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Role of the Oceans in the Climate Fluctuations of the Arctic Region during the Holocene

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Abstract—The temperature of the ocean waters and the heat content of the active layer of the ocean, sea currents and ice, salinity, and the characteristics of the water column are climatically important parameters of the World Ocean, between which there is a relationship. The ocean is in constant interaction with the atmosphere and the Earth's crust, which is manifested by the exchange of heat, moisture, and momentum. In turn, the atmosphere also influences the ocean, through the circulation of waters. Changes in the state of the continental ice and fluctuations in ocean levels lead to the key consequences of climate change in most regions of the world. The main global causes of the impact on climate should be noted: changes in the period of the Sun's revolution, solar activity, including solar radiation, volcanic emissions, and the greenhouse effect of the planet. This article considers the roles of the three oceans (Arctic, Atlantic, and Pacific) connected with the Arctic region and the role of ocean currents in the process of interlatitudinal heat transfer. The results of the analysis of both long-term and short-term ocean surface temperature variability covering different time intervals from the end of the last glacial period to the present and the connection of these changes with the causes generating them are presented. It is concluded that there is significant natural climate variability in the Arctic region over the studied time interval.

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1. INTRODUCTION. THE OCEAN-ATMOSPHERE INTERACTION

The complex climate system requires an interconnected study of global changes occurring in natural systems: ocean, atmosphere, biosphere, cryosphere, soil, etc. Oceans cover almost three quarters of the Earth's surface, are a huge accumulator of solar heat and moisture, and are the main regulator of the climate, which smooths sharp temperature fluctuations and moisturizes dry areas. Oceans play a fundamental role in shaping climate zones. Elucidating the role of oceans in long-term climate fluctuations has been of intense interest since the beginning of human interference with nature. Oceans are in constant interaction with the atmosphere and the Earth's crust. The interaction between the ocean and the atmosphere associated with the exchange and redistribution of heat, water, gases, particles, and momentum is of particular importance for climate formation and change. Ocean surface temperature, salinity, water column characteristics, heat content of the active ocean layer, sea currents, and ice are climatically relevant parameters for studying the World Ocean.

Three oceans are connected to the Arctic region: the Arctic, Atlantic, and Pacific. These three oceans surround the territory of Russia. The Arctic Ocean is the smallest ocean by area and depth on Earth. Its main feature is permanent ice cover. The border with the Arctic Ocean is the longest and this ocean affects not only the northern coastal regions but also reaches the southern regions. The Atlantic Ocean influences the transport of air masses in middle latitudes and has a significant impact on Russia's climate. The Pacific Ocean has an impact only on the territory of the Far East.

Ocean currents play an important role in the interlatitudinal heat transport. Of particular interest to researchers is the belt of the World Ocean between 30° N and 30° S, which absorbs a huge amount of solar radiation and accumulates heat that is transported to higher latitudes, thus changing the climate of middle and polar latitudes. The ocean currents, spreading in a wide band and including layers of water from different depths, have a significant influence on the climate. The direction of currents is greatly affected by the force of the Earth's rotation, which causes water currents to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. In general, sea (ocean) currents influence air temperature and its distribution. Glaciers, which change significantly during climatic warming and cooling, are one of the most sensitive indicators of climate change.

As a consequence of climate change during the last glacial-interglacial period, the ocean level fluctuated within ~130 m. The ocean level decreased during the glacial epochs. It should be noted that during the previous interglacial epoch (120000–125000 years ago), the ocean level was ~10 m higher than today (Kotlyakov, 2010). Many climate fluctuations (up to tens to hundreds of years) can be the result of the interaction between the atmosphere and the World Ocean. Thus, the Southern Oscillation (El Niño), as well as the North Atlantic and Arctic Oscillations, apparently occur due to the ability of the World Ocean to accumulate thermal energy and move it to different parts of the ocean. On a longer timescale, a thermohaline circulation occurs due to the heterogeneous distribution of temperature and salinity in the ocean. The thermohaline circulation is a large-scale system of currents in the ocean caused by the inhomogeneity of the horizontal distribution of water density in the World Ocean, which in turn is related to the distribution of water temperature and salinity (e.g., (Dianskii and Bagatinskii, 2019)). The global thermohaline circulation occupies a special place in the astronomical factors–ocean–atmosphere–land–ice sheets climate system, because it controls not only the heat and salt transport in the ocean but also the heat exchange with the atmosphere, i.e., the heat and precipitation inflow to the land. The ocean and the atmosphere are interconnected systems and climate change affects them both.

Among the main external causes of climate change, the following are critically discussed: changes in the Sun's orbit, solar activity and solar constant, etc. Of particular interest are climate fluctuations on both short- and long-term scales associated with variability in solar radiation (caused by changes in the position of the Earth's orbit over time, e.g., (Fedorov et al., 2020)). In terms of their influence on the climate, these changes are similar to variations in solar activity.

The warm interglacial period (Holocene), in which mankind lives, is at the stage of completion, which should be followed by the beginning of a new ice age. The Earth's climate has entered an unstable phase characterized by short periods of warming and cooling, as well as by the prevalence of cyclonic activity with typhoons and floods.

The effects of anthropogenic greenhouse gas emissions, which some researchers consider as one of the main causes of the observed climate variability over the last century due to changes in ocean temperature and melting ice, should be most pronounced in the polar region. Wind and current systems in the ocean form a strong relationship. The ocean warmed significantly in this time interval. The marine heat waves associated with these climate fluctuations are causing major changes in the structure and functions of marine ecosystems and are affecting their most important base species: corals and seagrasses (Hughes et al., 2018). If heat waves in the oceans continue to occur in the future there could be increased poleward expansion of corals and seagrasses and dramatic changes in ocean surface temperatures.

Paleoclimatic records show that climate change in the Arctic can be very significant and occur very rapidly. Praetorius et al. (2018) traced the relationship between abrupt temperature changes in the Arctic and sea surface temperature changes in the North Atlantic and in the North Pacific. In doing so, in (Praetorius et al., 2018) it was shown that changes in the heat flux in the North Pacific can have a greater impact on the Arctic climate than previously thought. Unfortunately, many features of the interconnected processes in the Arctic climate remain understudied, which makes it difficult to create a reliable model of future climate change. The focus will be on analyzing data based on the most accurate description of short-term changes in the Earth's orbit using (1) a table of celestial coordinates of the Sun, Moon, planets, and other astronomical objects calculated at regular intervals (ephemeris) and (2) errors in the insolation calculations.

2. CHANGES OF CLIMATIC PARAMETERS AFTER THE RETREAT OF THE LAST GLACIATION AND THE SOLAR IMPACT

Let us investigate the regularities of changes in the main climatic characteristics over this time interval. We consider fluctuations in global mean sea level during the last glacial-interglacial period, whose level is defined as the mean value of the relative sea level area or sea surface height above the World Ocean. In order to obtain a chronology of past changes in the relative sea level, the sought sea level proxy indicators should be dated. Radiocarbon dating is used to obtain chronologies from decades in the last ~50000 years. For the Holocene, reconstructions of relative sea level are more abundant and better resolved than for previous interglacial periods. Global temperature reconstructions for the Early and Middle Holocene (from 9500 to 5500 years ago) obtained from both marine and terrestrial sources suggest that global mean surface temperatures were 0.8°C higher than preindustrial temperatures (Marcott et al., 2013). However, this estimate contradicts climate models that show a warming trend during the Holocene.

Global mean sea level (GMSL) is defined as the area mean of either relative sea level or sea surface elevation above the World Ocean. Horton et al. (2018) reviewed the mechanisms that govern spatial sea-level variability at different time scales, as well as the sources and statistical methods applied to the indirect and instrumental data. Figure 1a shows GMSL reconstructions for the Holocene, curves (*1–4*) obtained by

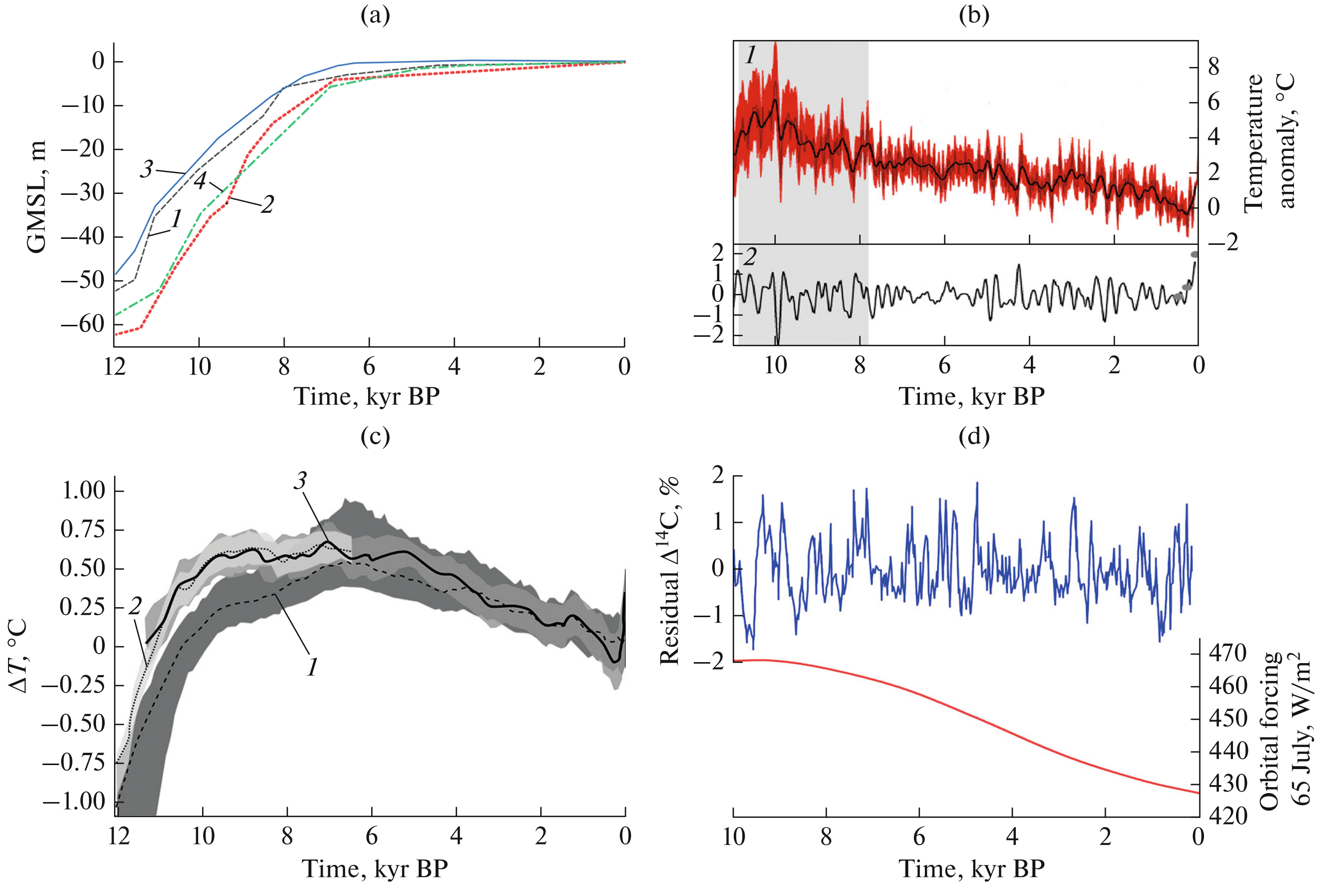

Fig. 1. Comparison of climate data with climate-influencing parameters on a timescale over the past 12000 years: (a) Reconstructions of the global mean sea level (GMSL) for the Holocene; the curves obtained by different authors: (*1*) (Peltier, 2004); (*2*) (Lambeck et al., 2014); (*3*) (Peltier et al., 2015), and (*4*) (Bradley et al., 2016). (b) Comparison of the multimode reconstruction of the mean global surface temperature (Kaufman et al., 2020) (*1*) (dashed curve) with previous (*2*) (Shakun et al., 2012) and (*3*) (Marcott et al., 2013) reconstructions over the last 12000-year interval. The uncertainty limits (standard deviation) of the multimode ensemble temperatures (shaded region) are bounded by thin lines. (c) Reconstructions of the annual Arctic temperature change rate from the Greenland Agassiz ice cap (Lecavalier et al., 2017). (d) Reconstructions of parameters reflecting solar influence on climate change: changes in ^{14}C concentration in samples of known age (Stuiver et. al., 1998)) and changes in insolation (Berger, 1978) over the past 12 000 years.

different authors: (*1.* (Peltier, 2004); *2.* (Lambeck et al., 2014); *3.* (Peltier et al., 2015), and *4.* (Bradley et al., 2016)). Given the high resolution of the data for the Holocene, sea level reconstructions from this period are important for assessing the rate of sea level change.

An extensive database of paleotemperature records from 470 terrestrial and 209 marine sites is now available for researchers to determine past temperature changes during the Holocene (Kaufman et al., 2020). This new multiparameter paleotemperature time-series database covers the past 12000 years and includes five different statistical methods for temperature reconstruction, which makes it possible to carry out a more robust analysis of the global mean temperature and associated uncertainties than previously available (Fig. 1b). Figure 1b shows median ensembles for global mean temperature reconstructions 1. (Kaufman et al., 2020) and a comparison with previous reconstructions 2. (Shakun et al., 2012) and 3. (Marcott et al., 2013). The main differences between the methods lie in the differences in approaches to averaging globally distributed time series data and to characterizing different sources of uncertainty associated with chronology and proxy temperatures. As Figure 1b shows, on average, the warmest interval in the Holocene was ~6500 years ago, when it was warmer by about 0.6–0.7°C than in the 19th century. Peak warming is followed by a cooling trend.

We consider the rate of temperature change (°C per century) by reconstructing the annual Arctic temperature from the Greenland Agassiz ice cap over the past 12000 years using high-resolution ^{18}O concentration data (Lecavalier et al., 2017) (Fig. 1c). The temperature reconstruction of the Agassiz ice cap provides the northernmost paleoclimatic record (~80° N) for the entire Holocene (Fig. 1c*1*). Over the time interval under consideration, temperature rate changes from fractions of a degree to ~2°C and periods of change of 600–400 years, 400–200 years, and 200 years, which are characteristic of long-term changes in solar activity, can be distinguished.

The annual Arctic temperature from the ice core of the Agassiz ice cap (Greenland) for the last 12000 years was reconstructed from high-resolution ^{18}O concentration data with a low pass filter (Fig. 1c*1*) (Lecavalier et al., 2017), which provides the northernmost paleoclimatic record (~80° N) for the entire Holocene. The rate of temperature change (°C/century) during the Holocene was calculated using a Gaussian filtered temperature reconstruction and linear regression (Fig. 1c*2*). Over the time interval, we can distinguish temperature rate changes from fractions of a degree to ~2°C and change periods of ~600–400 years, ~400–200 years, and ~200 years (Fig. 1c*2*), characteristic of long-term changes in solar activity. We note that the analysis of the 10000-year record of sediments from two Finnish lakes suggests climate and environmental fluctuations on scales from decades to millennia (Ojala et al., 2015), which the authors attribute to solar influence and North Atlantic oscillations. Statistically significant periodicities of 1500–1800, 1000, 600–800, nearly 300, about 200, 150–170, nearly 90, and 47 years were found, which show variable agreement with various climatic influencing factors and other paleoproxy records in the Northern Hemisphere. Among the obtained periodicities, some can be related to solar activity. Thus, observations of the Sun that began as early as the 17th century allow us to trace 40–45-, 88-, 140-, and 207-, and 2272-year variability (e.g., (Dergachev, 1994)).

Let us consider whether the recorded rates of temperature change in the Arctic can be related to changes in the solar influence (sunspots and solar radiation) over time. Figure 1d shows ^{14}C concentrations in samples of known age (Stuiver et al., 1998), which reflect changes over time in solar activity and changes in solar irradiance (insolation) (Berger, 1978) due to orbital influence on climate over the time interval under consideration. The insolation changes themselves are relatively small, but the climate response can be quite large due to its nonlinearity.

In general, there is a correlation between the data on the solar influence on climate, including the distinguished periods both in the solar influence and in the temperature changes.

3. THE NATURE OF CHANGES IN CLIMATIC PARAMETERS IN THE LAST 2000 YEARS

Let us analyze the patterns of change in ocean level, surface ocean temperature and global atmospheric temperature, and data on the solar influence on the climate in the epoch most covered by detailed studies of climate change.

In order to draw correct conclusions from the proxy data, it is important to rely on an accurate chronological pattern of the processes under study. Kotlyakov (2012) found a reliable indication of the temperature decrease since ~6500 years ago using radiocarbon and calendar dating of proxy temperature data (Fig. 2a). Detailed calculations that take many factors into account, including astronomical ones, suggest that the global temperature on Earth is in fact decreasing, although the decrease is small.

It is also important to note that the Holocene climatic optimum observed 5500 years ago turned out to be 1.5°C lower than the maximum temperature of the previous interglacial period, when there was no anthropogenic impact on the Earth's climate. This peak has already been passed; during the last 5000–6000 years, in general the temperature continues to decrease, and the modern epoch is on the downward section of the curve (e.g., (Dergachev, 2019)).

The study of ancient sea levels provides insight into the mechanisms and rates of sea level changes due to tectonic processes and climatic changes (e.g., insolation due to changes in the Earth's orbit).

Figure 2b presents the orbital effects (changes in insolation, orbital inclination, and precession) on climate in the Northern Hemisphere during the Holocene (Berger and Loutre, 1991).

Solar activity in the past was recorded in cosmogenic isotope data. Cycles of different durations of solar activity can be traced in atmospheric radiocarbon data after removal of the long-term trend (Fig. 2c) (Stuiver and Braziunas, 1993).

A time series of changes in the GMSL from 2000 BC to 2020 AD is shown in Fig. 2d (Miller et al., 2020). The darker and lighter shaded lines indicate error limits of 1σ and 2σ, respectively, in the statistical estimates.

Reconstructed (measured) temperature anomalies relative to 1961–1990 are shown in Fig. 2e (PAGES 2k Consortium, 2019). The lines represent 30-year ensemble medians with a low-pass filter for individual reconstruction methods. The gray area represents the area covering the reconstruction results from all seven methods. The black curve represents instrumental data for 1850–2017.

Reconstructions of Arctic surface temperature from direct measurements, as well as historical and proxy data for the last 2000 years are shown in Fig. 2f (1. (Kaufman et al., 2009); 2. (PAGES 2k Consortium, 2013)). One can see the difference in the temperature scales by a factor of 2.

Figure 2g shows global atmospheric surface temperatures (Lüdecke and Weiss, 2017); Fig. 2h presents global sea surface temperature averaged over 200-year

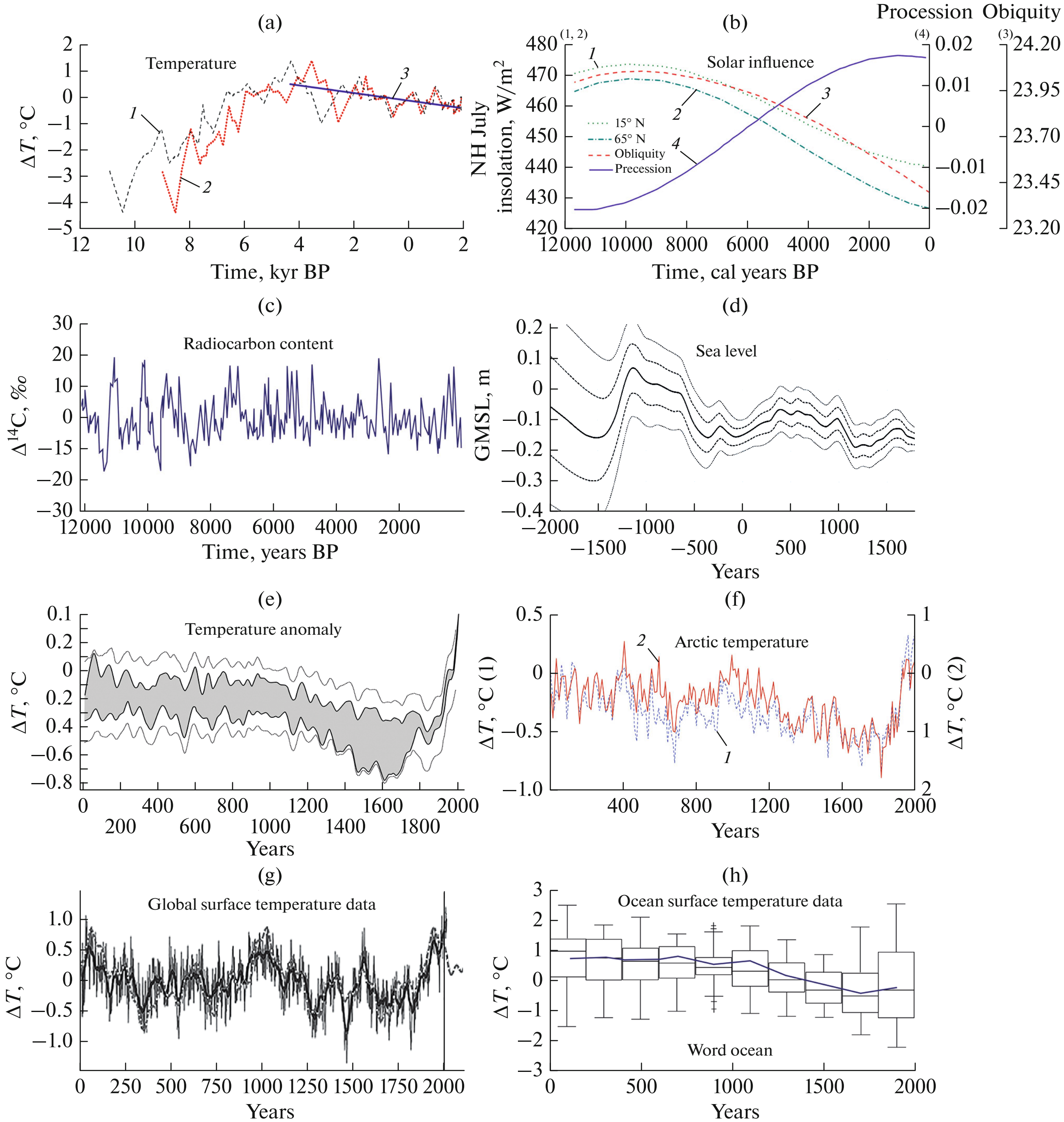

Fig. 2. Changes in climatic characteristics and solar influence on climate over the Holocene interval and in the last 2000 years: (a) Trend (straight line) in the changes in the annual mean temperature after the Holocene climatic optimum that occurred ~6500 years ago (Kotlyakov, 2012). Curves (*1*) and (*2*) show the calendar and radiocarbon dates of the studied samples. (b) Orbital effects on climate in the Northern Hemisphere during the Holocene (insolation in July at 15° N (1) and 65° N (2); precessions (3); and orbital inclination (4)) (Berger and Loutre, 1991). (c) Variations in atmospheric radiocarbon content after removal of the long-term trend (Stuiver and Braziunas, 1993). (d) Global mean sea level (GMSL) from 2000 BC to 2020 AD (Miller et al., 2020). (e) Global temperature change over the past 2000 years (PAGES 2k Consortium, 2019). (f) Comparison of Arctic surface temperature reconstructions for the last 2000 years using direct measurements as well as historical and proxy data ((*1*) (Kaufman et al. 2009), (*2*) (PAGES 2k Consortium, 2013)). (g) Global surface temperature over the past 2000 years (Lüdecke and Weiss, 2017). (h) Global sea surface temperature by 200-year intervals (rectangles) through which the trend passes (thick line) (McGregor et al., 2015).

intervals (McGregor et al., 2015). The World Ocean temperature reconstruction indicates a cooling trend over the last millennium, excluding recent decades.

4. CONCLUSIONS

The study of global climate change is a major scientific and practical challenge. The oceans are the Earth's life support system; they regulate the global climate, determine temperature, and control weather by determining precipitation, drought and floods, as well as responding to solar influence. In order to understand the role of natural climate variability and possible anthropogenic contributions to climate change, this article analyzed the results of studies of patterns of short-term changes in solar exposure due to orbital modulation on various timescales from decades to 13000 years in the past. It should be noted that insufficient attention has been given to this question in climate modeling so far. On the time interval of the last 12 000 years, it is possible to distinguish changes in temperature rate in the Arctic from fractions of a degree to ~2°C and periods of change: 600–400 years, 400–200 years, 200 years, and shorter. These results can be taken into account when analyzing climate changes, as well as modeling and forecasting its changes in the future.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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