Journal of Earth Science, Vol. 31, No. 2, p. 419–424, April 2020 *ISSN 1674-487X*
Printed in China
https://doi.org/10.1007/s12583-019-1239-4

Stable Isotope Evidence for Recent Global Warming Hiatus

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ABSTRACT: Global mean surface air temperature (SAT) has remained relative stagnant since the late 1990s, a phenomenon known as global warming hiatus. Despite widespread concern and discussion, there is still an open question about whether this hiatus exists, partly due to the biases in observations. The stable isotopic composition of precipitation in mid- and high-latitude continents closely tracks change of the air temperature, providing an alternative to evaluate global warming hiatus. Here we use the available long-term precipitation δ^{18}O records to investigate changes in SAT over the period 1970–2016. The results reveal slight decline in δ^{18}O anomaly from 1998 to 2012, with a slope of -0.000 4‰ decade^{-1} which is significantly different from that of pre-1998 interval. This downward δ^{18}O anomaly trend suggests a slight cooling for about -0.001 °C decade^{-1}, corroborating the recent hiatus in global warming. Our work provides new evidence for recent global warming hiatus and highlights the potential of utilizing precipitation isotope for tracking climate changes.

KEY WORDS: global warming hiatus, precipitation δ^{18}O, climate change.

0 INTRODUCTION

Considerable attention has been paid to global warming in the past few decades. Since the industrial revolution, the emissions of greenhouse gases have increased dramatically, contributing to a rapid rise in global mean surface air temperature (SAT), especially after the late 1970s (Foster and Rahmstorf, 2011). However, this rising trend in global SAT stalled in the late 1990s, followed by a relative stagnation and even slight cooling that had lasted for about 15 years (1998–2012) (England et al., 2014; Meehl et al., 2014; Watanabe et al., 2014; Kerr, 2009). This slowdown of global warming was recognized by the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) and termed as a hiatus (IPCC, 2013). Despite widespread attention both within and outside of the scientific community, it is still strongly debated whether there is a hiatus in global warming or not.

The idea of global warming stagnation first emerged in some websites and blogs (Kerr, 2009; Carter, 2006), largely based on the HadCRUT3 (Brohan et al., 2006) dataset that shows no warming or even slight cooling between 1998 and 2005. This is the later so-called global warming hiatus. A serious scientific investigation of global warming hiatus began in 2009 which confirms the existence of the hiatus in observations and models (Easterling and Wehner, 2009). Subsequent studies usually took 1998 as the starting point of global warming hiatus (Chen et al., 2018; Huber and Knutti, 2014; IPCC, 2013; Foster and Rahmstorf, 2011; Easterling and Wehner, 2009; Knight et al., 2009), albeit with a range from 1993 to 2003 (Lewandowsky et al., 2015). Although the magnitude and significance of global warming trend depend on these starting points, the hiatus is always clear in different observational datasets (Fyfe et al., 2016). The hiatus is also supported by most coupled model simulations which exhibit a weak warming since 1997 (Huber and Knutti, 2014). Therefore, global warming hiatus appears to be an accepted fact in both the public and scientific community (IPCC, 2013; Carter, 2006).

On the other hand, some recent studies argued that there had been no meaningful hiatus in global warming (Lewandowsky et al., 2016, 2015; Karl et al., 2015; Rajaratnam et al., 2015). Cahill et al. (2015) found that there was no statistically significant reduction in the global temperature through the analysis of the change-point of four global temperature records. Rajaratnam et al. (2015) used a comprehensive statistical analysis of three sets of different global temperature data that went beyond simple linear models to account for temporal dependence and selection effects, indicating no statistical evidence for global warming hiatus. Some also questioned the quality of datasets used to infer the hiatus and argued that there was hardly a slowdown in the bias-corrected global SAT data (Karl et al., 2015; Cowtan and Way, 2014).

The controversies on the global warming hiatus pose substantial challenges to the understanding of the global climate response to anthropogenic greenhouse gas emissions and natural variability. As mentioned above, the disagreements in recent global warming hiatus mainly arise from different sources, among which differences across observational SAT datasets may be a key contributor to the contradictory conclusions (Karl et al., 2015; Cowtan and Way, 2014). The datasets used to investigate global warming derive from different instrumental measurements, calibration and homogenization which strongly affect the estimate of the global SAT trends (Foster and Abraham, 2015; Karl et al., 2015).

To overcome the shortcomings, it is necessary to develop

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Manuscript received May 28, 2019.
Manuscript accepted August 11, 2019.

Wang, R., Liu, Z. F., 2020. Stable Isotope Evidence for Recent Global Warming Hiatus. *Journal of Earth Science*, 31(2): 419–424. https://doi.org/10.1007/s12583-019-1239-4. http://en.earth-science.net

some reliable proxies for global warming assessment. The stable isotope composition (e.g., δ^{18}O) of meteoric precipitation was widely used to investigate climate change at regional and global scales, as it is closely correlated with some climatic parameters and processes such as surface temperature, precipitation amount and atmospheric circulation (Dansgaard, 1964). Particularly, the robust correlation between precipitation δ^{18}O and surface temperature over the mid- and high-latitude regions led to widespread use of precipitation δ^{18}O as a proxy for SAT investigation (Rozanski et al., 1992; Dansgaard, 1964). However, the δ^{18}O/temperature correlation is weaker or even non-existent in the low-latitudes due to strong amount effect, which disables the δ^{18}O-based temperature assessment in the region. In this study, we develop a composite isotope index spanning 1970–2016 by combining twelve precipitation δ^{18}O records collected over mid- and high-latitude continents. We use this composite isotope index as a concise metric for the changes in SAT and evaluate recent global warming hiatus.

1 DATA AND METHODS

We compiled publicly available precipitation δ^{18}O records from the Global Network of Isotopes in Precipitation (GNIP) dataset meeting two criteria: each record (i) is continuous and at least covers a period from 1979 to 2013, (ii) is significantly correlated with local air temperature. Eventually, twelve stations are selected for our analysis, of which ten are located in Europe, and the remaining two in Antarctica and North America, respectively (Fig. 1, Table 1).

Among twelve precipitation δ^{18}O records, European stations usually have a common temporal pattern depicted by Vienna record (Rozanski et al., 1992). They bear a strong resemblance to record at North American station, as revealed by a significant correlation between the Vienna and Ottawa records (R=0.53, $p<0.001$) (Fig. 2). Similar pattern, but of opposite sign (R=0.32 and 0.36, $p<0.05$ for Vienna and Ottawa records, respectively), is also observed for record at Vernadsky (Antarctica) (Fig. 2). The presence of strong spatial coherence between isotopic records and their association with temperature suggests that temperature is a common driver of the long-term variability in precipitation δ^{18}O. This allows us to develop a composite isotope index to track change in global temperature. To this end, we follow Rozanski et al. (1992) and first eliminate the seasonal component from the monthly δ^{18}O and SAT records available by employing a 12-month running average. Then the δ^{18}O and SAT anomalies ($\Delta\delta^{18}$O and ΔT) for individual records are calculated as the departures from their long-term means. Finally, the composite $\Delta\delta^{18}$O and ΔT time series are constructed by calculating the arithmetic averages of $\Delta\delta^{18}$O and ΔT of all twelve records.

Table 1 List of twelve precipitation isotope records used in the study, with information about site, country, coordinates, time span, correlation with monthly temperature during their respectively overlapping periods. All correlations are significant at the 0.05 confidence level

Code	Site	Country	Lat. (°)	Long. (°)	Alt. (m)	Record period	R
1	Vernadsky	Argentine	-65.08	-63.98	20.00	1970–2016	0.57
2	Ottawa	Canada	45.32	-75.67	114.00	1970–2016	0.83
3	Vienna	Austria	48.25	16.36	198.00	1970–2016	0.75
4	Konstanz	Germany	47.68	9.19	443.00	1978–2013	0.76
5	Wasserkuppe	Germany	50.49	9.94	921.00	1978–2013	0.64
6	Wuerzburg	Germany	49.77	9.96	268.00	1977–2013	0.66
7	Groningen	Netherlands	53.23	6.55	1.00	1970–2012	0.62
8	Krakow	Poland	50.06	19.85	205.00	1975–2016	0.79
9	Grimsel	Switzerland	46.57	8.33	1 950.00	1970–2016	0.79
10	Guttannen	Switzerland	46.66	8.29	1 055.00	1970–2016	0.82
11	Meiringen	Switzerland	46.73	8.19	632.00	1970–2016	0.79
12	Wallingford	UK	51.60	-1.10	48.00	1979–2015	0.49

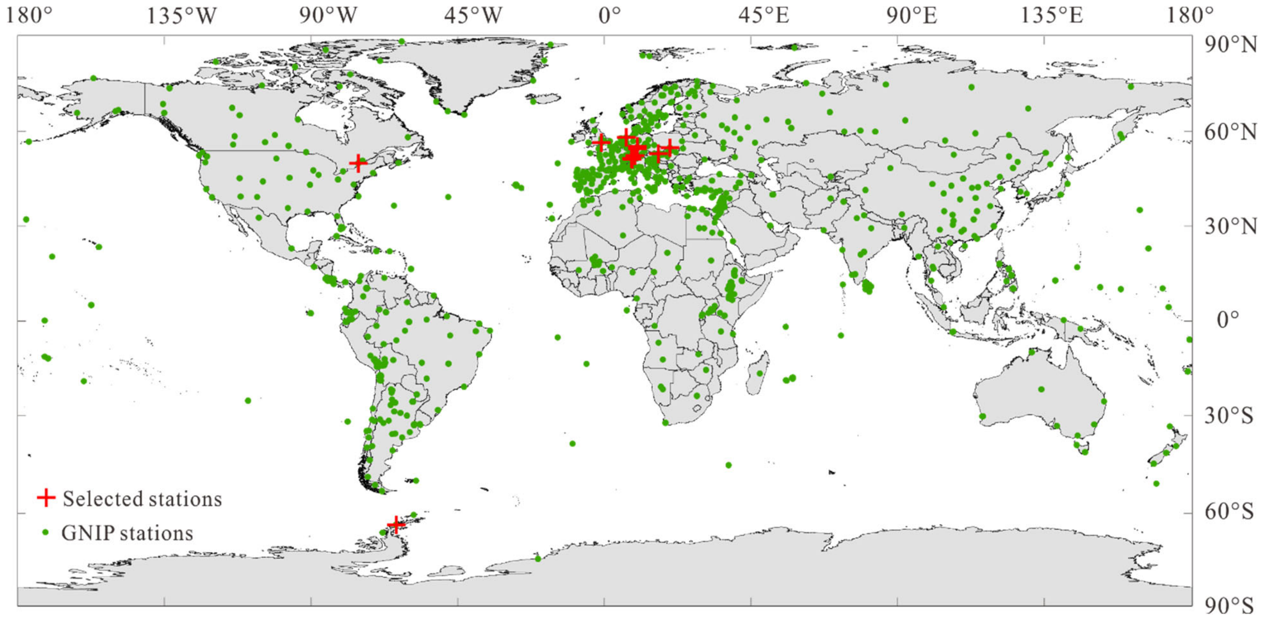

Figure 1. Spatial distribution of all GNIP monitoring stations (green dots). The twelve stations with long-term precipitation isotope records are highlighted with red crosses.

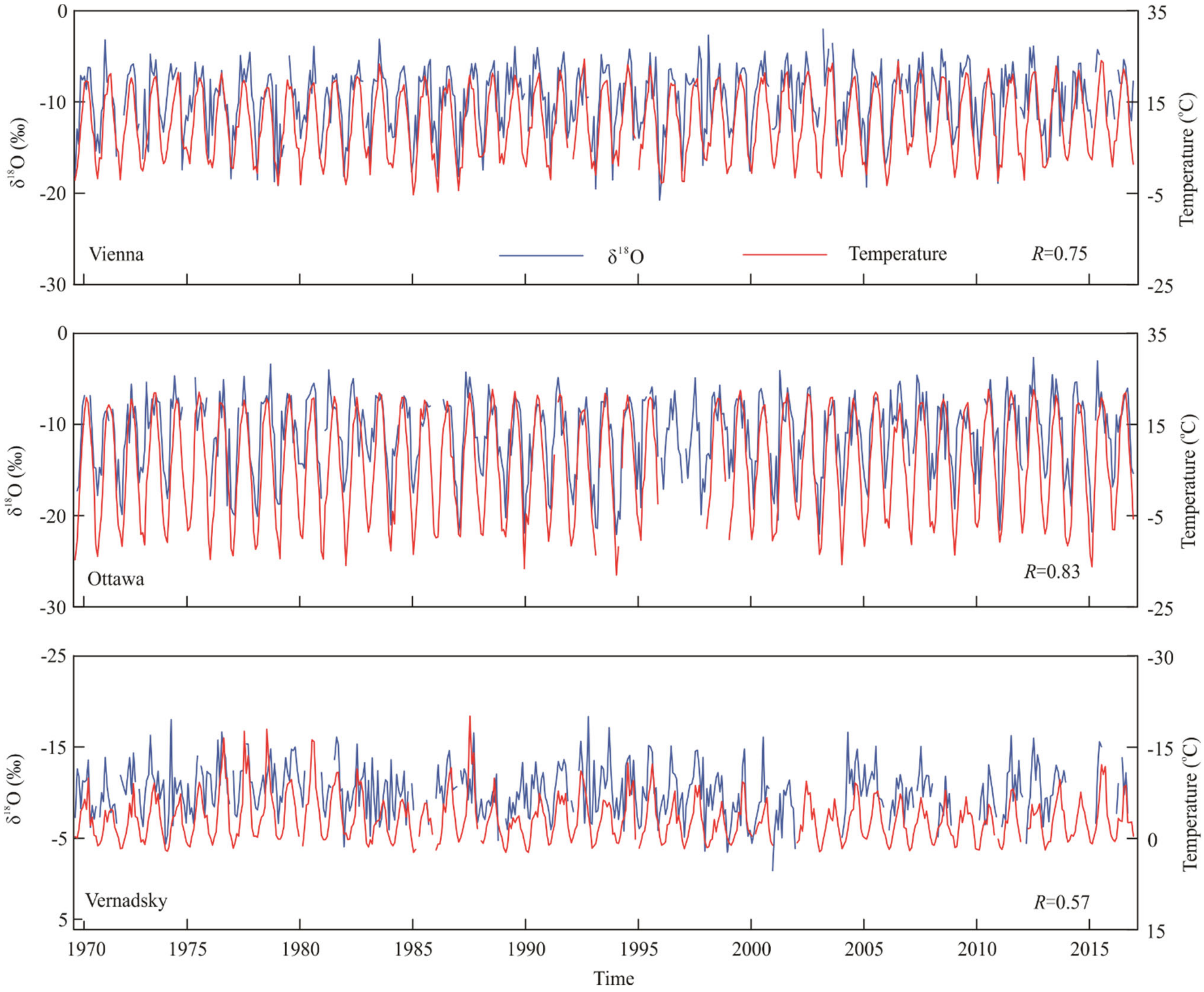

Figure 2. Time series of monthly precipitation $\delta^{\delta 18}$O records at three representative stations, along with corresponding surface air temperature over the period 1970–2016.

To determine whether there was a hiatus in global warming during the period 1998–2012, we split the δ^{18}O record into three segments such as 1970–1997, 1998–2012 and 2013–2016 for trend analysis. The linear trends of each interval are estimated using the standard least squares method. In addition, F-test is used to determine the significance of the slope $\hat{\beta}_1$ in the linear regression equations. The original hypothesis is H_0: $\hat{\beta}_1=0$, with F defined as

$$F_0=(n-2)SS_R/SS_E \ , \tag{1}$$

where SS_R with 1 degree of freedom is the regression sum of squares and SS_R is the residual sum of squares with $(n-2)$ degrees of freedom. Both are given by

$$SS_R=\sum(\hat{y}_i-\bar{y}_i), \tag{2}$$

$$SS_E=\sum(y_i-\hat{y}_i). \tag{3}$$

H_0 will be rejected if the calculated statistic, F_0, is

$$F_0>f_{\alpha,\,1,\,n\text{-}2} \ , \tag{4}$$

where $f_{\alpha,\,1,\,n\text{-}2}$ is the percentile of the F distribution, and n denotes the number of samples.

2 RESULTS AND DISCUSSIONS

Figure 3 shows long-term relationship between precipitation δ^{18}O and air temperature. Both arithmetic and amount-weighted annual δ^{18}O averages are significantly correlated with SAT ($R>0.84$, $p<0.000\ 1$), with slope values of 0.68‰ °C^{-1} and 0.66‰ °C^{-1}, respectively (Figs. 3a, 3b). These δ^{18}O/temperature slopes are well within the range (0.50‰ °C^{-1}–0.70‰ °C^{-1}) predicted by the theoretical distillation models (Dansgaard, 1964). In contrast, composite δ^{18}O anomaly ($\Delta\delta^{18}$O) exhibits a slightly weaker correlation ($R>0.69$, $p<0.000\ 1$) with corresponding air temperature anomaly (ΔT), with a slope of 0.54‰ °C^{-1} (Fig. 3c). This slope falls within the range (0.45‰ °C^{-1}–1.10‰ °C^{-1}) reported for individual stations across globe, but the R value is highly relative to the previous study (ranging from 0.37 to 0.66) (Rozanski et al., 1992). Strong correlations between precipitation δ^{18}O and SAT suggest that precipitation δ^{18}O record is an ideal proxy for exploring the SAT variation and can be used to assess recent global hiatus.

The $\Delta\delta^{18}$O displays strong interannual and decadal variability over the entire period from 1970 to 2016 (Fig. 4) (Rozanski et al., 1992). Superimposed on these short-term variabilities is a secular trend toward a positive anomaly (0.006‰ decade^{-1},

F=159.41, p<0.001). This upward trend in $\Delta\delta^{18}$O is approximately equivalent to a temperature increase rate of 0.01 °C decade^{-1}, similar to the observed global average (0.005 °C decade^{-1}), suggesting a secular global warming trend during the study period. This increasing trend in the $\Delta\delta^{18}$O is more robust for the period 1970–1997, with a larger magnitude (0.01‰ decade^{-1}, F=78.61, p<0.01). However, the $\Delta\delta^{18}$O time series for the 1998–2012 interval shows a slight but insignificant declining (-0.000 4‰ decade^{-1}, F=0.02, p>0.1), which is significantly different from that of pre-1998 interval (p<0.05). This decrease in the $\Delta\delta^{18}$O means a SAT decline of about -0.001 °C decade^{-1}, well consistent with those derived from the observed SAT datasets (England et al., 2014; Meehl et al., 2014; Watanabe et al., 2014; Kerr, 2009), supporting a hiatus in global warming during the period 1998–2012. After 2012, the $\Delta\delta^{18}$O exhibits a quick increase, with a magnitude of 0.168‰ decade^{-1} (F=223.24, p<0.000 1) over the period 2013–2016. This increase means a SAT rise of about 0.186 °C decade^{-1}, which is far beyond that of the 1998–2012 period. As a result, a hiatus in global warming is robust for the period 1998–2012.

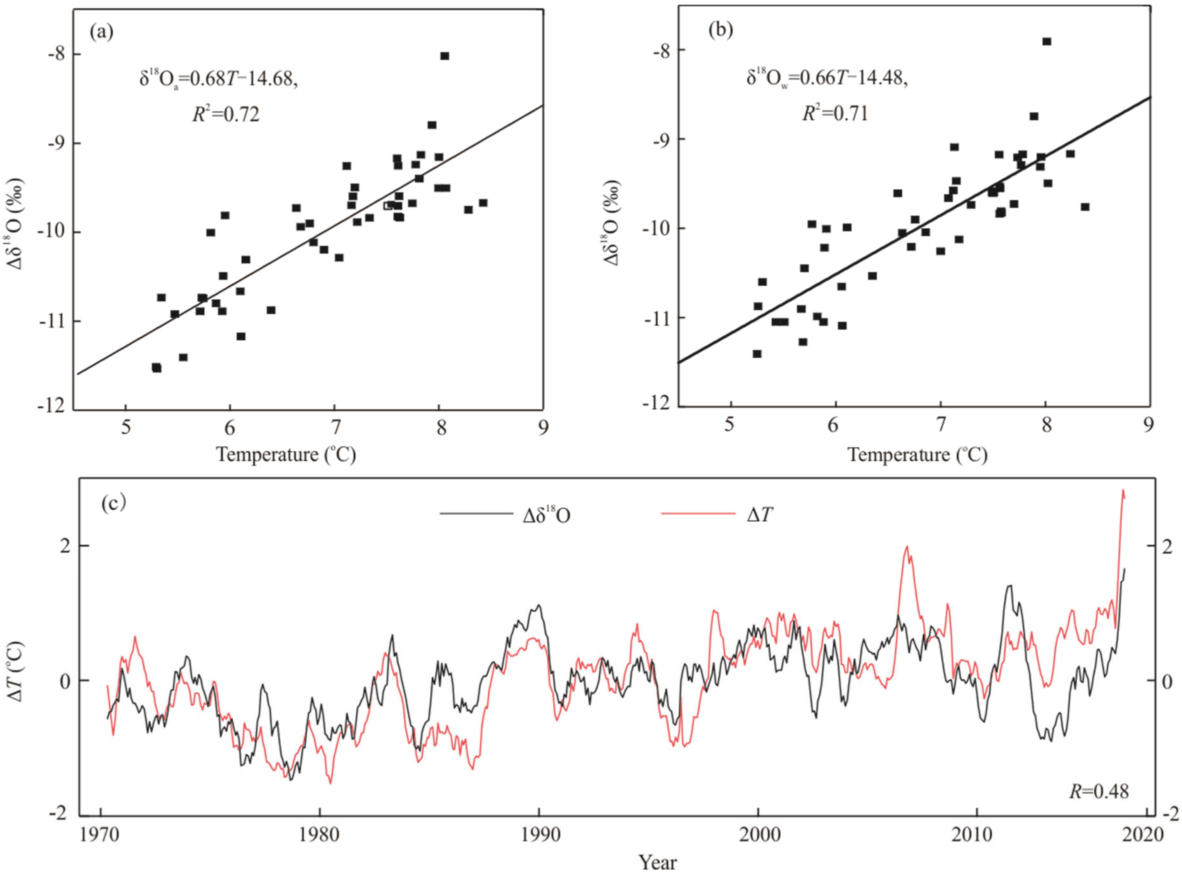

Figure 3. Long-term relations between annual precipitation δ^{18}O and surface air temperature over the period 1970–2016. (a) Arithmetic annual δ^{18}O averages. (b) Amount-weighted annual δ^{18}O averages. (c) Time series of precipitation isotope ($\Delta\delta^{18}$O) and air temperature (ΔT), with seasonal component removed.

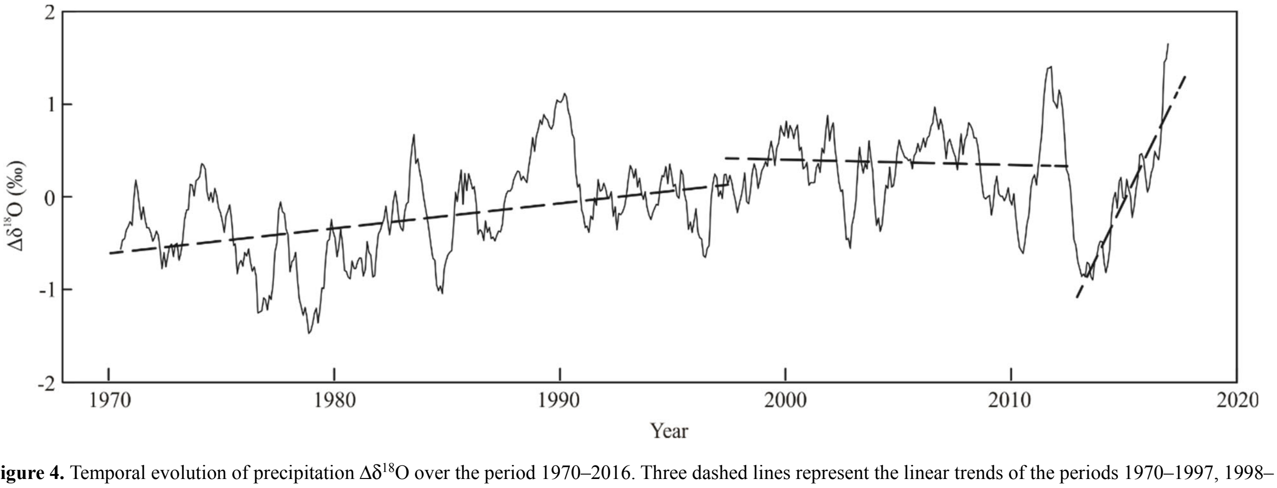

Figure 4. Temporal evolution of precipitation $\Delta\delta^{18}$O over the period 1970–2016. Three dashed lines represent the linear trends of the periods 1970–1997, 1998–2012 and 2013–2016, respectively.

Research on global warming hiatus and its associated physical mechanisms led to a growing number of scientific publications and public debate (Medhaug and Drange, 2016; Lewandowsky et al., 2015). In the study we focus only on whether there is a hiatus in global warming over the period 1998–2012 and provide an isotope-based analysis. Although our results offer a robust proxy for the recent hiatus in global warming, there are at least two caveats worth noting. First, precipitation δ^{18}O records adopted in our analysis exclusively involve the observations taken at the mid- and high-latitude continents, with a lack of data in oceans and low-latitude continents, which may lead to some uncertainties when they are used to represent a global mean SAT. For example, the isotope records in the mid- and high-latitude stations probably represent warming faster than the global average (Karl et al., 2015). To test the possible influences of data coverage, we calculate the linear trends of the observed SAT for the three period segments above (1970–1997, 1998–2012 and 2013–2016 periods) based on the Goddard Institute for Space Studies (GISS) dataset, and compare the observed surface temperature change between the global and mid- and high-latitudes (Fig. 5). Relative to the global averages, observed surface temperatures in mid- and high-latitudes exhibit the same rates of warming for the periods 1970–1997 and 1998–2012 (Table 2). For the interval 2013–2016, the mid- and high-latitudes temperature exhibits a slightly slower rate of warming than the global target, but they are not statistically different ($p>0.1$) from each other. Especially for the interval 1998–2012, both global and mid- and high-latitudes show a much weaker warming trend (0.001 °C decade^{-1}, $p>0.1$), which is largely consistent with our δ^{18}O-derived result and supports a slowdown in the increase of global SAT. These indicate that the linear trend of the SAT in the mid- and high-latitudes can reflect global average, corroborating the robustness of our results.

Table 2 Warming rate of global and mid- and high-latitudes for the periods 1970–1997, 1998–2012 and 2013–2016

Time interval	Linear trend (°C decade^{-1})	
	Global	Mid- and high-latitudes
1970–1997	0.005**	0.005**
1998–2012	0.001	0.001
2013–2016	0.024**	0.012*

* and ** denote 0.1 and 0.05 confidence levels, respectively.

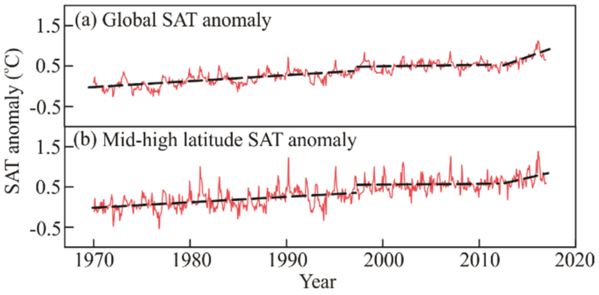

Figure 5. Time series of (a) global and (b) mid-high latitudes surface temperature anomalies over the period 1970–2016 provided by the Goddard Institute for Space Studies (GISS). Dashed black lines show the linear trends of the intervals 1970–1997, 1998–2012 and 2013–2016, respectively.

Secondly, we do not take into account the heterogeneity in onset and duration of the warming hiatus, which may challenge the robustness of our results. As mentioned above, the linear trend and its magnitude is largely dependent on the choice of the start and end years. Previous studies use different start and end years (with a duration of 10–20 years) to calculate the linear trends of global SAT and lead to the opposite conclusion (see review by Lewandowsky et al., 2015). Our study do not compare possible differences in trend of the $\Delta\delta^{18}$O record due to the choice of the start and end years, but adopted the starting point and duration (1998–2012) suggested by the IPCC AR5 (IPCC, 2013; Carter, 2006). In addition, the running average may bias the choice of the starting point and the trend length. Although several published works demonstrate that changes in onset and duration do not have a substantial impact on the assessment of the rate of warming (Lewandowsky et al., 2015; Rajaratnam et al., 2015), there remain considerable uncertainties (see review by Lewandowsky et al., 2015). Therefore, further investigation through spatially resolved precipitation isotope records and more rigorous statistical approach (Cahill et al., 2015; Rajaratnam et al., 2015) are needed in the future.

3 CONCLUSION

In the study, we use precipitation isotope measurements at mid- and high-latitude continents as proxy for global mean SAT to evaluate recent global warming hiatus. We find that the global average of precipitation δ^{18}O displays a slightly descending trend over the period 1998–2012, significantly different from that of the interval 1970–1997 which is characterized by a significant warming. This shift in precipitation δ^{18}O suggests a robust hiatus in global warming over the period 1998–2012. Our results provide new evidence for recent global warming hiatus and highlight the potential of utilizing precipitation isotopes for tracking climate changes.

ACKNOWLEDGMENTS

This work were supported by the China Young 1 000-Talent Program and the National Nature Science Foundation of China (No. 41876039). We acknowledge the Global Network of Isotopes in Precipitation (GNIP) for precipitation stable isotope records (http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html) and surface temperature anomalies data from Goddard Institute for Space Studies (GISS) dataset (https://data.giss.nasa.gov/gistemp/). The final publication is available at Springer via https://doi.org/10.1007/s12583-019-1239-4.

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