ADVANCES IN ATMOSPHERIC SCIENCES, 2024

• News & Views •

El Niño and the AMO Sparked the Astonishingly Large Margin of Warming in the Global Mean Surface Temperature in 2023

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(Received 14 December 2023; revised 25 December 2023; accepted 28 December 2023)

ABSTRACT

In 2023, the majority of the Earth witnessed its warmest boreal summer and autumn since 1850. Whether 2023 will indeed turn out to be the warmest year on record and what caused the astonishingly large margin of warming has become one of the hottest topics in the scientific community and is closely connected to the future development of human society. We analyzed the monthly varying global mean surface temperature (GMST) in 2023 and found that the globe, the land, and the oceans in 2023 all exhibit extraordinary warming, which is distinct from any previous year in recorded history. Based on the GMST statistical ensemble prediction model developed at the Institute of Atmospheric Physics, the GMST in 2023 is predicted to be 1.41°C ± 0.07°C, which will certainly surpass that in 2016 as the warmest year since 1850, and is approaching the 1.5°C global warming threshold. Compared to 2022, the GMST in 2023 will increase by 0.24°C, with 88% of the increment contributed by the annual variability as mostly affected by El Niño. Moreover, the multidecadal variability related to the Atlantic Multidecadal Oscillation (AMO) in 2023 also provided an important warming background for sparking the GMST rise. As a result, the GMST in 2023 is projected to be 1.15°C ± 0.07°C, with only a 0.02°C increment, if the effects of natural variability—including El Niño and the AMO—are eliminated and only the global warming trend is considered.

Key words: record-breaking temperature, global mean surface temperature, El Niño, AMO, global warming

Citation: Li, K. X., F. Zheng, J. Zhu, and Q.-C. Zeng, 2024: El Niño and the AMO sparked the astonishingly large margin of warming in the global mean surface temperature in 2023. *Adv. Atmos. Sci.*, https://doi.org/10.1007/s00376-023-3371-4.

1. Overview of extreme warming in 2023 and how it compares with the once-warmest year of 2016

In 2023, the globe experienced its warmest boreal summer and autumn, with extraordinary temperature anomalies ceaselessly occurring over both land and sea (https://berkeleyearth.org/opinion-i-study-climate-change-the-data-is-telling-us-something-new/). Shockingly high temperatures (https://news.cctv.cn/2023/12/02/ARTIQHydetRQQYsal2We09P5231202.shtml) and several climatic anomalies (https://wmo.int/media/news/it-was-hottest-june-record-unprecedented-north-atlantic-warmth-record-low-antarctic-sea-ice) were detected in lots of regions around the world. Based on these facts, the World Meteorological Organization emphasized that the global mean surface temperature (GMST) in 2023 is set to be the warmest year, surpassing the previously warmest year of 2016 (https://wmo.int/media/news/2023-shatters-climate-records-major-impacts). This draws the attention of the scientific community to explore what happened in 2023 and determine the cause of the record-breaking high GMST.

In this report, the monthly variations of GMST in 2023 are examined and compared with those in other years, particularly in 2016, which was the once-warmest year prior to 2023 (Fig. 1a). According to historical observations, anomalously warm GMSTs typically occur in boreal autumn and winter (October to March in the following year) (gray lines in Fig. 1a),

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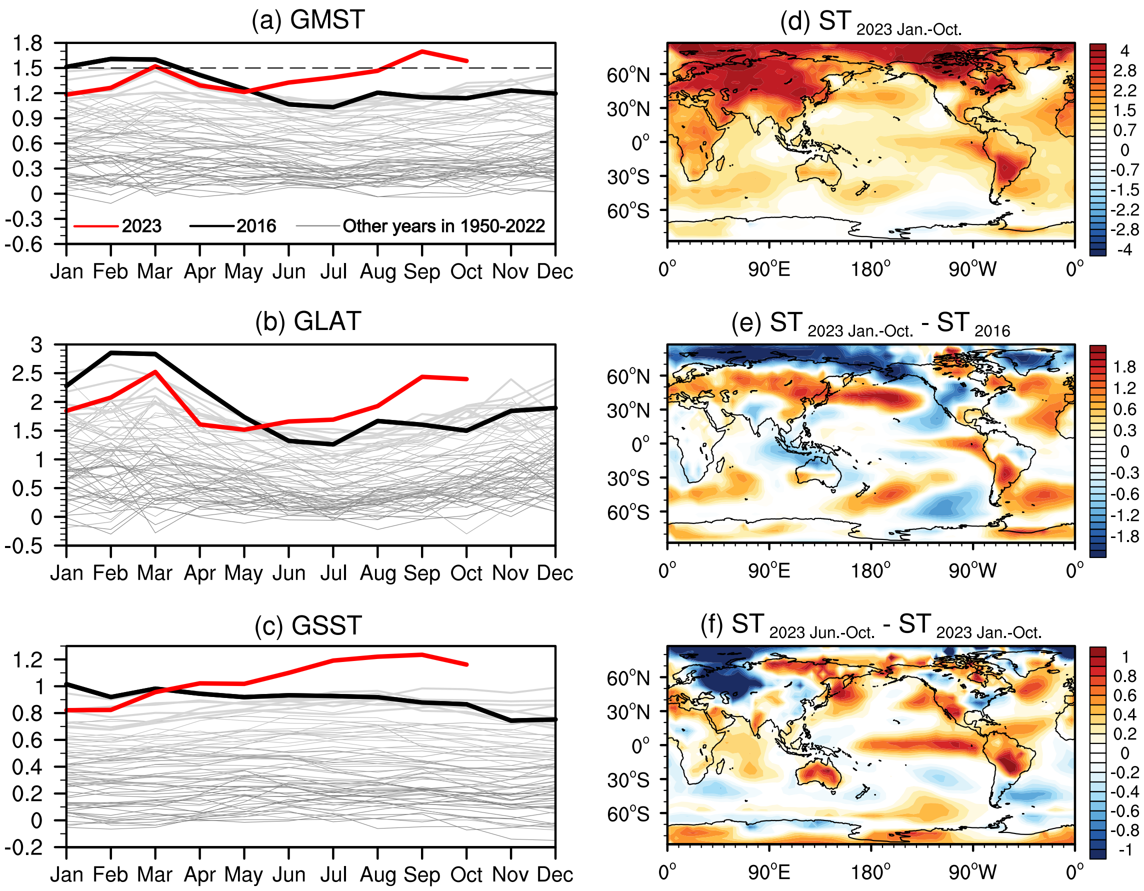

Fig. 1. The anomalies of (a) GMST, (b) GLAT, and (c) GSST above preindustrial levels during 1950–2023. The values of 2016 and 2023 are marked by the black line and red line, respectively. (d) The spatial distribution of mean surface temperature (ST) from January to October 2023. (e) The difference between the ST from January to October 2023 and the annual mean ST in 2016. (f) The difference between the ST from June to October 2023 and the ST from January to October 2023. The datasets used for the global surface temperature anomaly include HadCRUT5, NOAAGlobal-Temp5, and BEST (Rohde and Hausfather, 2020; Morice et al., 2021; Vose et al., 2021).

because the warming trend of surface temperature in boreal winter is more pronounced than that in boreal summer (Chapman and Walsh, 1993; Gong et al., 2006; Huang et al., 2012). The monthly changes of GMST in 2016 followed this characteristic (black line in Fig. 1a), whereas the changes in 2023 show a different trait (red line in Fig. 1a). From January to October 2023, the GMST peaked in March; then, following a small decline, it started to rise again in June and consistently set records dating back to 1850 (Table 1). The GMST in March, September, and October even exceeded 1.5°C above the pre-industrial 1850–1900 baseline.

Unique monthly variations of warming in 2023 were witnessed over land. Even if the global land surface air temperature (GLAT) from January to May 2023 did not reach the same level of warmth as in 2016, it soared and surpassed the 2016 GMST for five successive months from June 2023 (Fig. 1b). Nearly every continent experienced positive anomalies of global surface temperature from January to October 2023, with the mid-to-high latitudes in the Northern Hemisphere being the most affected (Fig. 1d). The unprecedent warm temperatures in summer and autumn 2023 boosted the occurrence of heat waves (Qian et al., 2024) that heated these areas and triggered severe climatic crises, which further induced severe wildfires and human deaths (Wang et al., 2024; https://bnn.network/world/the-year-of-the-heatwave-2023s-global-climate-crisis/).

Over the oceans, the monthly changes of global sea surface temperature (GSST) in 2023 also show unprecedented warming. In contrast to the cooling tendency of the GSST in 2016, the GSST in 2023 rose steadily from the beginning of the year, exceeded the 2016 GSST in April, and reached more than 1.2°C in July (Fig. 1c). The GSST directly increased by 0.3°C within the first eight months of this year, compared to only an approximate 0.9°C growth for the 173 years during 1850–2022. Anomalously warm waters were mainly located in the tropical Pacific, northern Pacific, and northern Atlantic. In the tropical Pacific, an eastern Pacific–type El Niño formed in June and quickly developed into a medium–strong event around October (Fig. 1f; Li et al., 2023; Zheng et al., 2023), making the eastern equatorial Pacific warmer than normal. The warm blob over the northern Pacific, formed in May 2023, gradually spread westward and became stronger, possibly because of the local heat budget or teleconnections associated with the North Pacific Oscillation and tropical Northern Hemisphere pattern (Liang et al., 2017; Tseng et al., 2017; Shi et al., 2022; Chen et al., 2023). At the same time, the positive phase of the Atlantic Multidecadal Oscillation (AMO) was also making the Northern Atlantic surface warmer than in 2016 (Li et al., 2024), and contributed significantly to the high GSST in 2023 relative to the anomalously cold SST over the same region in 2016.

Therefore, the unusual warmings of GMST, GLAT, and GSST in 2023 are crucial because these phenomena have rarely happened since 1850 (https://www.nature.com/articles/d41586-023-03775-z). Whether the GMST in 2023 will turn out to be the warmest, and what caused the year's unique warming signals, need to be determined.

2. GMST in 2023 is predicted to be approaching the 1.5°C global warming threshold

In order to obtain complete information for 2023 in advance and answer the question of whether the GMST in 2023 will set a new record, we used the GMST statistical ensemble prediction model developed at the Institute of Atmospheric Physics (IAP) to predict the 2023 GMST (Zheng et al., 2023). As illustrated by the forecasted result started from November, the annual GMST in 2023 is predicted to be 1.41°C ± 0.07°C higher than that during 1850–1900 (red dot and error bars in Fig. 2a), indicating that 2023 will undoubtedly be the warmest year (100% chance) since 1850. The predicted GMST in 2023 surpasses that in 2022 by 0.24°C (Table 2)—an astonishingly large margin of warming—and will beat the once-warmest year of 2016 by about 0.12°C. Significant warming of nearly 4°C is expected to be located in Eurasia, America, and the Arctic in 2023 (not shown). In the tropical Pacific and northern Pacific, the SST anomaly is about 1.5°C to 2.5°C, while in the areas around the Amundsen Sea and Ross Sea, the sea surface is going to be colder than the baseline temperature during 1850–1900.

Taking into account the uncertainties resulting from data measurement, climate noises, and prediction methods, the upper limit of the forecasted GMST in 2023 is 1.48°C, which is approaching the global warming threshold of 1.5°C. This raises extensive concern about whether some particular climate tipping points are approaching, which may trigger serious climatic disasters such as ice sheet collapse, dieback of biodiverse biomes, and permafrost thawing (McKay et al., 2022). Consequently, examining the sources of the phenomenal warming in 2023 and whether such sharp warming may continue in the future, is extremely urgent.

3. Strong El Niño and positive-phase AMO sparked the phenomenal rise in GMST in 2023

The variabilities of GMST are modulated by natural variabilities, such as the Madden–Julian Oscillation (Hsu et al., 2020; Kim et al., 2023), El Niño–Southern Oscillation (ENSO; Tung and Chen, 2018; Luo et al., 2021), Interdecadal Pacific Oscillation (Kosaka and Xie, 2016), and AMO (Dai et al., 2015). Another important factor that affects GMST changes is external forcings, which include greenhouse gas forcings, volcanic eruptions, and aerosols (Manabe and Wetherald, 1975; Solomon, 2010; Hansen et al., 2011; Bethke et al., 2017; Patterson et al., 2022). For the annual GMST, the effects of natural variabilities and external forcings often overlap with each other. Therefore, to detect the cause of abrupt

Table 1. The ranking of monthly GMST in 2023 since 1850.

Month of 2023	GMST	Ranking
January	1.18	7
February	1.26	4
March	1.52	2
April	1.29	4
May	1.21	3
June	1.33	1
July	1.39	1
August	1.47	1
September	1.70	1
October	1.58	1

Table 2. The GMST, ANV, MDV, and SCT components for 2022 and 2023, and their increment in 2023 relative to 2022 (units: °C).

	GMST	ANV	MDV	SCT
2022	1.17	−0.10	0.14	1.13
2023	1.41	0.11	0.15	1.15
Increment	0.24	0.21	0.01	0.02

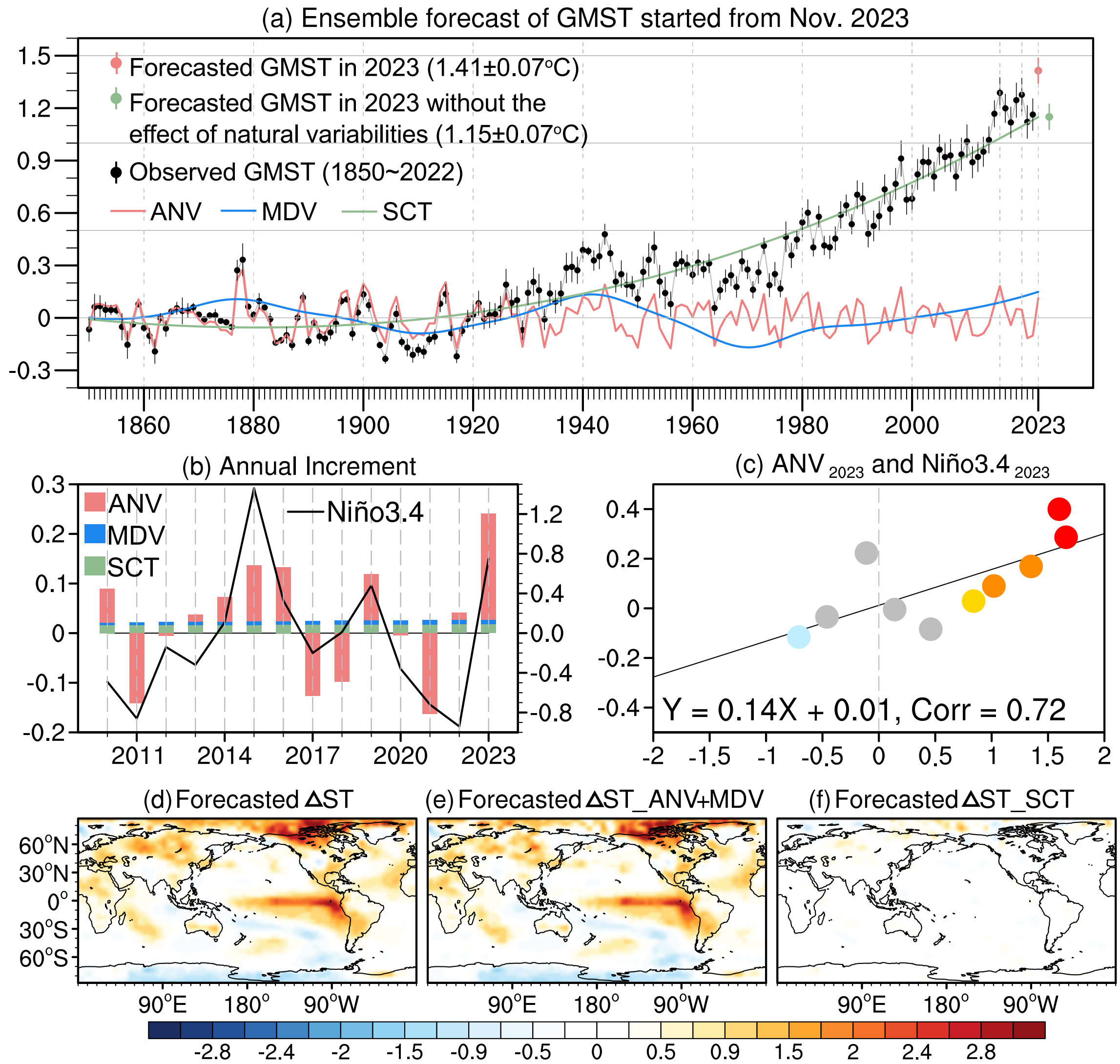

Fig. 2. (a) 2023 GMST prediction (relative to 1850–1900) started from November 2023 made by the IAP GMST statistical ensemble prediction model. The red dot and error bars represent the ensemble mean and ensemble spread of the forecasted result, respectively. The green dot and error bars show the predicted 2023 GMST without the effect of natural variabilities (ANV and MDV components). The black dots and error bars are the historical observed GMST during 1850–2022 and their uncertainties between different datasets. The red, blue and green lines show the three EEMD components of GMST. (b) The annual increments of the three EEMD components for GMST since 2010. The red, blue and green bars represent the annual increments of the ANV, MDV and SCT components, respectively. The black line represents the annual Niño-3.4 index. The values of annual increments and Niño-3.4 for 2023 all include prediction results. (c) Scatterplot of the ANV component and Niño-3.4 index during January to October 2023. Different colors represent the intensity of the Niño-3.4 index. The black line is the linear regression of the ANV component and Niño-3.4 index. (d) Increment of the forecasted ST in 2023 relative to that in 2022. (e) As in (d) but for the ANV and MDV components. (f) As in (d) but for the SCT component.

warming in the 2023 GMST, the ensemble empirical mode decomposition (EEMD) algorithm (Wu and Huang, 2009) was used to decompose the series of GMST anomalies into three components with different periods (Fig. 2a): the annual variability (ANV) component, the multidecadal variability (MDV) component, and the secular trend (SCT) component. The ANV and MDV components can be attributed to natural variabilities, while the SCT component is indicative of external forcing (Li et al., 2022).

The changes of ANV are greatly affected by ENSO, and its annual increment keeps pace with the Niño-3.4 index (Fig. 2b). During 2010–2022, the correlation between the annual increment of ANV and the Niño-3.4 index was 0.61 (Rypdal, 2018). As a result, enhanced by the medium–strong El Niño, the ANV component in 2023 is predicted to be 0.11°C (Fig. 2c), while it was –0.1°C in 2022, when successive La Niña events occurred at both the beginning and end of the year. The ANV component in 2023 is 0.21°C greater than that in 2022, accounting for 88% of the GMST increment (Table 2). Furthermore, the changes of MDV are significantly affected by the AMO, which has a correlation of 0.62 during the period of 1856–2022 (Wei et al., 2019). Motivated by the shift from the negative to positive phase of the AMO around 2000, the MDV component also changed to a state greater than zero, and has still been rising with an increasing AMO index in recent years (https://psl.noaa.gov/data/timeseries/AMO/). As a result, although the increment of the MDV component is relatively small, the 2023 MDV is forecasted to be 0.15°C, providing an important natural warming background for the abrupt increase in GMST in 2023. Besides, the negative phase of the Pacific Decadal Oscillation (https://www.ncei.noaa.gov/access/monitoring/pdo/) and positive phase of the AMO may have benefited the development of the warm blob over the northern Pacific (Henley et al., 2015; Amaya et al., 2020; Wu et al., 2020), contributing to the warming of GMST in 2023. Meanwhile, the sea-ice extent and snow-cover extent also decreased in 2023 compared to that in 2022, especially for the sea ice in the Antarctic (https://www.ncei.noaa.gov/access/monitoring/snow-and-ice-extent/sea-ice/G/0). The interannual sea-ice loss may be partly ascribed to the effect of El Niño and can favor ANV warming over the poles (Clancy et al., 2021; Li et al., 2021).

When the effects of natural variabilities, ANV and MDV, are eliminated and only the influence of SCT is considered in the prediction, the GMST in 2023 is expected to be 1.15°C ± 0.07°C (green dot and error bars in Fig. 2a). This is just 0.02°C higher than the SCT component in 2022 and not enough to beat the hottest record set in 2016. The forecasted spatial distribution of the annual increment for the global surface temperature in 2023 relative to that in 2022 is depicted in Fig. 2d. Obvious warming is situated in the eastern tropical Pacific, the north of North America, and the Arctic. Some cooling signals exist in Greenland and the mid-to-high latitudes over the Southern Hemisphere. The natural variabilities related to El Niño and the AMO contribute the vast majority of the increment (Fig. 2e), while the SCT component accounts for very little (Fig. 2f).

In conclusion, with the vital decadal-scale background warming mainly provided by the AMO, the natural variabilities that are mainly stimulated by the current El Niño event have made a prominent contribution to the astonishingly large margin of annual warming in the 2023 GMST. Global warming alone is still not enough to have caused the GMST to spike to the record high in 2023. Furthermore, because of the substantial heat released by strong El Niño events that spreads to the atmosphere in the extratropics (Zhai et al., 2016; Li et al., 2023), the GMST may climb to a higher level during years when such strong El Niños decay, as compared with the years in which they develop. Therefore, similar to the once-warmest year of 2016, the 2024 GMST may be much higher than the 2023 GMST, thereby setting another new record. However, even though natural variability is the cause of the abrupt increase in the exceptionally high GMSTs in 2023–2024, the abnormally warm background that the SCT component provides cannot be ignored. It might be easier for the GMST to hit record highs in the future as the share of the SCT component increases with future global warming.

Acknowledgements. This work was supported by the Key Research Program of Frontier Sciences, Chinese Academy of Sciences (Grant No. ZDBS-LY-DQC010), and the National Natural Science Foundation of China (Grant No. 42175045).

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