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Calculation of Long-Term Averages of Surface Air Temperature Based on Insolation Data

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Abstract—The solar radiation coming to the Earth's ellipsoid is considered without taking into account the atmosphere on the basis of the astronomical ephemerides for the time interval from 3000 BC to 3000 AD. Using the regression equations between the Earth's insolation and near-surface air temperature, the insolation annual and semiannual climatic norms of near-surface air temperature for the Earth as a whole and the hemispheres are calculated in intervals of 30 years for the period from 2930 BC to 2930 AD with 100 and 900- to 1000-year time steps. The analysis shows that the annual insolation rates of the near-surface air temperature of the Earth and the hemispheres decrease at all intervals. The semiannual insolation rates of the near-surface air temperature increase in winter and decrease in summer. This means that the seasonal difference decreases. The annual and semiannual rates of insolation near-surface air temperature of the Earth increase in the equatorial and decrease in the polar regions; the latitudinal contrast increases. The interlatitudinal gradient is higher in the Southern Hemisphere. It practically does not change in winter and increases in summer, most strongly in the Southern Hemisphere.

Keywords: climate change, insolation, surface air temperature, celestial-mechanical processes, interlatitudinal gradient

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INTRODUCTION

Temperature regime is among the most important characteristics of climate conditions, defining many aspects of population life and environment. The surface air temperature (SAT) characterizes the thermal state of the Earth climatic system, which is mostly defined by incoming solar radiation energy and the planet's greenhouse effect. In regulating solar radiation income to the Earth (without account for the atmosphere) and its distribution on the surface (solar climate of Earth), two mechanisms with different physical natures are distinguished (Bertrand and Van Ypersele, 1999). One mechanism is associated with changes in solar activity (not considered in the present study). Another mechanism is defined by celestial mechanical processes, which change Earth orbit parameters (distance between the Earth and the Sun, duration of tropical year, etc.) and inclination of the rotation axis and which determine changes in insolation of Earth. This is the mechanism considered in the present study.

Mechanisms of meridional and interlatitudinal heat exchange in ocean–atmosphere, ocean–continent, and other systems participate in the distribution and regulation of heat energy in the Earth climatic system. Atmosphere composition (foremost, H_2O and CO_2 contents) is an important factor in regulations of the Earth thermal regime determining the level of the greenhouse effect.

The main goal of this study is to assess the influence of insolation and its changes, determined by celestial mechanical processes, on the formation and changes of climate norms of the SAT. Hence, the insolation factor is distinguished from all factors influencing the thermal regime of the Earth climatic system and studied; its role in the formation and changing SAT norm, reflecting the state and dynamics of the thermal regime of Earth climatic system, is determined.

CALCULATION METHODS

Previously, together with A.A. Kostin, we calculated radiation energy incoming to the Earth ellipsoid (without account for atmosphere) (http://www.solar-climate.com/sc/mtd.htm; (Fedorov, 2014, 2015)). Insolation calculations were performed using high precision astronomical ephemerides data ((Giorgini et al., 1996); http://ssd.jpl.nasa.gov) for all latitudinal zones (with a 5° extent) of the Earth ellipsoid for the time interval from 3000 BC to 3000 AD. The Earth surface was approximated by an ellipsoid (GRS80, Geodetic Reference System, 1980) with semiaxes equal to 6378137 m (major) and 6356752 m (minor). In general terms, the calculation algorithm may be written as

$$I_{nm}(\varphi_1,\varphi_2) = \int_{t_1}^{t_2}\left(\int_{\varphi_1}^{\varphi_2}\sigma(H,\varphi)\left(\int_{-\pi}^{\pi}\Lambda(H,t,\varphi,\alpha)d\alpha\right)d\varphi\right)dt, \quad (1)$$

where I is incoming solar radiation for elementary n fragment of m tropical year (J); σ is areal factor (m^2), with the use of which areal differential $\sigma(H, \varphi)$ is calculated; $d\alpha d\varphi$ is the area of an infinitely small trapeze, which is cell of an ellispoid (α is hour circle and φ is geographic latitude, both expressed in radians); H is ellipsoid height relative to the Earth surface (m); $\Lambda(H, t, \varphi, \alpha)$ is insolation at a given time in a given location on the ellipsoid (W/m^2), and t is time (s). The following integration steps were used: 1° for longitude, 1° for latitude, and 1/360 of tropical year for time. The value of solar constant (average long-term TSI value) was set to 1361 W/m^2 (Kopp and Lean, 2011). Following the results, an open-access dataset of incoming solar energy for all latitudinal zones (with a 5° extent) for every astronomical month of every year for the time interval from 3000 BC to 3000 AD was compiled (http://www.solar-climate.com/sc/bd01.htm).

The main differences of our approach (in time, space, and initial data) known from astronomical climate theory calculations of low-frequency variations in insolation are outlined below.

(1) M. Milankovich and his followers calculated Earth insolation (without account for atmosphere) for long time periods (from several hundreds to millions of years) accounting only its century (low-frequency) variations, associated with changes in eccentricity, perihelion longitude, and inclination of the Earth rotation axis (with periods of several tens of thousands of years). The temporal resolution of calculations was approximately from 5000 years for calculations of M. Milankovich (1939), Sh.G. Sharaf and N.A. Budnikova (1969), and A.S. Monin (1982) to 1000 years in studies by A. Vernekar (Vernekar, 1972) and A. Berger ((Berger, 1978a, 1978b; Berger and Loutre, 1991); an e-mail from M.F. Loutre, 2016). M. Milankovich and his followers calculated daily and annual insolation for a certain initial year (for example, 1850 or 1950). Then, a step (from 1000 to 5000 years) in past (or in future) was made and the calculation procedure (with account of changes in eccentricity, perihelion longitude, and axis inclination) was repeated. Periodic (high-frequency) variations in insolation were not accounted for (the duration of the tropical year was assumed constant). In our calculations, hundred-year and periodic variations in distance from the Earth to the Sun, duration of tropical year, inclination of the rotation axis, etc., were accounted for. Temporal resolution during integration was 1/360 of the tropical year duration (approximately a day) accounting for variations in this duration.

(2) M. Milankovich and his followers performed calculations for certain geographical latitudes (parallels); the Earth was assumed to have a spherical form. In our calculations, insolation was calculated for the whole Earth surface, which was approximated by an ellipsoid. Spatial resolution during integrations was 1° in longitude and 1° in latitude.

(3) To perform calculations, M. Milankovich (or, rather, V. Mishkovich) calculated long-term astronomical ephemerides for eccentricity, perihelion longitude, and inclination of the Earth rotation axis, which were later corrected by his followers (Brouwer and Van Woerkom, 1950; Sharaf and Budnikova, 1969; Vernekar, 1972; Berge, 1978a, 1978b; Bretagnon, 1982). For insolation calculations, we used parameters from Eq. (1), which account for hundred-year and periodic variations in the Earth orbit elements and its rotation axis. As the initial data for calculations, we used high-precision astronomical ephemerides calculated at the Jet Propulsion Laboratory of the California Institute of Technology (time period from 3000 BD to 3000 AD) and distributed on the NASA website (http://ssd.jpl.nasa.gov).

Calculations, accounting periodic disturbances of the Earth orbit and associated high-frequency variations in solar radiation, were started in the Voeikov Main Geophysical Observatory, Russia (Borisenkov et al., 1983, 1985). However, these studies did not receive further development. Studies of high-frequency insolation variations were also started in the Lemaître Institute of Astronomy and Geophysics, Belgium (Loutre et al., 1992; Bertrand et al., 2002a, 2002b). Our calculations are a continuation of the line of Earth insolation studies, accounting its hundred-year (low-frequency) and periodic (high-frequency) variations.

Differences of our approach for an analysis of high-frequency insolation variations from methods of E.P. Borisenkov, M.F. Loutre, C. Bertrand, and their colleagues are associated, firstly, with the choice of the initial astronomical data used in calculations; secondly, with a different solution of insolation calculations relatively to the Earth surface; and, thirdly, with the duration of the time interval of calculations. As initial data, E.P. Borisenkov with his colleagues used ephemerides, calculated at Institute of Theoretical Astronomy, USSR Academy of Sciences (e-mail from A.V. Tsvetkova, 2015). VSOP82 (Bretagnon, 1982) ephemerides were used as initial data for calculations performed by Belgian researchers (Loutre et al., 1992; Bertrand et al., 2002a, 2002 b). In our calculations, the high-precision JPL Planetary and Lunar Ephemerides DE-405/406 (Standish, 1982) developed at the Jet Propulsion Laboratory of California Institute of Technology (http://ssd.jpl.nasa.gov) were used.

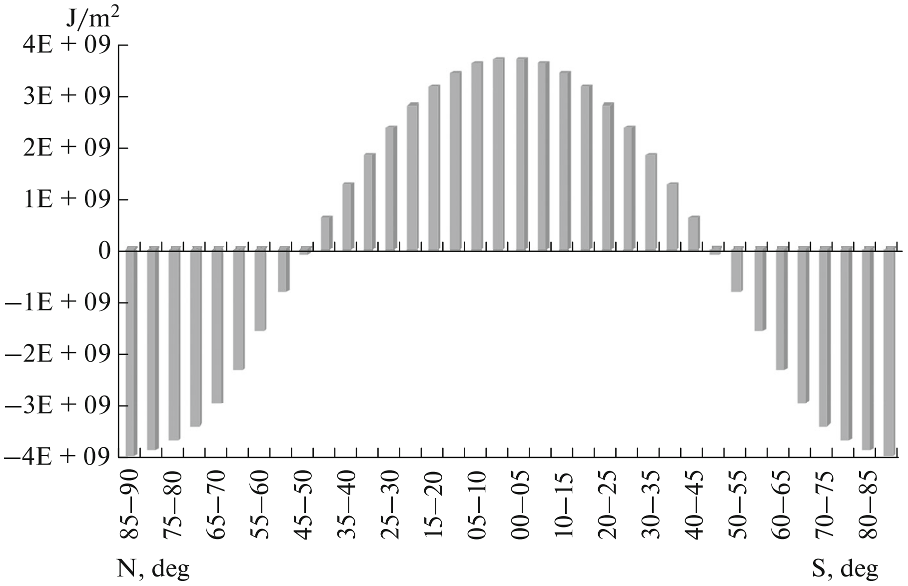

Fig. 1. Distribution of insolation (J/m^2) by latitudinal zones relative to the mean for 5-degree latitudinal zone value (mean over 1961–1990) (data from http://www.solar-climate.com/sc/bd01.htm).

For calculations of insolation, our predecessors assumed the Earth surface to be a sphere, and calculations were performed only for certain latitudes of this sphere. E.P. Borisenkov and his colleagues (Borisenkov et al., 1983, 1985) obtained values only for 20°, 40°, 60°, and 80° N. In studies by Belgian scientists (Loutre et al., 1992), calculations were performed (for middle of July or, rather, for a point with a geocentric longitude equal to 120°) for 65° N only, and for equinoctial and solstice points for the equator and 30°, 60° and 90° latitudes of both hemispheres. In the study by C. Bertrand and his colleagues (Bertrand et al., 2002a), insolation calculations encompass previous millennium and are also attributed to July; they are calculated for the latitudinal zone between 65 and 70° N. For our calculations, the Earth was approximated with an ellipsoid, and incoming radiation was calculated not for certain parallels (latitudes), but for the whole Earth surface and surfaces of certain latitudinal zones.

The temporal resolution of calculations of insolation high-frequency variations in the study by E.P. Borisenkov and his colleagues is approximately a day (Borisenkov et al., 1983). However, the calculations performed by them were presented for winter and summer half-year periods (and for the Northern Hemisphere only) from 1800 to 2100. In study (Loutre et al., 1992), calculations were performed for a 5000-year time interval (to the past) with annual resolution and for July only (or, rather, for a point with a geocentric longitude equal to 120°) for equinoctial and solstice points. In the study by C. Bertrand and his colleagues (Bertrand et al., 2002a), insolation calculations encompass previous millennium, but they are attributed for one month only, i.e., July (performed with annual resolution). Moreover, the value of the solar constant in our calculations was set to 1361 W/m^2 (Koop and Lean, 2011), while in studies by our predecessors it equals 1368 W/m^2 in study (Bertrand and Van Ypersele, 1999), 1367 W/m^2 in the study by E.P. Borisenkov and his colleagues (e-mail from A.V. Tsvetkova, 2015) and study (Loutre et al., 1992), and 1366 W/m^2 in study (Berger et al., 2010).

Thus, in general, our calculations are based on high-precision ephemerides, they utilize a new value of the solar constant (1361 W/m^2) and a time interval spanning 6000 years, all of the surface of the Earth is encompassed in more detail (calculated data are presented in an open archive with 5° latitude resolution for the Earth surface and 1 astronomical month temporal resolution for the whole 6000-year period), and the surface of the Earth in our calculations is approximated by an ellipsoid rather than a sphere.

As initial climate data for calculations of climatic norms we used SAT values averaged over the 1961–1990 period for latitudinal zones from a three-dimensional array of “Absolute Temperature for the Base Period 1961–1990” from the University of East Anglia and Met Office Hadley Centre (http://www.cru.uea.ac.uk/cru/data/temperature/absolute.nc; (Jones et al., 1999, 2012)).

Calculated for 5-degree latitudinal zones of the Earth ellipsoid (without account for the atmosphere), insolation estimates (http://www.solar-climate.com/sc/bd01.htm) (averaged for the period from 1961 to 1990) were compared to the SAT climatic norm for the 1961–1990 period (Figs. 1, 2, Table 1), which reflects the greenhouse effect associated with it, solar activity,

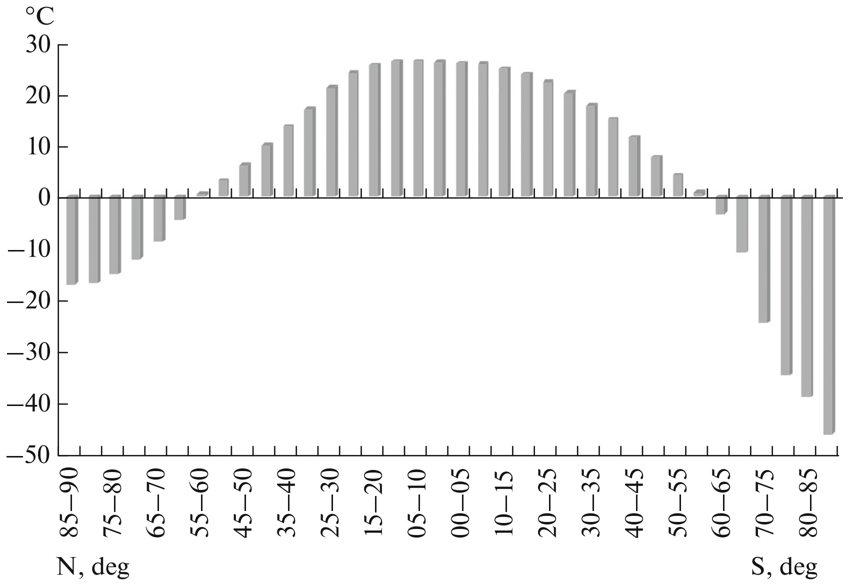

Fig. 2. Distribution of the SAT (°C) by latitudinal zones (mean over 1961–1990) (data from http://www.cru.uea.ac.uk/cru/data/temperature/absolute.nc).

heat-exchange mechanisms, participation in the formation of monthly and annual mean temperature, and characteristics associated with it, as well as its distribution by latitudes and seasons. For calculations of climatic norms, only insolation changes were considered. Changes in the greenhouse effect, solar activity, and heat-exchange mechanisms were not considered.

The latitudinal distribution of the SAT is characterized by a close correlation with the latitudinal distribution of solar radiation incoming to the Earth ellipsoid.

Table 1. Distribution of annual SAT* and insolation** by latitudinal zones (mean over 1961–1990)

Geographic latitude, deg.	Northern Hemisphere		Southern Hemisphere	
	SAT, °C	Insolation, J/m^2	SAT, °C	Insolation, J/m^2
0–5	26.15	1.3157702E+10	25.97	1.3157702E+10
5–10	26.35	1.3066533E+10	25.77	1.3066536E+10
10–15	26.42	1.2885110E+10	24.91	1.2885115E+10
15–20	25.66	1.2615274E+10	23.77	1.2615280E+10
20–25	24.03	1.2259823E+10	22.25	1.2259831E+10
25–30	21.27	1.1822573E+10	20.25	1.1822582E+10
30–35	17.09	1.1308453E+10	17.79	1.1308462E+10
35–40	13.62	1.0723690E+10	15.02	1.0723701E+10
40–45	10.07	1.0076137E+10	11.55	1.0076147E+10
45–50	6.16	9.3758823E+09	7.85	9.3758925E+09
50–55	3.12	8.6365123E+09	4.31	8.6365216E+09
55–60	0.48	7.8779475E+09	0.92	7.8779553E+09
60–65	−4.60	7.1344409E+09	−3.35	7.1344409E+09
65–70	−8.83	6.4931658E+09	−10.76	6.4931667E+09
70–75	−12.09	6.0573083E+09	−24.68	6.0573052E+09
75–80	−15.14	5.7629607E+09	−34.66	5.7629552E+09
80–85	−16.73	5.5762980E+09	−38.96	5.5762911E+09
85–90	−17.07	5.4853121E+09	−46.18	5.4853044E+09

* Data from website http://www.cru.uea.ac.uk/cru/data/temperature/absolute.nc.
** Data from website http://www.solar-climate.com/sc/bd01.htm.

Table 2. Factual and calculated insolation SAT norms for 1961–1990, °C

Object	Annual		Summer		Winter	
	fact.	calc.	fact.	calc.	fact.	calc.
Whole Earth	13.97	13.97	15.16	15.16	12.78	12.78
Northern Hemisphere	14.59	14.54	18.54	18.57	10.63	10.65
Southern Hemisphere	13.36	13.40	11.79	11.76	14.93	14.91

Correlation coefficient (*R*) between the SAT climatic norm (1961–1990) and incoming solar radiation for the whole latitudinal range is characterized by a value of 0.942, for the Northern Hemisphere it equals 0.997, and for the Southern Hemisphere it is 0.942. Regression equations were determined based on a separate approximation of three latitudinal ranges of the Earth (in such a way, optimal approximation was achieved). For an approximation of the annual SAT values in the range from 85–90° N to 10–15° N, a 6-order polynomial was used, and in the ranges from 5–10° N to 55–60° S and from 60–65° S to 85–90° S, 3-order polynomials were used. Approximation parameters (R^2) were found to be equal to 0.9997, 0.9996, and 0.9939, respectively. An approximation of the SAT latitudinal distribution for summer and winter half-years was also performed. Latitudinal ranges reflect an inhomogeneous (by the character of relation of surface air temperature with insolation) structure of the Earth surface in hemispheres (predominantly continental, predominantly oceanic, and ice continent Antarctica).

Using the obtained polynomial regression equations for 5-degree latitudinal zones and insolation data (from http://www.solar-climate.com/sc/bd01.htm), SAT norms (accounting only for insolation changes) were calculated with a resolution of 100 and 900–1000 years for the whole Earth and for separate hemispheres for space, and for a year and half-years for time. As such, calculated with an account of changes in insolation factor only (changes in insolation, determined by celestial mechanical processes), norms are termed by us insolation SAT norms. Therefore, the insolation SAT is surface air temperature under the condition of a stationary and compositionally unaltered atmosphere. These norms reflect the insolation factor role only; they account for greenhouse effect, solar activity, and heat exchange mechanisms for the 1961–1990 norm; and they do not account for previous or further changes in solar activity associated with atmosphere composition. As for the greenhouse effect and heat-exchange mechanisms, due to the fact that radiation incoming from Sun is the main source of energy for hydrometeorological processes, a theoretical assessment of this factor of formation and changing of SAT, which reflects basic state of thermal regime, appears important for the modern global climate.

RESULTS OF CALCULATIONS. ANNUAL INSOLATION SAT NORMS

The SAT norm calculated using regression equations for the period from 1961 to 1990 equals 13.97°C for Earth, 14.54°C for the Northern Hemisphere, and 13.40°C for the Southern Hemisphere. Per archive data of absolute temperatures, SAT norms (factual norms) from 1961 to 1990 were 13.97°C for the Earth, 14.59°C for the Northern Hemisphere, and 13.36°C for the Southern Hemisphere (Tables 1, 2).

This means that factual and insolation SAT norms for the Earth agree. In the Northern Hemisphere, the factual norm is 0.04°C higher than the calculated one, and in the Southern Hemisphere it is lower by the same magnitude.

The mean for the latitudinal zone (in modulus) for the whole latitudinal range (from 90° N to 90° S) value of the difference between calculated and factual SAT values is 0.29°C. Calculated for long-term time periods, insolation SAT norms change in accordance with previously obtained insolation change (Fedorov, 2015). For the Earth, the insolation SAT norm reduces by 0.03°C over 1000 years (Table 3), for the Northern Hemisphere by 0.01°C, and for the Southern Hemisphere by 0.05°C. For a longer period (5800 years), these values equal 0.17, 0.05, and 0.29°C, respectively (Fig. 3, Table 4).

In addition, in the distribution of the insolation SAT norm by latitudes, a certain increase is noted in the equatorial area and a noticeable decrease in polar regions (Fig. 4). Based on modeling for the 35–40° N latitudinal zone for the past millennium, Bertrand and his colleagues found that the SAT increased by 0.02°C (Bernard et al., 2002a). Our data (difference of 2021–2050 and 1021–1050 norms) suggests that this increase equals 0.01°C. For the 65–70° N latitudinal zone, there is a decrease of 0.04°C in the model data and 0.13°C in our calculations.

Hence, a tendency toward a latitudinal contrast increase is expressed in the distribution of insolation SAT norms. The difference in insolation SAT norms for 0–5° N and 85–90° N latitudinal zones for 1000 years increases by 0.26°C (from 43.22 to 43.48°C) or by 0.003°C per 1° of latitude (°φ). The difference in insolation SAT norms for corresponding zones in the Southern Hemisphere (0–5° S and 85–90° S) for the same period increases by 1.07°C (from 69.80 to 70.87°C) or by 0.013°C/°φ. For 5800 years these val-

Table 3. Calculated values of insolation SAT norms for a 1000-year time interval, °C

Years	Annual			Summer*			Winter*		
	Whole Earth	Northern Hemisphere	Southern Hemisphere	Whole Earth	Northern Hemisphere	Southern Hemisphere	Whole Earth	Northern Hemisphere	Southern Hemisphere
1021–1050	14.00	14.55	13.45	15.21	18.71	11.71	12.91	10.60	15.21
1121–1150	14.00	14.55	13.45	15.21	18.70	11.72	12.89	10.61	15.18
1221–1250	14.00	14.55	13.44	15.20	18.68	11.72	12.88	10.61	15.15
1321–1350	13.99	14.55	13.44	15.20	18.67	11.73	12.87	10.62	15.12
1421–1450	13.99	14.55	13.43	15.19	18.65	11.73	12.86	10.62	15.09
1521–1550	13.99	14.55	13.42	15.19	18.64	11.74	12.84	10.63	15.05
1621–1650	13.98	14.55	13.42	15.18	18.62	11.74	12.83	10.63	15.02
1721–1750	13.98	14.54	13.41	15.18	18.61	11.74	12.82	10.64	14.99
1821–1850	13.98	14.54	13.41	15.17	18.59	11.75	12.80	10.65	14.96
1921–1950	13.97	14.54	13.40	15.17	18.58	11.75	12.79	10.65	14.92
2021–2050	13.97	14.54	13.40	15.16	18.56	11.76	12.77	10.66	14.89

* Here and in Tables 4–6, half-years are referred to relatively to the Northern Hemisphere.

Table 4. Calculated values of insolation SAT norms for a 5800-year time interval, °C

Years	Annual			Summer			Winter		
	Whole Earth	Northern Hemisphere	Southern Hemisphere	Whole Earth	Northern Hemisphere	Southern Hemisphere	Whole Earth	Northern Hemisphere	Southern Hemisphere
2901–2930 BC	14.11	14.58	13.64	15.39	19.23	11.55	13.31	10.42	16.20
2001–2030 BC	14.09	14.58	13.60	15.36	19.13	11.58	13.24	10.46	16.02
1001–1031 BC	14.06	14.57	13.56	15.31	19.01	11.62	13.14	10.50	15.79
1–31 AD	14.03	14.56	13.51	15.27	18.87	11.66	13.04	10.55	15.52
1001–1030 AD	14.00	14.55	13.45	15.21	18.72	11.71	12.91	10.60	15.22
2001–2030 AD	13.97	14.54	13.40	15.16	18.56	11.76	12.78	10.65	14.90
2901–2930 AD	13.94	14.53	13.35	15.11	18.42	11.80	12.65	10.70	14.59

ues in the Northern Hemisphere increase by 1.41°C (0.016°C/°φ) and in the Southern Hemisphere by 5.75°C (0.068°C/°φ) (Fig. 5). Corresponding factual values of the interlatitude gradient for the 1961–1990 climatic norm (see Table 1) for the hemispheres are 0.509 (43.22°C) and 0.849°C/°φ (72.14°C). The value of the interlatitude gradient for the insolation SAT was determined as a quotient after the dividing temperature difference in 0–5° and 85–90° latitudinal zones of each hemisphere by 85° latitude separating the centers of these zones, i.e., 2.5 and 87.5°.

HALF-YEAR INSOLATION SAT NORMS

In the summer (for the Northern Hemisphere, from April to September) the half-year correlation between the distribution of the factual norm (1961–1990) by latitudes and distribution of ellipsoid solar radiation incoming to the Earth over the whole latitudinal range (Table 5) is characterized by R equal to 0.810. In the Northern Hemisphere, R equals 0.956 and, in the Southern Hemisphere, 0.909. In winter (for the Northern Hemisphere this includes values from October to March), half-year values of R are, respectively, 0.646, 0.993, and 0.947.

For calculations of insolation SAT norms for the summer (for the Northern Hemisphere) half-year, we used polynomial regression equations (3-order polynomials), which were obtained for three latitudinal

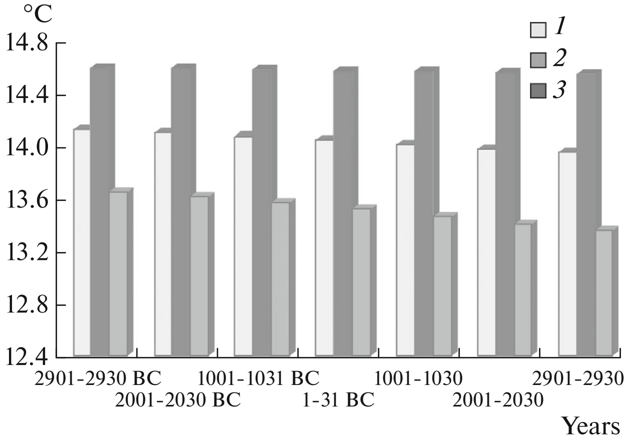

Fig. 3. Changes in annual insolation SAT norms for the whole Earth (*1*) and Northern (*2*) and Southern (*3*) hemispheres over 5800 years.

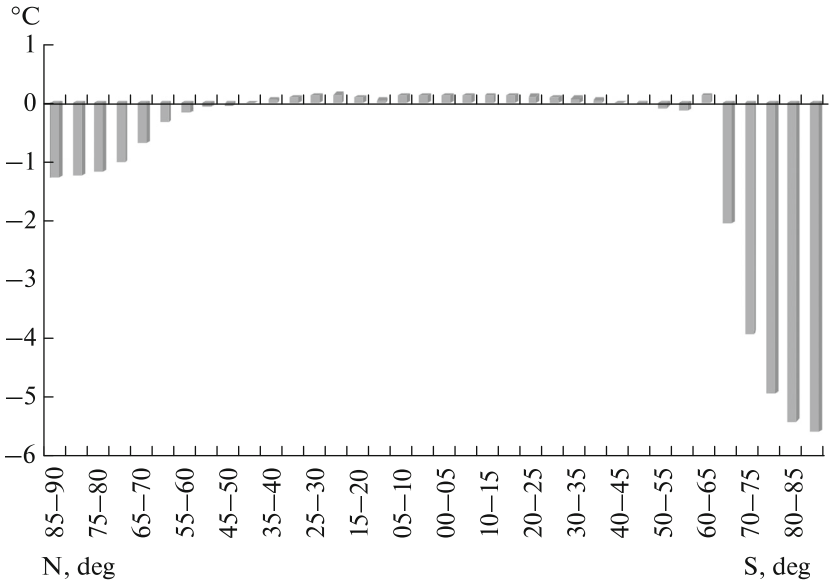

Fig. 4. Distribution of annual insolation SAT norms (°C) by latitudes over 5800 years.

ranges (90–85° to 30–25° N, 20–25° N to 55–60° S, and 60–65° to 85–90° S; approximation parameter R^2 equals 0.9972, 0.9988, and 0.9949, respectively), and insolation data (see: http://www.solar-climate.com/sc/bd01.htm).

The insolation SAT norm of Earth for the summer (in the Northern Hemisphere) decreases over 1000 years by 0.05°C (from 15.21 to 15.16°C); the SAT norm of the Northern Hemisphere decreases by 0.15°C (from 18.71 to 18.56°C). The insolation SAT norm of the Southern Hemisphere increases by 0.05°C (from 11.71 to 11.76°C). Over 5800 years (Fig. 6), the insolation SAT norm of the Earth decreases by 0.28°C (from 15.39 to 15.11°C), and that of the Northern Hemisphere decreases by 0.41°C (from 19.23 to 18.42°C). The insolation SAT norm of the Southern Hemisphere increases by 0.25°C (from 11.55 to 11.80°C).

The interlatitude gradient in the Northern Hemisphere for this half-year increases by 1.10°C over 1000 years, or by 3.26%. For 1° of geographical latitude (°φ), the increase over this period equals 0.013°C (the SAT difference between equatorial and polar zones changes from 33.19 to 34.29°C). In the Southern Hemisphere, the difference remains constant (79.67°C). Values of SAT difference between equatorial and polar zones in the factual 1961–1990 norm are 33.13°C (0.390°C/°φ) in the Northern Hemisphere and 81.37°C (0.957°C/°φ) in the Southern Hemisphere. Over 5800 years, the difference of the insolation SAT between equatorial and polar zones of the Northern Hemisphere increases by 5.55°C, or by 17.2%. This increase equals 0.065°C/°φ (Fig. 7). In latitudinal distribution, a decrease in the insolation SAT norm in the latitudinal range from 90 to 10° N may be noticed. For all latitudinal zones located southward, an increase in latitudinal SAT norm is noted for this half-year.

For the winter (in the Northern Hemisphere), half-year calculations of insolation SAT (Table 6) were also performed for three latitudinal ranges (90–85° N to 15–20° S, 4-order polynomial; 20–25° to 55–60° S, 3-order polynomial; and 60–65° to 85–90° S, 2-order polynomial) and for insolation data (website: http://www.solar-climate.com/sc/bd01.htm). Values of approximation parameter R^2 equal 0.9991, 0.9947, and 0.9921, respectively.

A decrease in insolation SAT norm for this half-year over 1000 years for Earth is 0.14°C (from 12.91 to 12.77°C) in total; for the Southern Hemisphere, it equals 0.32°C (from 15.21 to 14.89°C). In the North-

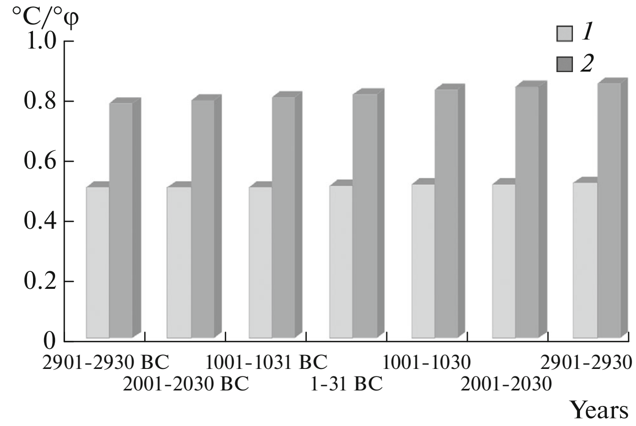

Fig. 5. Changes in the interlatitudinal gradient (°C/°φ) over 5800 years in the Northern (*1*) and Southern (*2*) hemispheres.

Table 5. Distribution of SAT* and insolation** by latitudinal zones (mean over 1961–1990 for summer half-year)

Geographic latitude, deg.	Northern Hemisphere		Southern Hemisphere	
	SAT, °C	insolation, J/m^2	SAT, °C	insolation, J/m^2
0–5	26.13	6.6979053E+09	25.86	6.4597848E+09
5–10	26.52	6.8895353E+09	25.55	6.1769872E+09
10–15	27.04	7.0333252E+09	24.36	5.8517758E+09
15–20	26.98	7.1284097E+09	22.73	5.4868567E+09
20–25	26.19	7.1744367E+09	20.68	5.0853808E+09
25–30	24.40	7.1716094E+09	18.40	4.6509589E+09
30–35	20.96	7.1207500E+09	16.10	4.1876997E+09
35–40	18.29	7.0234022E+09	13.74	3.7002867E+09
40–45	15.55	6.8820060E+09	10.48	3.1941305E+09
45–50	12.57	6.7002182E+09	7.08	2.6756652E+09
50–55	10.20	6.4835489E+09	3.46	2.1529655E+09
55–60	8.04	6.2407919E+09	–0.42	1.6371584E+09
60–65	5.09	5.9880267E+09	–5.96	1.1464116E+09
65–70	1.40	5.7679218E+09	–15.13	7.2524590E+08
70–75	–2.88	5.6313372E+09	–31.14	4.2597196E+08
75–80	–6.08	5.5457174E+09	–42.70	2.1724364E+08
80–85	–6.98	5.4936723E+09	–47.71	8.2625721E+07
85–90	–7.00	5.4688851E+09	–55.51	1.6426966E+07

* Data from website http://www.cru.uea.ac.uk/cru/data/temperature/absolute.nc.
** Data from website http://www.solar-climate.com/sc/bd01.htm.

ern Hemisphere for this half-year, an increase in insolation SAT norm by 0.06°C (from 10.60 to 10.66°C) is observed. Over the time interval of 5800 years, corresponding values are –0.66, –1.21, and +0.28°C (Fig. 8). In the latitudinal range from 90° N to 20° S, a slight increase in insolation norm is noticed, while a decrease is observed southward.

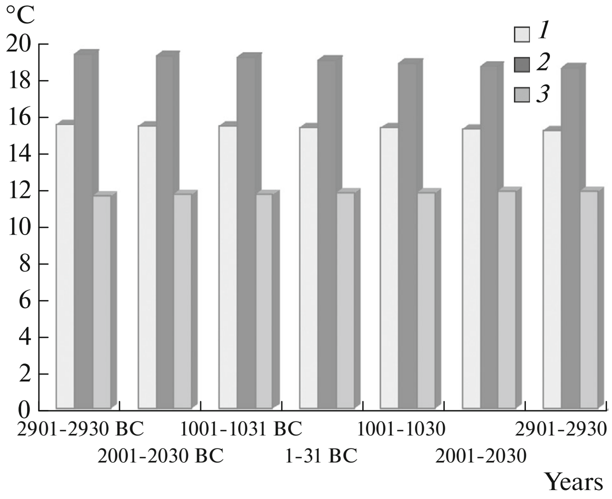

Fig. 6. Changes in the insolation SAT norm (°C) in the summer (for the Northern Hemisphere) half-year for the whole Earth (*1*) and Northern (*2*) and Southern (*3*) hemispheres over 5800 years.

Hence, in summer for hemispheres half-years, a decrease in values of insolation SAT norms is observed and an increase in winter ones. Seasonal differences in this setting are leveled. In the latitudinal range from 90° N to 20° S, a slight increase of insolation norm is observed, while a decrease is observed southward.

In the Northern Hemisphere, the difference in the insolation SAT between equatorial (0°–5°) and polar (85°–90°) zones remains constant over 1000 years and equals 54.18°C (the value of the factual norm for 1961–1990 equals 53.32°C). In the Southern Hemisphere, this difference increases by 3.67°C (from 58.71 to 62.37°C), or by 6.05%. Hence, this increase corresponds to 0.043°C/°φ, while the factual norm for 1961–1990 equals 62.83°C (0.739°C/°φ). Over 5800 years, in the winter, the half-year difference in the insolation SAT between the equatorial and polar zones of the Northern Hemisphere changes by just 0.01°C, while for the Southern Hemisphere this value equals 18.31°C (or 32.77%). This value corresponds to an increase in the gradient in the Southern Hemisphere by 0.215°C/°φ (Fig. 9).

Characteristics of the thermal regime notably differ in hemispheres (see Tables 2–4). Summer in the

Table 6. Distribution of SAT* and insolation** by latitudinal zones (mean over 1961–1990 for the winter half-year)

Geographic latitude, deg.	Northern Hemisphere		Southern Hemisphere	
	SAT, °C	insolation, J/m^2	SAT, °C	insolation, J/m^2
0–5	26.17	6.4597962E+09	26.08	6.6979177E+09
5–10	26.17	6.1769974E+09	25.98	6.8895485E+09
10–15	25.80	5.8517847E+09	25.46	7.0333389E+09
15–20	24.34	5.4868641E+09	24.81	7.1284236E+09
20–25	21.88	5.0853867E+09	23.82	7.1744505E+09
25–30	18.13	4.6509633E+09	22.10	7.1716229E+09
30–35	13.22	4.1877025E+09	19.47	7.1207628E+09
35–40	8.95	3.7002881E+09	16.29	7.0234140E+09
40–45	4.59	3.1941305E+09	12.61	6.8820166E+09
45–50	–0.24	2.6756641E+09	8.63	6.7002273E+09
50–55	–3.96	2.1529634E+09	5.17	6.4835561E+09
55–60	–7.08	1.6371557E+09	2.27	6.2407970E+09
60–65	–14.30	1.1464088E+09	–0.73	5.9880293E+09
65–70	–19.06	7.2524403E+08	–6.39	5.7679208E+09
70–75	–21.30	4.2597109E+08	–18.21	5.6313333E+09
75–80	–24.21	2.1724329E+08	–26.62	5.5457116E+09
80–85	–26.48	8.2625691E+07	–30.22	5.4936654E+09
85–90	–27.15	1.6426973E+07	–36.85	5.4688775E+09

* Data from website http://www.cru.uea.ac.uk/cru/data/temperature/absolute.nc.
** Data from website http://www.solar-climate.com/sc/bd01.htm.

Northern Hemisphere is warmer (18.54°C) than in the Southern Hemisphere (14.93°C), while winter is colder (10.63°C against 11.79°C). Summer differences of insolation SAT norms in hemispheres increase by 0.17°C over 1000 years and by 0.8°C over 5800 years (see Tables 3, 4). Differences in the winter insolation SAT norms between hemispheres practically do not change; they slightly decrease, i.e., by 0.01°C over 1000 years and by 0.03°C over 5800 years. In the present time, values of the interlatitude gradient in the Southern Hemisphere are higher than in the Northern Hemisphere in corresponding half-years. The winter gradient in the Southern Hemisphere (0.937°C/°φ) is 1.47 times higher than the winter gradient in the Northern Hemisphere (0.637°C/°φ). The summer gradient in the Southern Hemisphere (mean over 1000 years is 0.714°C/°φ) is 1.8 times higher than the summer gradient in the Northern Hemisphere (0.397°C/°φ). Differences between the winter and summer gradients in the Southern Hemisphere are lower (0.223°C/°φ), and in the Northern Hemisphere they are higher (0.240°C/°φ). Annual values of anomaly for 2015 based on the data from HadCRUT4 archive (https://crudata.uea.ac.uk/cru/data/temperature) in the Southern Hemisphere (0.492°C) are 2.03 times lower than in the Northern Hemisphere (1.001°C), while the annual gradient (in 1961–1990 norm), on contrary, is 1.63 times higher.

CONCLUSIONS

Based on archive data, the anomaly of surface temperature (HadCRUT4 array contains joint data for anomalies of surface temperature over land and anomalies of ocean surface layer temperature) in 2015 equals 0.745°C for the whole Earth, 1.001°C for the Northern Hemisphere, and 0.492°C for the Southern Hemisphere (see http://crudata.uea.ac.uk/cru/data/tem-

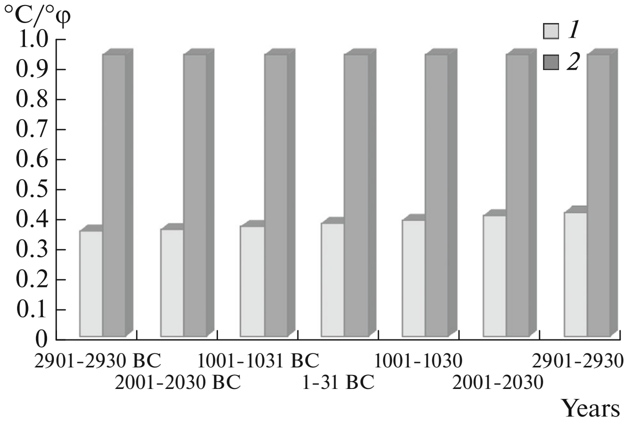

Fig. 7. Changes in interlatitudinal gradient (°C/°φ) in the Northern (*1*) and Southern (*2*) hemispheres over 5800 years in the summer (for the Northern Hemisphere) half-year.

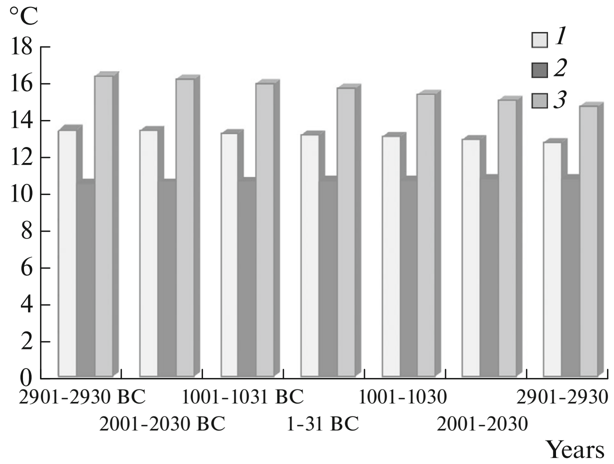

Fig. 8. Changes in the insolation SAT norm (°C) for the whole Earth (*1*) and Northern (*2*) and Southern (*3*) hemispheres in the winter (for the Northern Hemisphere) half-year over the interval of 5800 years.

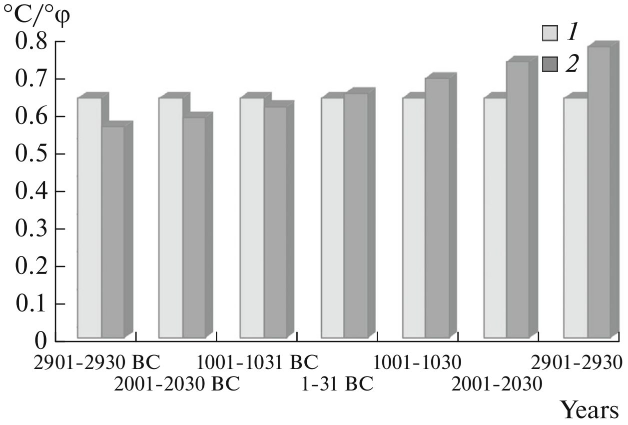

Fig. 9. Changes in the interlatitudinal gradient (°C/°φ) in the Northern (*1*) and Southern (*2*) hemispheres over 5800 years in the winter (for the Northern Hemisphere) half-year.

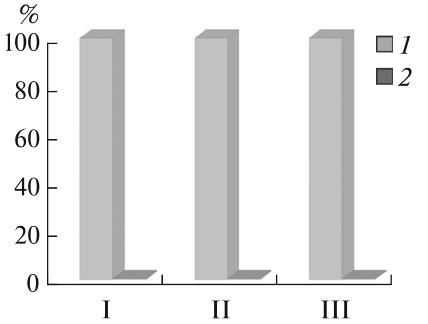

Fig. 10. Proportion of the SAT norm (*1*) and annual anomaly of surface temperature in the Earth temperature regime (*2*) for the whole planet (I) and Northern (II) and Southern (III) hemispheres.

perature). Since the space surrounding Earth has a temperature of absolute zero in Kelvins, or –273°C, then change of surface temperature anomaly relatively to absolute value of its norm (reflecting basic state of thermal regime) for 1961–1990 is just 0.26% for the whole Earth, 0.35% for the Northern Hemisphere, and 0.17% for the Southern Hemisphere (Fig. 10).

This implies that the basic state of the thermal regime (which is characterized by the insolation SAT norm) of the global climate is determined by insolation and the greenhouse effect of the planet. This composes 99.74% for the whole Earth, 99.65% for the Northern Hemisphere, and 99.83% for the Southern Hemisphere. Ongoing changes (SAT anomalies) are weakly related to the direct radiation income (its income to Earth marginally changes over the study periods), but they may be related to its distribution, i.e., interlatitudinal gradient, which varies notably. Ongoing SAT changes in the Northern Hemisphere considerably exceed the ongoing changes in the Southern Hemisphere, where the thermal regime is more stable (http://crudata.uea.ac.uk/cru/data/temperature). In the Southern Hemisphere, heat advected from the equatorial area is presumably mostly absorbed by the ocean. In the Northern Hemisphere, heat advection due to interlatitudinal heat exchange results in an increased greenhouse effect due to an increased concentration of H_2O and other greenhouse gases (Monin and Shishkov, 2000; Bertrand et al., 2002b; Alekseev, 2015). A positive compensation ("overcompensation" based on positive feedback) of decreasing in time radiation energy income to Earth (and heat related to it) occurs due to a mechanism of its spatial distribution (increased interlatitudinal gradient), increased greenhouse effect[1] (H_2O, CO_2, etc.), and the operation of an "oceanic conveyor" (Gulfstream and other currents). A certain increase in the SAT anomaly (in both hemispheres) is also possible due to an increase in solar activity (Lean et al., 1995; Koop and Lean, 2011). The Earth climatic system appears to be sensitive to these small variations (see Fig. 10) in the thermal regime (http://public.wmo.int/en; http://www.ipcc.ch).

A calculation of the annual insolation SAT values for the period covered by instrumental meteorological observations (1850–2015) and a comparison of the factual and insolation anomalies might aid in deter-

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[1] We understand the greenhouse effect on Earth to be the difference between the factual surface temperature T and Earth effective temperature T_e (Monin and Shishkov, 2000). The effective temperature T_e corresponds to the flow L of infrared radiation of the Earth on a unit-area basis and is estimated according to the Stefan–Boltzmann law $L = \sigma T_e^4$, i.e., under the assumption that the Earth is a black body. Hence, the Earth greenhouse effect $\Delta T = (T - T_e)$. $T_e = 249$ K (or –24°C), $T = -$ 288 K (or +15°C); therefore, $\Delta T = 39°$. Hence, the proportion of factors of insolation and greenhouse effect in the formation of the Earth thermal regime is 86.46% (249°) and 13.54% (39°), respectively.

mining the precise contribution of insolation anomaly to ongoing climate changes (along with the cumulative contribution of solar activity, greenhouse effect, heat-exchange mechanisms, and direct and inverse relationships in the climatic system).

MAIN FINDINGS

(1) Annual insolation SAT norms of the whole Earth and both hemispheres separately decrease over all time intervals. Half-year insolation SAT norms increase in the winter for hemisphere half-years and decrease in summer ones (seasonal differences are smoothed). Annual and half-year insolation SAT norms increase in the equatorial area and decrease in the polar regions (latitudinal contrast increases).

(2) The interlatitudinal gradient of insolation SAT norm has higher values in the Southern Hemisphere than in the Northern Hemisphere. In the winter, for hemispheres, half-years values of interlatitude gradient practically do not change, remaining quite high. In the summer half-years over the whole interval and in both hemispheres, they increase, which is more pronounced in the Southern Hemisphere. An increase in atmospheric instability (turbulence) and an increase in interlatitudinal heat exchange (foremost, in the form of heat advection by vortex structures, i.e., tropical or frontal cyclones, and by oceanic currents) may be consequences of increased values of interlatitudinal gradient.

(3) The fraction of the ongoing temperature changes in the Earth thermal regime is from 0.17% in the Southern Hemisphere to 0.35% in the Northern Hemisphere. The Earth climatic system appears to be sensitive to small ongoing changes in the thermal regime. The main reasons for these changes presumably include ongoing changes in solar activity, the greenhouse effect, heat-exchange mechanisms, and direct and inverse relationships in the climatic system. The main part of the thermal energy (the basic part of thermal regime) of the Earth climatic system (from 99.65% in the Northern Hemisphere to 99.83% in the Southern Hemisphere) is determined by the insolation and greenhouse effect of the planet. The insolation SAT norm is a characteristic of the basic component of the thermal regime. Hence, insolation SAT norms are reference points of thermal regime and indicators of global climate stability over the interval from 3000 BC to 3000 AD, which is covered by precise insolation calculations. Ongoing SAT changes (anomaly) over the interval covered by meteorological measurements do not differ much from the climatic SAT norm (http://crudata.uea.ac.uk/cru/data/temperature). However, the reasons for small values of the SAT anomalies need to be studied due to the high sensitivity to them of the climatic system of the Earth.

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