Surface energy budget diagnosis reveals possible mechanism for the different warming rate among Earth's three poles in recent decades

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Short Communication

Surface energy budget diagnosis reveals possible mechanism for the different warming rate among Earth's three poles in recent decades

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With the introduction of the "Third Pole" [1], the Arctic, Antarctic, and Tibetan Plateau (TP) can be collectively referred to as the "three poles of the Earth". The cryosphere is an important component of the climate system because of its effect on Earth's surface albedo and its role in reducing the amount of heat exchanged between the atmosphere and ocean or land [2]. As the dominant parts of the cryosphere, the Arctic, Antarctic, and TP are pivotal and sensitive areas of global climate change. Global warming will weaken the inherent stability of the cryosphere, such as its ice shelves, glaciers and permafrost [3,4]. Therefore, with the advent of global warming, the associated climate change and its impact on the Arctic, Antarctic, and TP have attracted extensive attention. In recent years, satellite data have indicated that the sea-ice cover in the Arctic has been decreasing rapidly, while that in the Antarctic has had an increasing trend [5]. The reduction in Arctic sea ice is closely related to so-called "Arctic amplification" [6]. However, in the Antarctic, different views exist on the anomalous changes in Antarctic sea ice. Specifically, the temporal variability of surface temperature around the Antarctic continent shows different trends that are consistent with sea-ice cover [7]. Meanwhile, in contrast to the cooling trend for the rest of China and the so-called "global warming hiatus", an accelerated warming since the end of the 1990s has been reported in the TP [8], but the possible mechanisms for this have still not been determined.

Surface temperature (T_s) is not only an important factor affecting sea-ice cover, mainland snow coverage, and the surface heat sources or sinks, but is also a key indicator of climate change and a critical factor for vegetation growth. However, so far, the similarities and differences among the dominant factors controlling the T_s change at these three poles remain almost unknown. Therefore, investigating the characteristics of T_s change and their factors of influence in these three regions of Earth are important for improving our understanding of the role of the cryosphere in global climate change. In this work, based on the method of Lu and Cai [9], we attempt to address this knowledge gap by diagnosing the surface energy balance equation.

The T_s linear trend from reanalysis datasets over the three poles during the period of 1980–2017 indicates that the T_s of the Arctic region, whether ocean or mainland, and the TP region, exhibit much larger warming rates compared with the global average (Table S1 online), known as warming amplification. Meanwhile, a weak warming trend can be detected in the Antarctic continent, accompanied by a slight cooling trend in the surrounding ocean (Fig. S1 online). By comparing the T_s and surface air temperature (T_a) of *in-situ* station observations (Figs. S2 and S3 online), the most reliable reanalysis dataset for each region was selected to carry out the attribution analysis of T_s change. Accordingly, except for MERRA2, which was used for the Antarctic continent, JRA-55 was utilized in all other regions. More details on the selected datasets used in this work can be found in the Supplementary data.

Besides, the T_s of the TP, Arctic mainland and ocean, Antarctic mainland, and the entire globe shifted from a dominant negative anomaly period to an overall positive anomaly period around the end of the 1990s (Fig. 1a, b, c, d and f). In contrast, the Southern Ocean had a different pattern of variation and experienced a shift from a positive to negative anomaly in the early 21st century (Fig. 1e). Hence, according to a method by which a climatic jump in the given climatic state can be detected [10], the whole period can be divided into two periods, with all datasets passing the *t*-test

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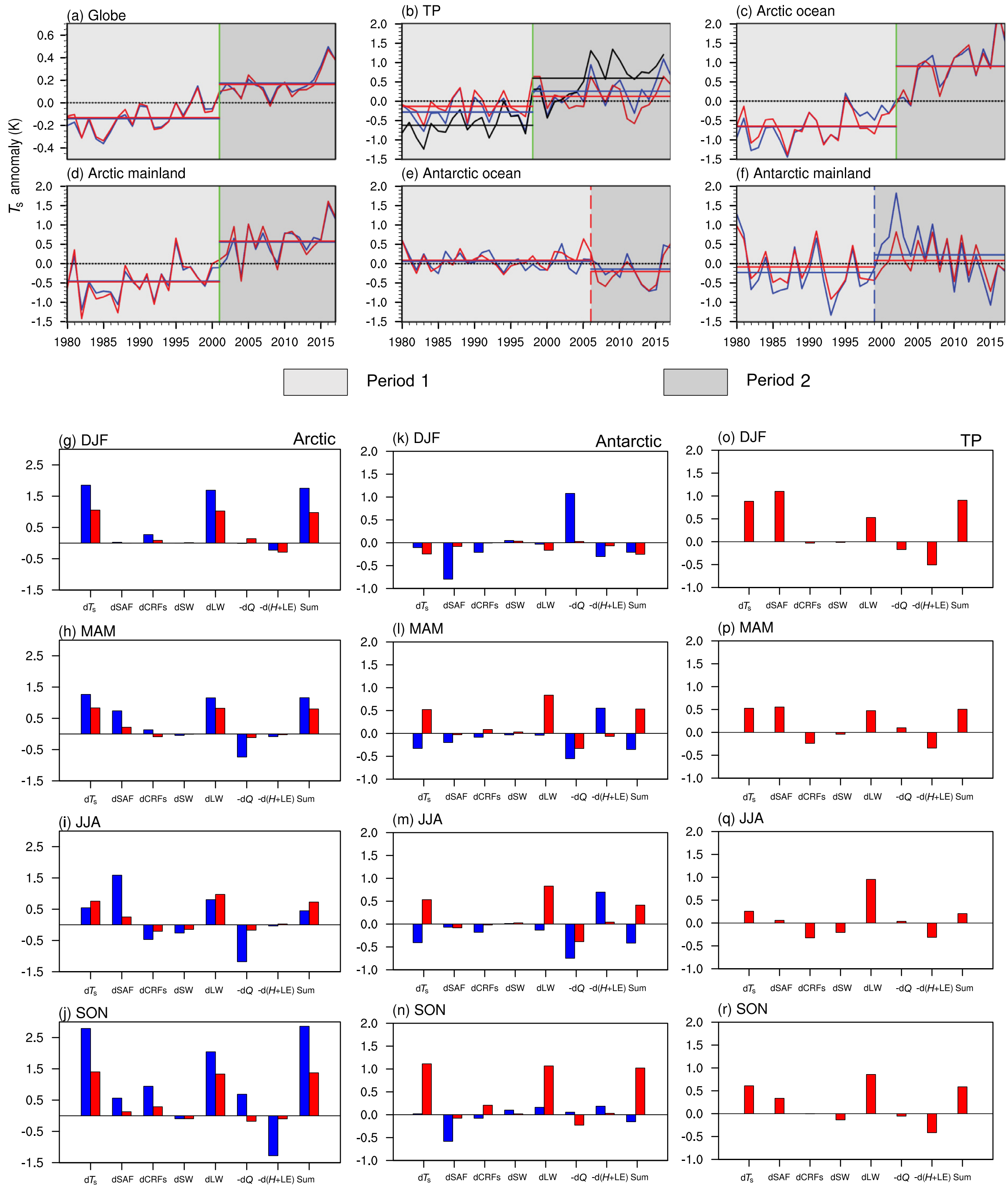

Fig. 1. Temporal variation of the annual average T_s (surface temperature) anomaly, averaged over the (a) whole globe, (b) Tibetan Plateau, (c) Arctic Ocean, (d) Arctic mainland, (e) Antarctic Ocean, and (f) Antarctic mainland. The blue curves represent JRA-55, except in (f) where it represents MERRA2; the red curves represent ERA-Interim; and the black curve in (b) represents station observations (Fig. S4c online). The period 1980–2017 (2016) is divided into two periods according to the jump points identified, indicated by the green solid lines, which pass the *t*-test at the 95% confidence level in all datasets. The red (blue) dotted line represents a jump-point passing the *t*-test at the 95% confidence level in ERA-Interim (MERRA2) only. Changes in (a–d) Arctic, (e–h) Antarctic, and (i–l) TP T_s and the partial temperature changes (PTCs; units: K) due to the changes in SAF (surface albedo feedback), CRF_s (surface cloud radiative forcing), SW (downward clear-sky shortwave) radiation, LW (downward clear-sky longwave) radiation, *Q* (surface heat storage), and the sum of *H* and LE (latent and sensible heat fluxes) between the two periods, in different seasons, is based on the JRA-55 dataset, except for the Antarctic mainland, which is based on MERRA2. The blue and red bars represent the ocean and mainland, respectively.

at the 95% confidence level for the globe, TP, and Arctic (Fig. 1a–d). Meanwhile, only ERA-Interim and MERRA2 passed the 95% confidence level in the Southern Ocean (Fig. 1e) and the Antarctic continent (Fig. 1f), respectively.

Based on the two selected reanalysis datasets for 1980–2017 with *in-situ* observational verification, we investigated the T_s changes in these regions and the possible reasons for them by diagnosing the surface energy balance equation and comparing the differences between the two periods. In order to explore the seasonal variation characteristics of the impact factors contributing to T_s, the partial temperature changes of different factors of influence in different seasons are shown (Fig. 1g–r). We found that the downward clear-sky longwave (LW) radiation, surface albedo feedback (SAF), and surface heat storage (Q) are the three key factors affecting the change in T_s between the two periods for the three poles. However, the relative importance of them is seasonally and regionally dependent (Fig. 1g–r).

For the Arctic, the seasonal variation of LW radiation is highly consistent with the seasonal variation of T_s amplification over the mainland and ocean. Specifically, in boreal winter, spring, and fall (Fig. 1g, h and j), the increase in T_s and the positive contribution of LW radiation over the ocean are both higher than those over the mainland. Meanwhile, the opposite is true in summer (Fig. 1i). Therefore, LW radiation is the primary factor affecting the warming amplification of the Arctic mainland and ocean. SAF is negligible in boreal winter owing to the absence of solar radiation (Fig. 1g). However, it contributes to Arctic warming in the other three seasons (Fig. 1h, i and j). Thus, SAF is a secondary factor for the surface warming amplification in the Arctic.

For the Antarctic, the oceanic and continental T_s changes are opposite in phase in austral fall and winter (Fig. 1l and m). Over the Antarctic mainland, the magnitude of warming in austral spring reaches a maximum in MERRA2 (Fig. 1n). The negative contribution of SAF is very small in all seasons, which is likely related to the negligible decrease in snow cover. The contribution of surface cloud radiative forcing (CRF_s) and downward clear-sky shortwave (SW) radiation to continental T_s changes are insignificant across all seasons. The contribution of LW radiation is highly consistent with that of mainland warming in all seasons; hence, LW radiation is also a primary factor affecting the T_s changes in the Antarctic mainland. Meanwhile, the effect of an increase in Q, inhibiting the surface warming over the mainland in austral fall, winter, and spring, is greater than the changes of SAF (Fig. 1l, m and n). Therefore, Q is a secondary factor for the surface warming in the Antarctic mainland. Over the Southern Ocean, the cooling trend is strongest in austral winter (Fig. 1m). The Q of the Southern Ocean is reduced in austral summer, which inhibits the cooling of the Southern Ocean (Fig. 1k). In contrast, it increases in austral winter and autumn, enhancing the cooling of the Southern Ocean (Fig. 1l and m). However, the LW radiation over the Southern Ocean makes little contribution to the change in T_s compared with Q and SAF. This indicates that Q and SAF are the primary and secondary factors for the cooling.

For the TP, the surface warming amplification is the strongest in boreal winter and weakest in summer (Fig. 1o and q). The SAF is the primary factor affecting the TP's warming amplification in boreal winter and spring (Fig. 1o and p). However, in boreal summer and fall, the primary factor affecting the TP's warming amplification is LW radiation (Fig. 1q and r). Furthermore, the warming amplification is the strongest in boreal winter, which can be attributed to the combined effect of SAF and LW (Fig. 1o). The remaining terms make negative or negligible contributions to the TP's warming. Thus, the positive contributions of SAF and LW radiation are the main factors affecting the TP's warming amplification. Over the TP, the increase of SAF is related to the decrease of snow cover in recent decades, which is regulated by positive snow/ice-albedo feedback processes [11].

Overall, in the land areas of the three poles, the warming over the Arctic and TP is affected mainly by the LW radiation and SAF, while in the Antarctic both the change in LW radiation and Q are important. As for the polar oceans, the warming over the Arctic Ocean is mainly affected by the LW radiation, SAF, and Q, but the cooling over the Southern Ocean is mainly affected by the SAF and Q.

The oceanic SAF and Q are closely linked to the change in sea ice in the polar ocean (Fig. S5 online). On the one hand, sea ice can influence the contribution of SAF by the ice-albedo feedback. Moreover, the contribution of SAF is more significant in the polar oceans and TP the polar continents. On the other hand, sea ice can also regulate the change in Q by affecting the sea surface heat storage capacity. Sea ice has less heat storage capacity than sea water. In the warm season, the atmosphere supplies energy to the sea surface. When the sea ice increases (decreases) (Fig. S5 online), the average heat storage capacity of the sea surface layer decreases (increases). Therefore, the oceanic Q decreases (increases) and promotes sea surface warming (cooling) (Fig. 1i and k). In the cold season, the sea surface provides energy to the atmosphere. When the sea ice increases (decreases) (Fig. S5 online), the average heat storage capacity of the sea surface decreases (increases) and the oceanic Q increases (decreases), promoting sea surface cooling (warming) (Fig. 1g and m). Therefore, sea ice can affect the sea surface temperature by adjusting the heat storage capacity of the sea surface layer. Meanwhile, the positive contribution of LW radiation is mainly affected by the increases in atmospheric water vapor (Fig. S6 online). However, the change in atmospheric water vapors over the Southern Ocean (Fig. S6d online) is much weaker compared with those in the Arctic and TP (Fig. S6a–c online); thus, the LW radiation has a limited impact on the change in T_s.

In other words, the T_s changes at the three poles are closely related to changes in sea-ice cover or atmospheric water vapor. In the Arctic and TP, LW radiation affected by atmospheric water vapor is the dominant factor regulating the T_s change, whereas the change in sea ice plays an important role in modulating the T_s over the polar seas efficiently by influencing the ice-albedo feedback and sea surface heat storage capacity.

On a final note, it is important to acknowledge that the conclusions drawn in this study rely on the quality of the reanalysis data used. Despite progress over recent years, a lack of observations at the three poles still poses a challenge for obtaining high-quality reanalysis datasets over these regions. More high-quality observational evidence is needed in the future to support our findings.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Kailun Gao made preliminary investigation and visualization and wrote the original draft based on the formal analysis. Anmin Duan offered the conceptualization for the article and wrote the review editing as a leader of project administration. Deliang Chen provided dataset resources and made a validation for the article. Guoxiong Wu gave important advice for the analytical methodology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.06.023.

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