Review

Geology

Global Mean Surface Temperature

What Can We Learn from the Trajectory over a Millions-year Span?

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Global mean surface temperature serves as a crucial metric in understanding the Earth's climate dynamics, providing insights into long-term climate trends and variability. Over the course of a million years, the trajectory of global temperatures has been shaped by a multitude of factors, including natural climatic cycles, human activities, and external influences. By examining the historical trends and drivers influencing global mean surface temperature, researchers can gain valuable insights into the past, present, and future climate scenarios. This article delves into the intricate interplay of these factors and explores the lessons we can learn from studying the temperature trajectory over a million-year span.

Keywords: Global Mean Surface Temperature; Climate Dynamics; Influencing Factors; Historic Trajectory

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Introduction

SIGNIFICANT climate changes and environmental impacts have been the consequence of the significant variation in the global mean surface temperature over the course of millions of years (Clark et al., 2024; Parmesan & Yohe, 2003). The Earth's temperature has fluctuated as a result of natural factors, including continental drift, solar radiation, and volcanic eruptions, etc. (Zachos et al., 2001). Throughout the history of the Earth, there have been periods of extreme cold and ice ages, as well as periods of global warming and warmth (Jones & Mann, 2004; Tickell, 1993). These temperature fluctuations have had a significant impact on biodiversity and ecosystems.

The Pleistocene Ice Age, which occurred approximately 2.6 million to 11,700 years ago, is one of the most well-known periods of global decline (Elderfield et al., 2012; Ehlers & Gibbard, 2006; Ferrusquá-Villafranca et al., 2017). During this period, the Earth's surface was largely covered by glaciers, which resulted in a decrease in sea levels and the formation of substantial ice sheets in North America and Eurasia. The climate and landscape of the Earth were significantly altered during the Ice Age, as the average global temperature was several degrees lower than it is today (CLIMAP Project Members, 1976; Rapp, 2012).

Conversely, there have been instances of global warming throughout the earth's history. The Paleocene-Eocene Thermal

Maximum, which occurred approximately 55 million years ago, was one of the most significant warming periods (Robinson et al., 2008; Winguth, 2011). During this span of a few thousand years, the earth's temperature increased by 5-8 degrees Celsius. The pervasive extinction of plankton and other sea creatures was a significant consequence of this rapid warming event for marine life (Gibbs et al., 2006; Pielou, 2008). During this period, it is widely believed that the emission of substantial quantities of greenhouse gases, including carbon dioxide and methane, was a significant factor in global warming (Zachos et al., 2005).

Human activities, particularly the combustion of fossil fuels and deforestation, are frequently blamed for the recent global warming trend that commenced in the late 19th century (Denman et al., 2007; Keeling, 1997). The past few decades have been the highest on record, because of the rise in global temperatures caused by the increase in greenhouse gas emissions (Karl & Trenberth, 2003; Oloyede et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) has issued a warning that the planet could face catastrophic repercussions as a result of continued warming (Stern, 2022). These consequences include increasing sea levels, more frequent extreme weather events, and threats to food security.

It is crucial to bear in mind that the earth's temperature has always been subject to natural fluctuations, despite the present warming trend. In the long term, the Earth's climate will be impacted by a multifaceted interplay of factors, such as volcanic activity, solar radiation, and ocean currents, etc. By comprehending the GMST over a million-year period, we can gain a better understanding of the current state of the climate and devise strategies to reduce their effects on society and the environment. Scientists can develop a more precise understanding of the Earth's climate system and make more accurate predictions about future climate trends by examining past climate fluctuations.

Significance of Studying Long-Term Temperature Trends

The global mean surface temperature (GMST) over millions of years is a subject of considerable interest to scientists and researchers who are studying climate change (Bunde et al., 2021; Judd et al., 2024; Lunt et al., 2013). This long-term temperature record offers valuable insights into the Earth's past climate conditions, aids in the comprehension of the natural variability of the climate system and illuminates the factors that drive global warming and cooling trends.

By studying GMST, we can gain an understanding of the Earth's natural climate variability and can recognize patterns and cycles in the Earth's climate system by examining the temperature trends over such a long period (Mann et al., 1998; Mann et al., 2000). This information can be beneficial for predicting future climate changes and comprehending the factors that influence them.

Furthermore, we can gain a more comprehensive understanding of the mechanisms that drive natural climate change by examining the GMST over millions of years (Mann, 2006). For instance, scientists can investigate the extent to which the Earth's temperature has been affected by variations in solar radiation, volcanic activity, greenhouse gas concentrations, and other factors over time. This information has the potential to enhance the accuracy of climate models and future temperature predictions.

The long-term temperature record can offer a comprehensive understanding of the effects of human activities on the Earth's climate system. Scientists can evaluate the extent to which human activities, including deforestation and the combustion of fossil fuels, are contributing to global warming by comparing current temperature trends to historical data (Baswald et al., 2002; Karl & Trenberth, 2003). This information is essential for the development of effective strategies to acclimate to the impacts of climate change and mitigate its effects. The GMST over millions of years is also a critical factor in comprehending the Earth's geological history (Kaufman et al., 2020). Sea level, the growth and disintegration of ice sheets, and the distribution of plant and animal species can all be influenced by temperature fluctuations. Scientists could gain a more comprehensive understanding of the impact of these changes on the Earth's biodiversity and landscape by examining historical temperature trends (Alley et al., 2003; Lunt et al., 2013). Additionally, the GMST can offer valuable insights into the Earth's climate sensitivity. This pertains to the manner in which the Earth's temperature adjusts in response to fluctuations in solar radiation, greenhouse gas concentrations, and other variables (Mann et al., 2000; Ribes et al., 2021). Scientists can enhance their predictions of future temperature changes and obtain a deeper understanding of the Earth's climate sensitivity by examining long-term temperature trends.

Examining the GMST over millions of years can assist researchers in gaining an understanding of the role of feedback mechanisms in the Earth's climate system (Friedrich & Timmermann, 2019). The Earth's temperature can be further warmed or cooled because of feedback mechanisms that can either amplify or mitigate the effects of changes in greenhouse gas concentrations (Schwartz, 2018; Wolff et al., 2015). By examining historical temperature trends, scientists determine the extent to which feedback mechanisms have contributed to past climate changes and enhance our comprehension of their potential influence on future climate change (Andrews et al., 2018; "Understanding Earth's Deep Past: Lessons for Our Climate Future", 2012; Zickfeld et al., 2009).

Furthermore, it can offer critical insights into the Earth's carbon cycle. The absorption and release of carbon dioxide from the atmosphere, oceans, and biosphere can be influenced by fluctuations in temperature (Sellers et al., 2018; Wong et al., 2021). The comprehension of the factors that drive carbon cycling could be enhanced by examining past temperature trends, which provide them with insights into how the Earth's carbon cycle has responded to temperature fluctuation (Dunstan et al., 2018; Sabine & Feely, 2007; Xu et al., 2021). Besides, studying GMST can also offer valuable insights into the effects of climate change on human societies (Mills et al., 2018). Agricultural productivity, water resources, extreme weather events, and the transmission of infectious diseases can all be affected by temperature fluctuations (Zhang et al., 2020). By examining historical temperature trends, scientists can gain a more comprehensive understanding of the ways in which climate change has impacted human societies in the past and develop more effective strategies for adapting to its effects in the future (McMichael, 2012; Xu et al., 2020).

Therefore, it is imperative to investigate the GMST over the course of millions of years to understand the intricacies of the Earth's climate system. Valuable insights into the Earth's past climate variability, the mechanisms that drive climate change, and the environmental effects of human activities are provided by this long-term temperature record. Scientists can enhance climate models, anticipate future temperature fluctuations, and devise strategies to adapt and mitigate climate change by comprehending historical temperature trends.

Historical Climate Trends and Variability

For many years, scientists have been deeply interested in and concerned about climate trends and variability. Historical climate data offers valuable insights into the Earth's climate system and its evolution over time. Researchers can gain a more comprehensive understanding of the causes and effects of climate change and variability by examining historical climate patterns.

The examination of temperature records is one of the primary factors in the analysis of historical climate trends and variability (Jones, 2002). Valuable information regarding past temperature patterns is obtained from a variety of sources, including temperature readings, ice cores, and tree rings. Scientists detected long-term trends and temperature fluctuations, such as the warming trend that has been observed in recent decades, by examining this data (Mann & Jones, 2003; Mann et al., 2008; Scotese et al., 2021).

The examination of precipitation patterns is an additional critical component of historical climate trends. Ecosystems, agriculture, and water resources may be significantly affected by fluctuations in precipitation levels (Chu et al., 2015; Lausier & Jain, 2018; Sayemuzzaman & Jha, 2013). Researchers ascertained the extent to which rainfall and snowfall patterns have evolved over time and how these changes may be associated with factors such as global warming and natural climate variability by analyzing historical precipitation data (King et al., 2024; Liu et al., 2015; Takahashi, 2024).

The scarcity of long-term data is one of the obstacles to investigating historical climate trends. It is frequently challenging to accurately evaluate long-term trends since climate data only extends back a few decades or less (Sun et al., 2018; Wang et al., 2007). Nevertheless, researchers have devised innovative approaches to reconstructing past climate conditions, including the use of proxy data from sources such as tree rings, ice cores, and sediment layers (Holbourn et al., 2024; Li et al., 2010; Mann, 2002).

The recognition that climate variability is a natural component of the Earth's climate system is a critical lesson to be learned from the examination of historical climate trends (Barboza et al., 2014; Jones & Mann, 2004; Mann, 2006). The climate has consistently been subject to fluctuations in temperature, precipitation, and other variables, which have been influenced by a variety of factors, such as solar activity, volcanic eruptions, and natural variations in the Earth's orbit (Holbourn et al., 2024; Willett, 1949).

Nevertheless, in the past few decades, human activities have emerged as a significant contributor to climate change. Global warming and other changes in the climate system have been induced by the increased levels of greenhouse gases in the atmosphere, which have been caused by the combustion of fossil fuels, deforestation, and other activities (Folberth et al., 2014; Gilruth et al., 2021; Hasyimi & Azizalrahman, 2018; Karl & Trenberth, 2003). Consequently, the Earth is currently undergoing rapid and unprecedented climate changes, which have the potential to have catastrophic effects on human well-being, economies, and ecosystems (Carraro, 2016; Kemp et al., 2022; Ripple et al., 2019).

It is pivotal to comprehend historical climate trends and variability to anticipate future climate changes and devise effective strategies for mitigating their effects. Researchers evaluated the potential hazards and opportunities associated with future climate scenarios and identify key drivers of climate change by examining past climate patterns (Anandhi & Bentley, 2018; Collins et al., 2012; Ebi et al., 2013; Hulme et al., 1999; Lawrence et al., 2021). This information has the potential to influence policy decisions and assist societies in adjusting to the challenges posed by a changing climate.

In short, historical climate trends and variability offer valuable insights into the Earth's climate system and its evolution over time. Researchers can develop strategies for adapting to a changing climate, evaluate the risks and opportunities associated with future climate scenarios, and gain a more comprehensive understanding of the drivers of climate change and variability by analyzing past climate data. To confront the obstacles of climate change and guarantee a sustainable and resilient future for the planet, it is imperative to conduct ongoing research and monitoring of historical climate trends.

Factors Influencing GMST

The GMST is a critical metric that is employed to quantify the Earth's climate and is a critical factor in the comprehension of climate change. GMST is influenced by a variety of factors, such as human activities and natural processes.

Solar radiation is an additional factor that affects the GMST (Bindoff et al., 2014; Zhang et al., 2012). Variations in the sun's output, as well as changes in the Earth's orbit and inclination, can significantly affect the quantity of solar radiation that reaches the Earth's surface (Solanki et al., 2013). Global temperatures may fluctuate over time as a result of these inherent variations in solar radiation.

Greenhouse gas emissions are one of the primary factors that influence the GMST (White, 1994). Carbon dioxide, methane, and nitrous oxide are greenhouse gases that capture heat in the Earth's atmosphere, resulting in an increase in global temperatures (Houghton, 2013; Keeling, 1997; Mastrandrea & Schneider, 2008). Burning fossil fuels and deforestation are among the human activities that have substantially increased the concentration of greenhouse gases in the atmosphere, thereby contributing to global warming (Gurjar et al., 2013; Ismail et al., 2020; Saklani & Khurana, 2019).

The Earth's surface albedo can be altered by land use changes, such as urbanization and deforestation, which can affect the GMST (Ghimire et al., 2014; Hibbard et al., 2017). The concentration of greenhouse gases in the atmosphere increases as a result of deforestation, which reduces the quantity of vegetation that can absorb carbon dioxide (Bala et al., 2007; Canadell et al., 2009; Deng et al., 2014). By substituting natural landscapes with heat-absorbing materials like asphalt and concrete, urbanization can also elevate surface temperatures (Kullberg & Feeley, 2023).

Another factor that affects the GMST is the melting of polar ice sheets and glaciers. The melting of ice reveals darker surfaces that absorb more heat, resulting in an additional increase in temperature (Garuma et al., 2018). This feedback cycle has the potential to accelerate the pace of climate change and contribute to the increase in global temperatures (Wunderling et al., 2020).

The GMST of the planet is significantly influenced by the Earth's orbit. The Earth's distance from the Sun can fluctuate throughout the year due to its elliptical orbit (Kostadinov & Gilb, 2014; Marsh, 2020). The Earth's temperature is influenced by the quantity of solar radiation it receives, which is influenced by this variation in distance (Pierrehumbert, 2010). The GMST is generally higher when the Earth is in closer proximity to the Sun, as it receives a greater amount of solar radiation (Wen et al., 2016). In contrast, the Earth experiences a decrease in GMST as it is situated farther from the Sun, as it receives less solar radiation (Kopp, 2016; Shindell et al., 2001; Zhang et al., 2012). The GMST is also influenced by the tilt of the Earth's axis, in addition to the variable distance from the Sun (Kopp, 2016; Marsh, 2020). The Earth's axis is inclined at an angle of approximately 23.5 degrees, which results in the planet experiencing seasons as it orbits the Sun (Linsenmeier et al., 2014a; Rönnelid, 2000). The hemisphere that is tilted toward the Sun experiences higher temperatures and more direct sunlight during the summer months, whereas the hemisphere that is tilted away from the Sun experiences cooler temperatures (Ahlers, 2016; Dobrovolskis, 2009; Dobrovolskis, 2014; Linsenmeier et al., 2014b). The GMST is influenced by this seasonal variation in temperature. In addition, the earth's orbital eccentricity, or the geometry of its orbit, is another significant factor that affects the GMST. The distance between the Earth and the Sun can fluctuate over time, as the Earth's orbit is not a perfect circle, but rather an ellipse (Ahlers, 2016; Cohen & Stanhill, 2015; Grotjahn, 2014; Oostra, 2015). Changes in orbital eccentricity are believed to be a contributing factor to the natural climate cycles, including the ice ages, and occur over extended periods of time (Lourens & Tuenter, 2009).

It has been recognized for a long time that volcanic eruptions have an effect on the GMST (Stothers, 1989). When a volcano erupts, it discharges substantial quantities of sulfur dioxide, ash, and other gases into the atmosphere (McGee et al., 1997). Volcanic winter is a cooling effect that results from the blockage of sunlight from reaching the Earth's surface by these particulates (Zielinski, 2002). Depending on the magnitude and intensity of the eruption, this temporary cooling may persist for months or even years. Nevertheless, not all volcanic eruptions induce a cooling effect. Carbon dioxide, a greenhouse gas that can contribute to global warming, is released in significant quantities during certain eruptions (Miles et al., 2004; Robock, 2000; Zanchettin, 2023). When these eruptions occur in conjunction with other natural or human-induced factors that are already causing warming, they can result in an increase in the GMST.

The GMST is significantly influenced by ocean currents, which are essential for the regulation of the Earth's climate (Yan et al., 2016). Water's movement across the globe facilitates the transfer of heat from the equator to the extremes, thereby regulating temperatures and distributing warmth across various regions (Dowling & Showman, 2007; Ferrari & Ferreira, 2011). For the purpose of preventing extreme temperature fluctuations and preserving a balanced climate, this process is indispensable. The phenomenon of thermohaline circulation is one of the primary ways in which ocean currents influence GMST (Wang et al., 2012; Wunsch, 2002). This process entails the movement of warm, salty water from the equator to the poles, where it cools and descends before returning to the equator. The thermohaline circulation aids in the regulation of temperatures in various regions of the world and the preservation of a relatively stable GMST by redistributing heat in this manner (Alley et al., 2003; Döös et al., 2012). Changes in GMST can result from disruptions to this circulation system, which can have a significant impact on climate patterns. In recent years, scientists have observed changes in ocean currents and their prospective impact on GMST (Seidov et al., 2019). For example, certain studies have hypothesized that the Gulf Stream's deterioration, a significant ocean current that transports warm water from the Gulf of Mexico to the North Atlantic, may be a factor in the reduction of temperatures in parts of Europe (McCarthy et al., 2018; Palter, 2015; Seager et al., 2002). Likewise, changes in the intensity and direction of other ocean currents can have both local and global effects on GMST, affecting the overall climate system, sea levels, and weather patterns (Seidov et al., 2019).

The El Niño-Southern Oscillation (ENSO) is a climatic pattern that affects the Pacific Ocean, resulting in modifications to atmospheric circulation patterns and sea surface temperatures ("Chapter 16: El Niño–Southern Oscillation," 2013; Latif & Keenlyside, 2008). The global weather patterns are significantly influenced by the two primary phases of ENSO: El Niño and La Niña (Rial et al., 2004; Scaife et al., 2019). The relationship between ENSO and GMST is of particular interest to scientists, as fluctuations in ENSO can have a significant impact on global climate (Niedzielski, 2014; Trenberth et al., 2002; Vecchi & Wittenberg, 2010). When an El Niño event occurs, the central and eastern Pacific Ocean's Sea surface temperatures exceed the average, resulting in altered atmospheric circulation patterns (Cai et al., 2014; Latif & Keenlyside, 2008). This may lead to precipitation increases in certain regions, such as the western coast of South America, and drought conditions in others, including Australia and Indonesia. These modifications in precipitation patterns can have a cascading effect on global weather systems, resulting in global temperature and precipitation patterns that are altered (Putnam & Broecker, 2017; Rivera & Arnould, 2020; Sanderson et al., 2011). El Niño's contribution to long-term warming trends is one of its most significant effects on GMST. While the duration of individual El Niño events may vary from a few months to a year, the elevated temperatures that accompany these events can contribute to the broader trend of increasing global temperatures (Cai et al., 2014; Yeh et al., 2009). This is because El Niño events discharge heat stored in the oceans into the atmosphere, which in turn contributes to an increase in the GMST. In contrast, La Niña events, which are distinguished by sea surface temperatures in the central and eastern Pacific Ocean that are lower than the average, can have the inverse impact on the GMST (Cai et al., 2019; Hwang et al., 2024; Liu et al., 2024; Loeb et al., 2020; Turkington et al., 2018). GMST may decrease because of the milder temperatures in the tropics that are frequently observed during La Niña phenomenon (Kohyama et al., 2017; Kosaka & Xie, 2013; Samset et al., 2023). Nevertheless, the overall warming trend associated with climate change typically outweighs the chilling effect of La Niña events.

Patterns of Temperature Fluctuations over a Million-Year Span

Over millions of years, Earth's temperature has undergone significant fluctuations in cycles of glacial (cold) and interglacial (warm) periods, characterized by a predominant cycle of approximately 100,000 years during which global temperatures oscillate by several degrees Celsius (Scotese et al., 2021; Zachos et al., 2001). This phenomenon is primarily influenced by alterations in Earth's orbital patterns and the consequent variations in solar radiation received by the planet. These temperature fluctuations are predominantly regulated by changes in atmospheric carbon dioxide concentrations, with elevated CO2 levels resulting in increased temperatures.

Ice Age Cycles

For millions of years, the climate history of Earth has been significantly influenced by the occurrence of ice age cycles. These cycles are the result of periodic fluctuations in the Earth's temperature and ice cover, which are influenced by variations in the Earth's orbit around the sun (Cooke, 2012; Muller & MacDonald, 1997). The Earth's climate and the landscapes we observe today have been significantly influenced by these cycles, which typically occur over tens of thousands of years.

During an ice age, the Earth's surface is significantly covered in ice and snow, resulting in a decrease in global temperatures and alterations in weather patterns (CLIMAP Project Members, 1976; Fu et al., 2024; Hays et al., 1976; Muller & MacDonald, 1997). The most recent ice age, which endured for several thousand years, took place approximately 20,000 years ago (McManus, 2004; Denton et al., 2010). During this period, the sea levels were substantially lower than they are today, and glaciers encircled a significant portion of North America, Europe, and Asia.

Throughout its history, the Earth's climate has undergone numerous ice age cycles, with periods of glaciation interspersed with milder interglacial periods (Clarke et al., 2003; Milliman & Emery, 1968; Rapp, 2012). The Earth's orbit and axial tilt are thought to be the driving forces behind these cycles, which can lead to fluctuations in the quantity of sunlight that reaches the Earth's surface (McGehee & Lehman, 2012; Paillard, 2006). The Earth's climate can be affected by these fluctuations in solar radiation, which can result in periods of warming and cooling (Woods et al., 2022; Raymo & Huybers, 2008).

It is essential to investigate the long-term trends in global temperature and climate change by examining the impact of ice age cycles on the Earth's climate. Scientists gained a more comprehensive understanding of the factors that influence the Earth's climate and predict how it may change in the future by examining past ice age cycles (Fahey et al., 2017; Falkowski et al., 2000). This is crucial for the development of effective strategies to safeguard the Earth's environment and mitigate the effects of climate change.

Warm periods and ice ages occur at regular intervals of hundreds of thousands to millions of years, which is one of the primary patterns observed in the climate history of Earth (Alley et al., 2003; Tickell, 1993). These patterns, which are referred to as Milankovitch cycles, are the result of changes in the axial inclination and orbit of the Earth, which influence the quantity of solar radiation that reaches the Earth's surface (Hinnov, 2005; Maslov, 2014; Park & Oglesby, 1991). By examining these cycles, we can gain a more comprehensive understanding of the factors that affect the Earth's climate and make more precise predictions about future climate changes.

Paleocene-Eocene Thermal Maximum

The Paleocene-Eocene Thermal Maximum (PETM) is a period that transpired approximately 55.5 million years ago (Nunes & Norris, 2006; Zachos et al., 2003). Global temperatures rose by as much as 5-8 degrees Celsius over a span of just a few thousand years during this time, as the Earth experienced a rapid and extreme warming event (Gibbs et al., 2006; McInerney & Wing, 2011; Winguth, 2011). The Earth's climate and ecosystems were significantly affected by this warming event, which persisted for approximately 200,000 years.

The PETM's rapid discharge of greenhouse gases into the atmosphere was one of its most remarkable characteristics (Bowen et al., 2014; Gibbs et al., 2006; Holbourn et al., 2024). The melting of methane hydrates, which are frozen deposits of methane gas located beneath the ocean floor, is suspected to have initiated this discharge (Cramer & Kent, 2005; Katz et al., 1999; Röhl et al., 2007; Storey et al., 2007). The melting of these methane hydrates resulted in the discharge of significant quantities of methane gas into the atmosphere, which in turn caused a significant rise in global temperatures and a significant increase in greenhouse gas concentrations (Guan & Lei, 2009; Collett et al., 2014; Sahling et al., 2014).

Another critical inquiry that scientists are currently endeavoring to resolve regarding the PETM is the initial cause of this significant warming event (Cramer & Kent, 2005; Jones et al., 2010). Some researchers contend that the abrupt increase in volcanic activity was the catalyst for the release of methane from the melting of hydrates (Frieling et al., 2016; Higgins & Schrag, 2006), while others propose that it may have been the result of a significant meteorite impact (Frieling et al., 2016; Jones et al., 2010). It is evident that the PETM is a dramatic illustration of the Earth's climate's ability to change swiftly in response to external forces, irrespective of the precise cause.

The PETM also offers significant insights into the potential consequences of future climate change. The rate of warming during the PETM event was significantly slower than the rapid increase in temperatures that we are currently witnessing because of human-induced greenhouse gas emissions, even though it occurred over millions of years (Foster et al., 2018; Röhl et al., 2007; Sluijs et al., 2014; Witkowski et al., 2024). This implies that the PETM may function as a cautionary tale regarding the potential repercussions of unrestrained climate change.

Conclusion

The examination of the GMST over a millions-year period offers valuable lessons for comprehending current climate change trends and provides critical insights into the Earth's climate fluctuations. Scientists can identify patterns, drivers, and potential inflection points in the Earth's climate system by analyzing past temperature trajectories. Over the course of millennia, historical records have demonstrated the impact of natural factors on global temperatures, including changes in solar radiation, volcanic activity, and ocean currents. Furthermore, researchers can distinguish between human-induced climate change and natural variability by examining long-term temperature trends. This information is essential for policymakers, as it facilitates the development of informed decisions regarding adaptation strategies and mitigation efforts to mitigate the effects of global warming. In conclusion, the examination of the GMST trajectory over millions of years contributes to our comprehension of the intricacies of Earth's climate system and emphasizes the necessity of addressing the anthropogenic effects on our environment.■

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