DOI:10.28974/idojaras.2023.1.2

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 127, No. 1, January – March, 2023, pp. 23 –42

Southern Hemisphere temperature trend in association with greenhouse gases, El Niño Southern Oscillation, and Antarctic Oscillation

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(Manuscript received in final form March 31, 2022)

Abstract— In this study, the trend of mean seasonal and annual temperatures of the Southern Hemisphere was calculated based on the HadCRUT5 and NASA-GISS data networks, for the period 1901–2021 and 1951–2021. In order to determine the possible effects on temperature, man, or nature, the relationship with CO_2 concentration, GHG (greenhouse gases) radiation exposure, and teleconnections ENSO (El Niño Southern Oscillation) and AAO (Antarctic Oscillation) was examined. The obtained results indicate that there is a significant increasing trend of seasonal and annual temperatures in the Southern Hemisphere, which intensified in the period between 1951 and 2021 (from 0.11 to 0.12 °C per decade). According to climate models, one of the indicators of the dominance of the anthropogenic greenhouse effect is the polar amplification (more intense temperature rise going from the equator to the poles). However, polar amplification was not recorded in the Southern Hemisphere, due to the fact that there was the smallest increase in temperature in the belt between 44°S–64°S. Moreover, in the mentioned zone, the positive trend was smaller in the period between 1951 and 2021 than in the period between 1901 and 2021, which was not to be expected. Nevertheless, the Southern Hemisphere temperature showed a statistically significantly strong correlation with the concentration of CO_2 observed at the Mauna Loa station. It was also found that there is a significant relationship between the energy impact of greenhouse gases and the Southern Hemisphere temperature, which is logical, because with the growth of GHG, positive radiative forcing increases. When it comes to the impact of telecommunications, both considered teleconnections (ENSO and AAO) have an impact on changes in the temperature of the Southern Hemisphere.

Key-words: temperature trend, Southern Hemisphere, GHG, radiative forcing, ENSO, AAO

1. Introduction

Compared to previous announcements of the Intergovernmental Panel on Climate Change (IPCC), the Sixth Assessment Report with a high degree of certainty confirms the dominance of the anthropogenic factor on the climate. The report emphasizes that people are certainly causing global warming. In other words, human impact is primarily related to the excessive combustion of fossil fuels, which increases the concentration of greenhouse gases, primarily carbon dioxide (CO_2), in the atmosphere. The Paris Agreement, adopted in 2015, aimed to limit global warming to below 2 degrees, i.e., to increase the global average temperature by 1.5 °C by the end of this century compared to the pre–industrial level. If the global temperature rises by 2 degrees or more compared to the pre–industrial period, irreversible and possible large negative changes in natural and human systems can be expected according to the models (IPCC, 2021).

However, the aforementioned IPCC Report says that the increase in global temperature of 1.5 °C will be exceeded in the next 20 years (until 2040), because the growth of atmospheric CO_2 concentration has not stopped. According to official data provided by the NOAA, the average annual value of CO_2, obtained from measurements at the Mauna Loa Observatory (Hawaii), for 2021 was 416.45 ppm. Despite the decline in human activity over the past two years due to the COVID–19 pandemic, global temperature and CO_2 concentrations continued to rise (*Fig. 1*). Since the beginning of the Industrial Revolution (1750s), the concentration of CO_2 (47%) and methane (CH_4, 156%) has been exceeded by far, and the increase in nitrogen suboxide (N_2O, 23%) is similar to the increase which occurred between the glacial and interglacial periods, in the last 800,000 years (very high increase). The IPCC Report further points out that of the total anthropogenic CO_2 emissions, 91% originate from the combustion of fossil fuels, and 9% arise as a result of excessive land use. Of the total amount of CO_2 emitted, about 56% is absorbed by the oceans and land (mainly vegetation), and the rest (about 46%) accumulates in the atmosphere. Individually, vegetation absorbs slightly more CO_2 (30%) than the oceans (26%). Ocean acidification is very likely to lead to the extinction of many marine life. Most of the heat energy from the atmosphere is absorbed by the oceans – it is estimated that 80–90% of the heat of the climate system is absorbed by the oceans. Thus, study shows an increase in the average temperature of the World Sea to a depth of 3000 m, and that up to a depth of 100 m, the water temperature has risen by 0.33 °C since 1969 (IPCC, 2021).

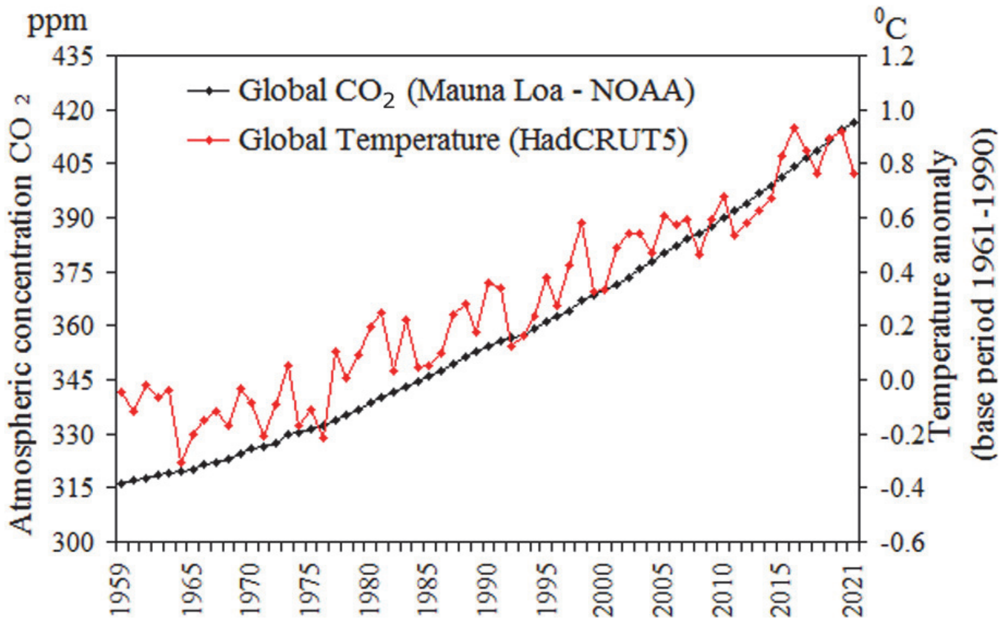

Fig. 1. Average values of global temperature and atmospheric concentration of carbon dioxide in the period from 1959 to 2021.

Recently, *Morice et al.* (2021) and *Osborn et al.* (2021) updated the global data of the HadCRUT network (Hadley Center and the Climatic Research Unit at the University of East Anglia). Based on the mentioned data set, the new version of HadCRUT5, it has been concluded that 2016 was the warmest year on our planet since the beginning of the instrumental period (since 1880), with an average deviation of 0.93 °C. During 2015 and 2016, especially in the winter, the strongest El Niño since 1870 was recorded, and this certainly had an impact on global temperature. The year 2020 (+0.92 °C) was the second warmest, while 2021 was the same as 2018, so they share the 6th and 7th places on the list of the warmest years, with a deviation of 0.76 °C. On the other hand, the *IPCC* (2021) points out that 2020 was the warmest year in the world and in Europe. In 2020, the global temperature was 1.1 °C higher than in the pre–industrial period. When it comes to changes in precipitation, the IPCC points out that the global amount of precipitation has probably increased since the 1950s, and that the increasing trend has been more intense since the 1980s. In any case, the IPCC believes that the human factor "extremely likely" contributed to global warming and changes in rainfall, and that modern climate change has led to more frequent and intense extreme events: heat waves, heavy rains, droughts, storms, fires, tropical hurricanes, etc.

In general, global temperatures have been rising since the mid–20th century, there is no doubt about that. The IPCC and most of the scientific community members believe that global warming is a consequence of the anthropogenic greenhouse effect and that there is a climate crisis. Although taking place at different time intervals, many researches point out that anthropogenic climate change and COVID-19 are currently the biggest problems of today (*Vinaya Kumar et al.,* 2017; *Klenert et al.,* 2020; *Phillips et al.,* 2020; *Schmidt,* 2021; *IPCC,* 2021; *Feldman* and *Hart,* 2021; *Geiger et al.,* 2021; *Meijers et al.,* 2021). The solution to the climate crisis is to stop the anthropogenic emissions of CO_2 and other gases that pollute the atmosphere, i.e., to decarbonize the global economy, which means stopping the burning of fossil fuels and switching to the use of so-called green energy (*Waldhoff* and *Fawcett,* 2011; *Friman* and *Hjerpe,* 2015; *Yang et al.,* 2019; *Wei et al.,* 2020; *IPCC,* 2021; *Murali et al.,* 2021). It should be noted that higher temperatures also mean excess energy in the atmosphere, and it is very likely that more frequent weather and climate extremes occur as a consequence of the release of that excess energy (*Burić et al.,* 2011). Thus, it is generally known that most of the scientific community and public opinion believe that global warming is a consequence of the anthropogenic greenhouse effect, but there are many authors who point out that changes in temperature, precipitation, clouds, and other climatic elements can be attributed to natural factors, i.e., variations in atmospheric oscillations (e.g., *Burić et al.,* 2018, 2019, 2021; *Tosunoglu et al.,* 2018; *Serykh* and *Sonechkin,* 2020; *Burić* and *Stanojević,* 2020; *Han* and *Sun,* 2020; *Mihajlović et al.,* 2021).

When it comes to the impact of variations in ocean–atmosphere oscillations (common name for teleconnection) on weather and climate, much more work is focused on the Northern Hemisphere. Therefore, the aim of this paper is to investigate the dynamics and possible causes of temperature change in the Southern Hemisphere region. The two oscillations that are, among others, spatially related to the Southern Hemisphere are the El Niño–Southern Oscillation (ENSO) phenomenon and the Antarctic Oscillation (AAO). However, the ENSO phenomenon has an impact on a global scale as well. All oscillations have a positive and negative phase. When a certain phase dominates, in some areas it is warmer, and in others it is colder, i.e., in some places it is wetter, while in other parts there is less precipitation compared to the usual state. One of the most well-known interactive connections between the ocean and the atmosphere is the occurrence of ENSO, which refers to periodic changes in water temperature in the central and eastern areas of the tropical Pacific Ocean. In the time intervals ranging from about three to seven years, surface water temperatures in the tropics of the Pacific Ocean increase (El Niño) or decrease (La Niña) by 1–3 °C, compared to the normal (*Ducić* and *Luković,* 2005; *Zubair et al.,* 2007; *Burić et al.,* 2011).

The Antarctic Oscillation (AAO) is the dominant pattern of non-seasonal variations of tropospheric circulation south of 20°S latitudes, and is characterized by anomalies of surface pressure of opposite sign compared to the usual state between two dipoles – one above Antarctica and the other in the zone between 40–50°S (*Thompson* and *Wallace,* 2000; *Thompson et al.,* 2000). Typical fluctuations in the altitude of AAO are associated with anomalies greater than 30 m above the pole and the opposite sign of 5–10 m magnitude across the width of New Zealand. The AAO counterpart in the Northern Hemisphere is the Arctic Oscillation (AO). AAO is also called Southern Annular Mode (SAM). Some authors believe that there is a link between ENSO and AAO (e.g., *González-Reyes* and *Muñoz,* 2013), and these two patterns have a link to the Pacific Decadal Oscillation (*Boisier et al.,* 2018). In essence, AAO refers to strong winds orbiting Antarctica. When they are strong, which is characterized as a positive phase of AAO (AAO+), cold air does not descend to lower latitudes, air pressure over Antarctica is lower, so the southwest winds (SWW) and southern subtropical front (STF) are stronger and shifted to the pole. During AAO+, Antarctica is colder than usual, especially the eastern part (the Ross Sea ice and the Marie Byrd Land). Also, AAO+ usually lowers temperatures on the continents of the Southern Hemisphere, especially in the south of Argentina. As for precipitation, during AAO+, the western part is wetter, and the eastern part of Antarctica is drier. During the negative phase (AAO-), the strong Antarctic vortex weakens, while the cold air descends further south and brings a drop in temperature in the middle latitudes. At that time, the temperature and the pressure in Antarctica were higher, and a bigger part of the continent received less rainfall than usual (*Carvalho et al.,* 2005), while SWW and STF shifted to lower latitudes (*Fig. 2*). *Baldwin* and *Dunkerton* (2001) emphasize that the vortex ring around the South Pole (AAO) is wider and stronger than above the North Pole (AO). This is explained by the fact that there are large land masses in the Northern Hemisphere, which do not allow the polar air ring to expand and strengthen as in the Antarctic region.

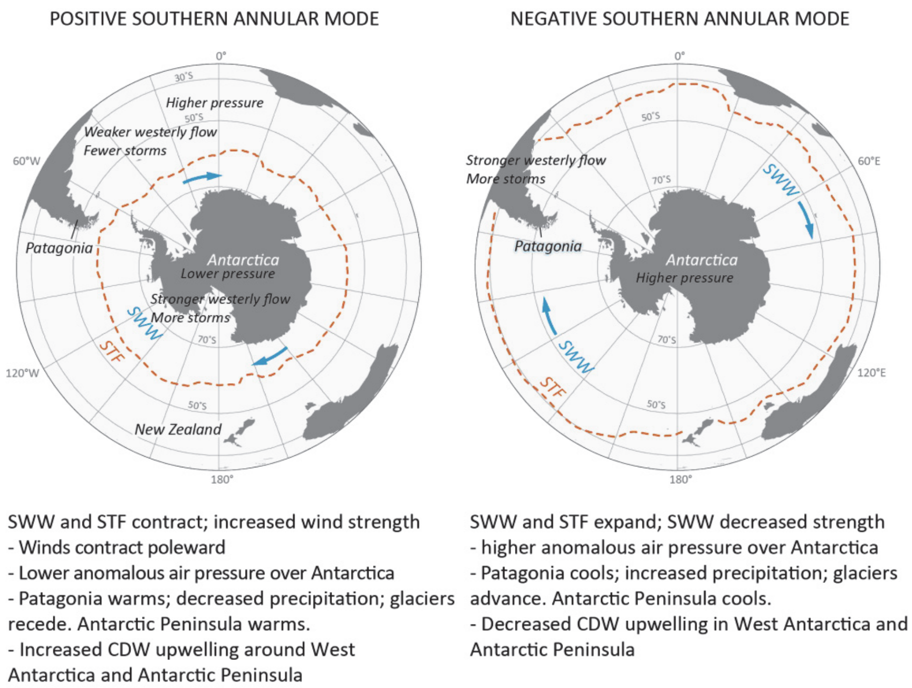

Fig. 2. Positive and negative phase of the Southern Annular Mode (SAM) (https://www.antarcticglaciers.org/glaciers-and-climate/changing-antarctica/southern-annular-mode/).

2. Databases and methodology

Because there is no single index, many researchers use multiple indicators to diagnose ENSO events (*Charles et al.,* 1997; *Hasegawa* and *Hanawa,* 2003; *van Oldenborgh* and *Burgers,* 2005; *Bonham et al.,* 2009; *Alampay* and *dela Torre,* 2019). Data for water surface anomalies in the equatorial Pacific are available for 4 regions (*Fig. 3*), which are designated as: Ninjo 1+2 (0–10°S, 90°W–80°W), Ninjo 3 (5°N–5°S, 150°W–90°W), Ninjo 4 (5°N–5°S, 160°E–150°W), and Ninjo 3.4 (5°N–5°S, 170–120°W). Positive values of the SST–ENSO (sea surface temperature -ENSO) index indicate the occurrence of El Niño (higher water temperature), and negative deviations of this indicator indicate La Niña (lower water temperature in the equatorial part of the Pacific). Differences in water temperature in relation to the usual state cause changes in air oscillation (Southern Oscillation). Thus, this phenomenon is collectively called ENSO.

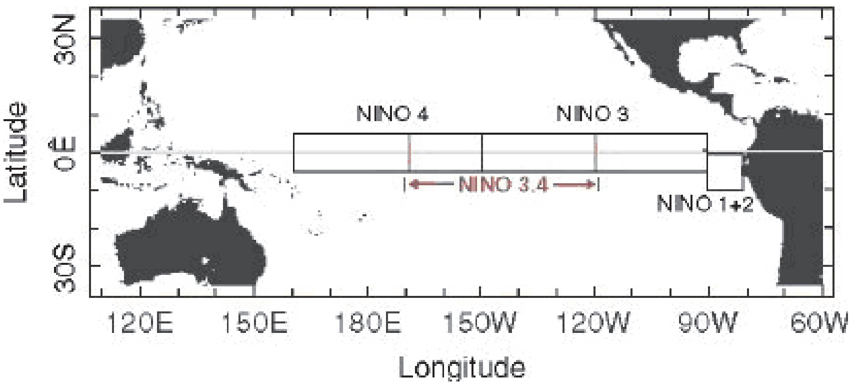

Fig. 3. Regions of the equatorial Pacific for wich SST-ENSO anomalies are monitored (*Zubair et al*., 2007).

There are several indices for AAO as well (*Garreaud et al.,* 2009; *Villalba et al.,* 2012; *Boisier et al.,* 2018). For example, one indicator of AAO variability is the change in ground pressure (*Gong* and *Wang,* 1999; *Marshall,* 2003). Other indices are related to the variations in geopotential heights of 850, 700, and 500 hPa. Based on data on geopotential altitudes, the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), at NOAA, using a special so–called rotating technology, calculated AAO indices in the range between 20°–90°S.

For the purposes of this paper, a Southern Hemisphere temperature database of the latest versions of HadCRUT5 and NASA–GISS was formed. For ENSO we used data from the Ninjo 3.4 region (otherwise the most frequently used index when it comes to this teleconnection), and for AAO we used the ground pressure variability index and the index of changes in geopotential altitudes of 850 and 700 hPa, as well as the SAM (SAMI) index which represents a modification of the AAO index. We also used data on atmospheric CO_2 concentration, the energy impact of greenhouse gases (GHG) in W/m^2 (radiation forcing), and the Annual Greenhouse Gas Index (AGGI) on temperature. AGGI was introduced by NOAA, and calculations have been performed since 1979 (*Hofmann et al.,* 2006).

Monthly AAO is defined as the difference in normalized monthly zonal mean sea level pressure (SLP) between 40°S and 70°S (*Nan* and *Li,* 2003), while SAM (Southern Annular Mode) is a modification of the AAO index defined by *Gong* and *Wang* (1999), as a difference in the normalized mean zonal SLP between 40°S i 65°S. Thus, the southern dipole at SAMI is somewhat more to the north compared to AAO. *Table 1* contains lists and sources of data used.

Table 1. Lists and data sources for the variables used

Variable	Source	Unit	Period
HadCRUT5	https://crudata.uea.ac.uk/cru/data/temperature/#datdow	°C	1901–2021
NASA–GISS	https://data.giss.nasa.gov/gistemp/graphs_v4/	°C	1901–2021
CO_2	https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt	ppm	1959–2021
CO_2, CH_4, N_2O, CFCs (AGGI)	https://gml.noaa.gov/aggi/aggi.html	W/m^2	1979–2020
NINO3.4	https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/	°C	1901–2021
AAO–slp	https://psl.noaa.gov/data/20thC_Rean/timeseries/monthly/AAO/	hPa	1901–2012
AAO–850	http://research.jisao.washington.edu/data/aao/	gpm (geopotential)	1948–2002
AAO–700	https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml	gpm	1979–2021
SAM–slp	http://www.nerc-bas.ac.uk/public/icd/gjma/newsam.1957.2007.seas.txt	hPa	1957–2021

According to the recommendation of the World Meteorological Organization (*WMO,* 1966), as well as others (e.g., *Mondal et al.,* 2012), we used the nonparametric Sen method in order to calculate the trend, and its significance was tested by the Mann–Kendall test (*Mann,* 1945; *Kendall,* 1975; *Salmi et al.,* 2002). Significance of the trend was assessed at the risk level of 0.001, 0.01, 0.05, and 0.1 (degree of hypothesis accuracy of 99.9, 99, 95, and 90%). The Pearson's correlation coefficient was calculated in order for the the relationship between the Southern Hemisphere temperature and ENSO, i.e., AAO (SAM) to be examined, while statistical significance was tested using a student test at the hypothesis level of 95% ($p<0.05$) and 99% ($p<0.01$). Estimates of the considered variables were made on annual and seasonal levels.

3. Results

3.1. Southern Hemisphere temperature trend

According to HadCRUT5 data, the results of trend calculations indicate that in the previous 121 years (1901–2021), the mean temperature in the Southern Hemisphere increased, both annually and seasonally (*Fig. 4*). Trend values are uniform and range from 0.08–0.09 °C/decade. Both annual and seasonal values show a statistically significant trend of increasing temperature at the risk level of $p<0.001$ (the highest degree of accuracy of the hypothesis of 99.9%). The trend is also calculated for the period from 1951 to 2021 and the same qualitative results were obtained, but there is a greater trend of increasing temperature (0.11–0.12 °C/decade). In other words, the temperature in the Southern Hemisphere has been increasing more intensely since the middle of the 20th century, but the increase in temperature of the Northern Hemisphere is still larger (about 0.19 °C/decade).

For the NASA–GISS network, we had only the average annual temperatures for the Southern Hemisphere. This network shows that in the period from 1901 to 2021, the trend of annual temperature in the Southern Hemisphere was 0.09 °C/decade, while for the period 1951–2021, the trend is slightly higher (0.12 °C/decade) compared to the HadCRUT5 database. The NASA–GISS database gives temperature anomalies for certain belts, which we found very interesting for analysis. Namely, according to climate models, one of the most indicative indicators of global warming should be the polar amplification (more intense warming at the poles compared to the rest of the planet). In other words, as many authors point out (e.g., *Budyko,* 1969; *Sellers,* 1969; *Holland* and *Bitz,* 2003; *Taylor et al.,* 2013; *Lee,* 2014; *Cvijanovic* and *Caldeira*, 2015; *Oldfield,* 2016; *Stuecker et al.,* 2018), in the conditions of increasing GHG concentration, the ground temperature should increase more intensively going from the equator to the poles.

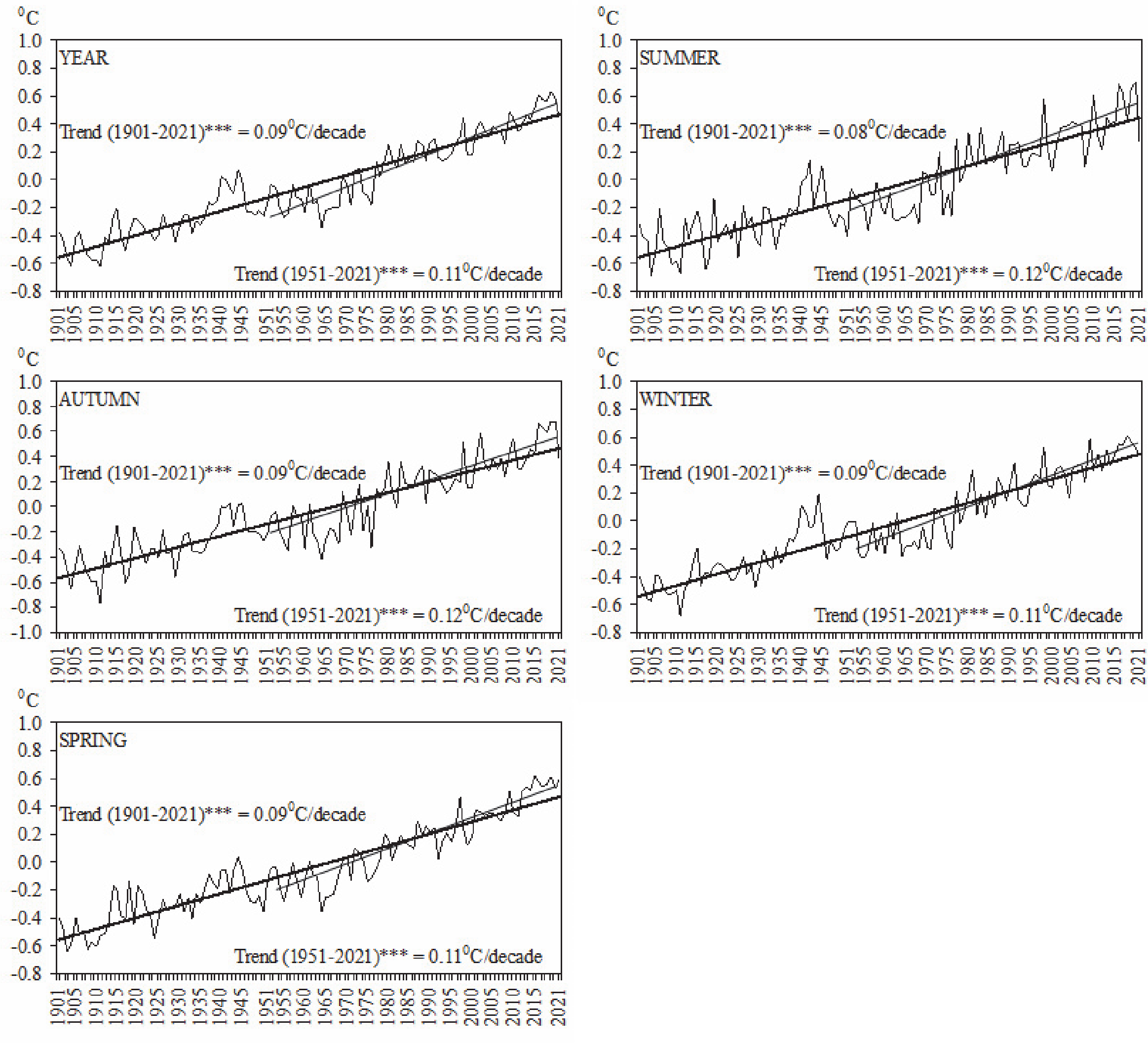

Fig. 4. The trend of seasonal and annual temperatures in the Southern Hemisphere in the periods 1901–2021 and 1951–2021 (***Significant trend: $p<0.001$).

To test this, a trend was calculated for four belts in the Southern Hemisphere: 0°–24°S, 24°S–44°S, 44°S–64°S, and 64°S–90°S. In all four belts, the temperature trend is positive and statistically significant at the highest level of hypothesis acceptance ($p<0.001$), both in the period 1901–2021 and 1951–2021. However, in the most temperate latitudes (44°S–64°S) temperatures rise more slowly than in the tropics. Moreover, in the period 1951–2021, there was a slightly more intense trend of temperature increase in the tropical (0.14 °C/decade) than in the polar (0.13 °C/decade) latitudes. This was unexpected taking into consideration the models of dominance of anthropogenic greenhouse effect, i.e., the opposite should be expected. Interestingly, in this belt (44–64°S), the positive trend in the period 1951–2021 (0.06 °C/decade) even decreased compared to the period 1901–2021 (0.07 °C/decade). We conclude that the polar amplification does not work in the Southern Hemisphere. On the other hand, in the Northern Hemisphere, polar amplification exists, because the trend of increasing annual temperature is more intense going from the equator to the Arctic. The results further showed that in the period between 1951 and 2021, temperate and polar latitudes heat up significantly faster in the Northern Hemisphere than in the Southern Hemisphere (*Fig. 5*).

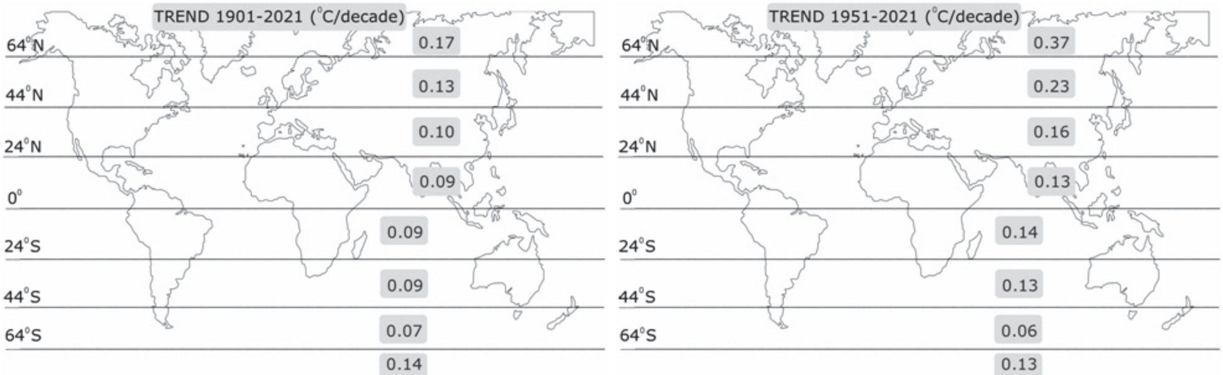

Fig. 5. Trend of average annual temperature on the planet by belts in the periods 1901–2021 and 1951–2021.

3.2. Possible causes of rising temperatures in the Southern Hemisphere

It could be said that there is a scientific consensus that the dominant cause of the rise in temperature is the increased atmospheric concentration of greenhouse gases (GHG). In this regard, the correlation between the Southern Hemisphere temperature and CO_2 concentration was examined. Data from the Mauna Loa station for 1958 are not complete, thus the correlation for the period between 1959 and 2021 was calculated and coefficients from 0.83 (southern summer) to 0.93 (southern spring) were obtained. Annually, the correlation between the mean Southern Hemisphere temperature and CO_2 concentration (in ppm) is 0.92. Both annual and seasonal values of correlation coefficients meet the conditions of statistical significance at the highest level of hypothesis acceptance ($p<0.01$).

It was previously mentioned that higher temperature also means excess energy in the atmosphere, which is a consequence of a very probable increase in the concentration of greenhouse gases. Beginning in 1979, NOAA used several empirical equations to calculate the atmospheric concentrations of greenhouse gases and the energy impact, and thus determined the radiation effect (in W/m^2) on air temperature (*Fig. 6*). Therefore, the available data for the period between 1979 and 2020 (*Table 2*) on the energy impact of CO_2, CH_4, N_2O, and several gases from the group of chlorofluorocarbon compounds (CFCs) was used. Based on the concentration of all gases, i.e., their energy impact, NOAA has defined an unique Annual Greenhouse Gas Index (AGGI).

For the period between 1979 and 2020, the relationship between the annual values of the Southern Hemisphere temperature and the energy impact of GHG is positive (direct correlations) and statistically significant at the highest level of hypothesis acceptance (on the 99% hypothesis level). The correlation coefficient between the radiation effect of annual CO_2 values (AGGI) and the Southern Hemisphere temperature is 0.87 (0.85). This is a result of the fact that with the growth of GHG, positive radiation forcing increases (*Table 3*).

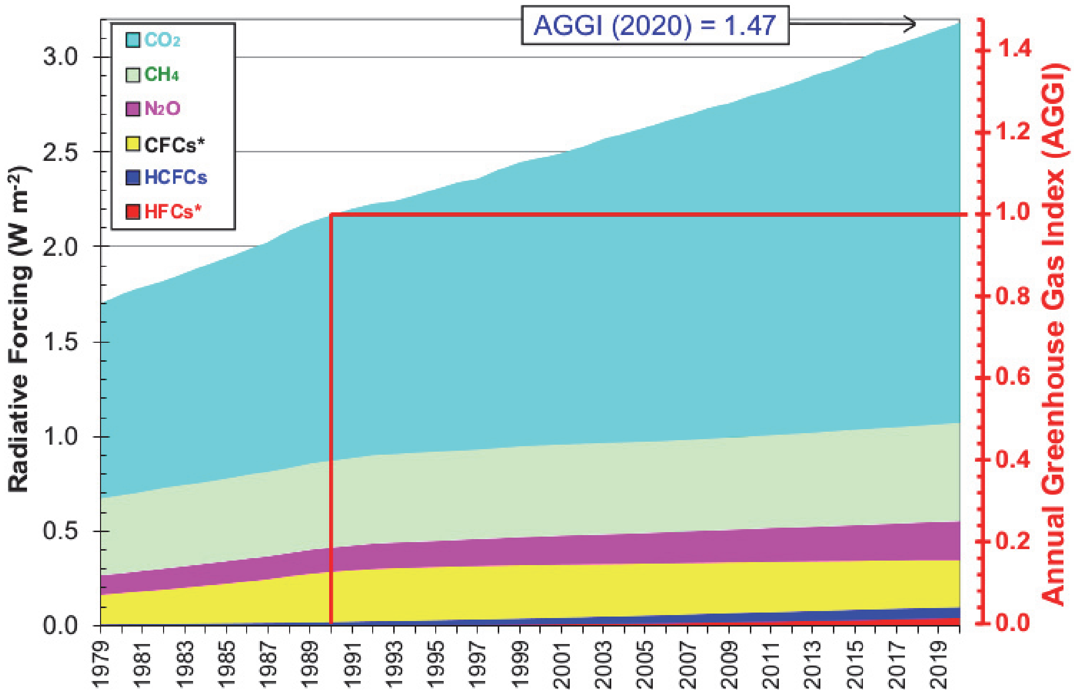

Fig. 6. Radiative forcing, relative to 1750, of virtually all long–lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis. The "CFC*" grouping includes some other long–lived gases that are not CFCs (e.g., CCl_4, CH_3CCl_3, and Halons), but the CFCs account for the majority (95% in 2020) of this radiative forcing. The "HCFC" grouping includes the three most abundant of these chemicals (HCFC–22, HCFC–141b, and HCFC–142b). The "HFC" grouping includes the most abundant HFCs (HFC–134a, HFC–23, HFC–125, HFC–143a, HFC–32, HFC–152a, HFC–227ea, and HFC–365mfc) and SF6 for completeness, although SF6 only accounted for a small fraction of the radiative forcing from this group in 2020 (13%). (Source: https://gml.noaa.gov/aggi/aggi.html)

Table 2. Annual global energy impact of GHG (W/m^2) and GHG index (AGGI) for the period 1979–2020

Year	CO_2	Others (CH_4, N_2O, CFC+ other)	Total (CO_2+ other)	AGGI (1990=1)	Year	CO_2	Others (CH_4, N_2O, CFC+ other)	Total (CO_2+ other)	AGGI (1990=1)
1979	1.03	0.67	1.70	0.79	2000	1.52	0.95	2.47	1.14
1980	1.06	0.69	1.75	0.81	2001	1.54	0.96	2.49	1.15
1981	1.08	0.71	1.79	0.83	2002	1.57	0.96	2.53	1.17
1982	1.09	0.73	1.82	0.84	2003	1.60	0.97	2.57	1.19
1983	1.12	0.74	1.86	0.86	2004	1.63	0.97	2.60	1.20
1984	1.14	0.76	1.90	0.88	2005	1.66	0.97	2.63	1.21
1985	1.16	0.78	1.94	0.90	2006	1.69	0.98	2.67	1.23
1986	1.19	0.80	1.98	0.92	2007	1.71	0.98	2.70	1.24
1987	1.21	0.81	2.03	0.94	2008	1.74	0.99	2.73	1.26
1988	1.25	0.84	2.09	0.96	2009	1.76	1.00	2.76	1.27
1989	1.28	0.86	2.13	0.98	2010	1.79	1.00	2.80	1.29
1990	1.29	0.87	2.17	1.00	2011	1.82	1.01	2.83	1.31
1991	1.31	0.89	2.20	1.02	2012	1.85	1.01	2.86	1.32
1992	1.33	0.90	2.23	1.03	2013	1.88	1.02	2.90	1.34
1993	1.34	0.91	2.24	1.04	2014	1.91	1.03	2.94	1.36
1994	1.36	0.91	2.27	1.05	2015	1.94	1.04	2.98	1.38
1995	1.39	0.92	2.30	1.06	2016	1.99	1.04	3.03	1.40
1996	1.41	0.93	2.34	1.08	2017	2.02	1.05	3.07	1.42
1997	1.43	0.93	2.36	1.09	2018	2.05	1.06	3.11	1.43
1998	1.47	0.94	2.41	1.11	2019	2.08	1.06	3.14	1.45
1999	1.50	0.95	2.45	1.13	2020	2.11	1.07	3.18	1.47

Table 3. Values of correlation coefficients between Southern Hemisphere temperature and greenhouse gases (GHG)

Period	GHG	Correlation coefficient				
		Year	Summer	Autumn	Winter	Spring
1959–2021	CO_2 (ppm)	0.92**	0.83**	0.85**	0.89**	0.93**
1979–2020	CO_2 (W/m^2)	0.87**	/	/	/	/
1979–2020	Others (CH_4, N_2O, CFC+other) inW/m^2	0.77**	/	/	/	/
1979–2020	Total (CO_2+others) inW/m^2	0.84**	/	/	/	/
1979–2020	AGGI	0.85**	/	/	/	/

Significant correlation: *$p < 0.05$, **$p < 0.01$

Previous results show that the anthropogenic greenhouse effect (AGE) undoubtedly has an impact on the Southern Hemisphere temperature as well as on a global scale (not shown). But, we believe that it is wrong to exclude the consideration of the influence of natural factors, primarily the variations of atmospheric and oceanic circulations. Therefore, the relationship between the temperature of the Southern Hemisphere and the indicators of variation of ENSO and AAO was examined in the following text.

When it comes to the ENSO phenomenon, the calculation results show that this phenomenon has an impact on the temperature of the Southern Hemisphere, statistically significantly during summer, autumn, and winter in the Southern Hemisphere, as well as annually. During the spring in the Southern Hemisphere, ENSO has no statistically significant impact (correlation is 0.16).

We used several indicators (indexes) for the variability of the Antarctic Oscillation (AAO and SAM). The ground temperature depends on the structure of the atmosphere at sea level and 850 hPa altitude, while events at 700 hPa altitude do not have a dominant impact, in general. Correlation calculations have confirmed this. Namely, the correlation between the AAO–700 hPa index and the Southern Hemisphere temperature is statistically insignificant. On the other hand, the correlation of annual values of SAM–slp, AAO–slp, and AAO–850 with the Southern Hemisphere temperature is 0.46, 0.66, and 0.69, and is statistically significant at 99% of the hypothesis acceptance level ($p < 0.01$). At the seasonal level, it is noticed that the influence of AAO–slp, SAM–slp, and AAO–850 on the temperature is strongest during the winter and spring in the Southern Hemisphere (*Table 4*).

Table 4. Values of correlation coefficients between the Southern Hemisphere temperature and ENSO and AAO

Period	**Teleconnection**	**Corelation coefficient**				
		Year	**Summer**	**Autumn**	**Winter**	**Spring**
1901–2021	ENSO3.4	0.19*	0.27**	0.32**	0.19*	0.16
1957–2021	SAM–slp	0.46**	0.20	0.10	0.47**	0.38**
1901–2012	AAO–slp	0.66**	0.31**	0.40**	0.46**	0.48**
1948–2002	AAO–850	0.69**	0.37**	0.44**	0.47**	0.47**
1979–2021	AAO–700	0.21	–0.19	–0.03	–0.14	0.03

Significant correlation: *$p < 0.05$, **$p < 0.01$

4. Discussion

Analyzing the global annual temperature for the entire observed period (1901–2021) using both datasets (HadCRUT5 and NASA–GISS) shows the dominance of negative deviations until 1976, while since 1977, each year has been warmer than the base period. This is in line with the IPCC and WMO reports. Namely, the IPCC in the Third Report (IPCC, 2001) pointed out that in the 20th century most of the warming took place during two periods: 1910–1945 and 1976–2000, while the period from 1945 to 1975 registers the cessation of global warming. According to the IPCC, natural factors (primarily changes in solar radiation and volcanic activity) can be attributed to the observed warming in the first half of the 20th century, while the rise in temperature in the last five decades is attributed to human activities (primarily to fossil fuel combustion).

In the period of positive anomalies, it is interesting to see the period 1977–2021, during which decade (10-year-long period) the trend was the lowest, and during which it was the highest, because the Sena method and Mann-Kendall test are not recommended for series shorter than 10 parameters. If there is an intensification of warming, then it is to be expected that the value of the positive trend is the lowest in the first, and the highest in the last 10-year-long period. However, according to the HadCRUT5 database, the budget results showed that the positive trend had the greatest value in the decade from 2008 to 2017 and from 2011 to 2020. In both periods the trend is the same (0.42 °C/decade) and statistically significant at the highest level of hypothesis acceptance (at 99.9% significance level). On the other hand, the lowest value of the trend (which was statistically insignificant) was registered in the first decade, which was to be expected. But the trend in the first 10-year-long period (1977–1986) was not positive but negative (–0.01 °C/decade), which was not to be expected. All other 10-year-long periods, with a shift of one year (1978–1987, 1979–1988, ... 2012–2021) register a positive trend.

Thus, in the 1977–1986 subperiod the trend of global temperature is insignificantly negative, and it received a positive sign as early as the following year (1987) maintained until the end of the period (1977–1987, 1977–1988, ..., 1977–2021). The significance of the positive trend was obtained from the time series: 1977–1990 and further (1977–1990, 1977–1991, 1977–1992, ...). According to the above mentioned facts, it could be concluded that in the period from 1977 to 1990 there was a slowdown in global temperature rise. This slowdown or so-called t cessation of global warming is also observed in the 1987–1996 subperiod, when the trend was insignificant: 0.026 °C/decade. Also, in the 1980–1989 subperiod, a slowdown in global warming was recorded as well, and the positive trend was insignificant until 1994 (1980–1994). *Xie* and *Kosaka* (2017) note the cessation of global warming in the 1998–2013 subperiod, although our estimates do not confirm this. It is a known fact that in 1997 and 1998, an extremely strong El Niño event took place, and that this phenomenon was even stronger in 2015 and 2016. Thus, the mentioned authors explain the slowdown in global warming in the mentioned period using variations in the surface temperature of water in the tropical Pacific. The authors point out that the tropical Pacific effect of slowing global temperature rise has a stronger impact on the decadal than interannual variability.

Our analyses also show that the mentioned "pauses" in the increase in global temperature were registered after stronger ENSO phenomena (after 1977, 1987). 2016 was rated as the warmest on our planet in the period of instrumental measurements, and the strongest ENSO phenomena happened in 2015 and 2016. The slowdown in the rise in mean annual temperature is more pronounced in the Southern Hemisphere. For example, in the period from 1977 and 1996 (20 years) and in the period from 1998 and 2013 (16 years), the positive trend is insignificant (*Fig. 7*). Moreover, during the 10-year-long period of 1987–1996, there was a slight cooling in the Southern Hemisphere (–0.07 °C/decade).

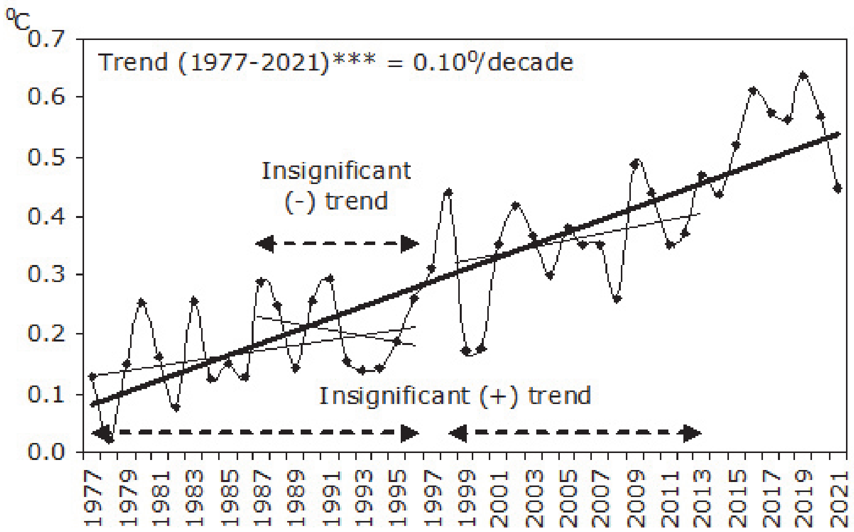

Fig. 7. The trend of the average annual temperature in the Southern Hemisphere in the period of constant positive deviations (1977–2021) (***Significant trend: p<0.001).

When observing the entire period of the 20th and the past years of the 21st century (1901–2021), the trend of rising global temperature, as in the Southern Hemisphere, is statistically significant, and the prevailing opinion is that it is caused by human activities. There were sub–periods of slowing (interruption) of global (hemispheric) warming during this period and this is mentioned in several papers (eg: *Kosaka* and *Xie*, 2013; *Chen* and *Tung*, 2014; *England et al*., 2014; *Amaya et al*., 2015; *Xie* and *Kosaka*, 2017). Our analysis confirms the interruptions in temperature rise (global and in the southern hemisphere) and shows that even in the period with constant positive deviations (1977–2021), there were shorter subperiods with mild cooling. The intention is not to open a debate on the validity of the theory of the dominance of the anthropogenic greenhouse effect, but to point out that there were shorter and longer subperiods when natural factors had a dominant influence on temperature. This study shows the impact of some of them (ENSO, AAO), with the aim of emphasizing the need to consider variations of natural factors in the era of modern climate change, in addition to anthropogenic impact. Of course, the impact of the so-called feedback effect, i.e., the fact that changes in one factor in the climate system are reflected in variations in other components of the system, should be taken into consideration.

5. Conclusion

The main goal of this paper was to determine the magnitude and significance of the trend of mean seasonal and annual temperatures in the Southern Hemisphere and to examine the relationship with the GHG radiation exposure and ENSO and AAO teleconnections. The period between 1901 and 2021 and the subperiod between 1951 and 2021 are considered. According to the HadCRUT5 database, the calculation results showed that there was a significant increase in seasonal and annual temperatures in the Southern Hemisphere, and that it got intensified in the period between 1951 and 2021 (0.11–0.12 °C/decade) more than in the entire observed period, from 1901 to 2021 (0.08–0.09 °C/decade). In order to check the polar amplification in the Southern Hemisphere, using the NASA–GISS database, the annual temperature trend was calculated separately for four belts: 0°–24°S, 24°S–44°S, 44°S–64°S, and 64°S–90°S. The results showed that polar amplification did not function in the Southern Hemisphere, which was not in line with the models of dominance of the anthropogenic greenhouse effect.

Taking the considered factors into consideration, it was determined that GHG concentration indicators had the strongest interactive connection with the Southern Hemisphere temperature. For example, for the period between 1959 and 2021, the correlation coefficients between CO_2 concentration (in ppm) and Southern Hemisphere temperature range from 0.83 (southern summer) to 0.93 (southern spring). It was further determined that a significant positive radiation forcing (in W/m^2) of GHG (CO_2, CH_4, N_2O, CFCs, and AGGI) was exerted to the Southern Hemisphere temperature. There was a positive correlation between ENSO and the temperature of the Southern Hemisphere, and it was significant during the southern summer, autumn, and winter, as well as on annual basis. Variations in the structure of the atmosphere at the sea level and the altitude of 850 hPa, shown via the AAO and SAM index indicated, that this oscillation had a significant impact on the temperature of the Southern Hemisphere. Thus, it would not be superfluous to repeat that today's civilization should do everything not to contribute further to pollution of the GHG in the atmosphere and warming of our planet, but in order to understand modern climate change, it is necessary to consider natural factors, such as variations in atmospheric oscillations.

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