of warm waters from the Southern Hemisphere, a shift of the APF towards the equator and an increase in the maximum area of the Antarctic sea ice.

The reduction of the Arctic sea ice extent occurs with an increase of SST in the tropical Atlantic with the participation of another mechanism. This mechanism includes the interaction of oceanic and atmospheric (NAO) circulation in the North Atlantic, which develops under the influence of SST anomalies in the tropics proposed in [18–20]. The increase in SAT and SST in the tropics can occur with the participation of an increase of insolation at low latitudes [27].

Author Contributions: Conceptualization, G.A.; methodology, G.A.; software, A.V. and A.S.; validation, A.V. and A.S.; formal analysis, G.A.; investigation, G.A.; resources, A.V. and A.S.; data curation, A.V. and A.S.; writing—original draft preparation, G.A.; writing—review and editing, G.A.; visualization, A.V.; supervision, G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to Yaromir Angudovich, Nicolai Ivanov and Natalia Kharlanenkova for help in data processing and preparation of figures and to creators of ERA5 and HadISST reanalysis.

Conflicts of Interest: The authors declare no conflict of interest.

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