Contrast patterns and trends of lapse rates calculated from near-surface air and land surface temperatures in China from 1961 to 2014

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Abstract

The near-surface lapse rate reflects the atmospheric stability above the surface. Lapse rates calculated from land surface temperature ($\gamma_{Ta}$) and near-surface air temperature ($\gamma_{Ts}$) have been widely used. However, $\gamma_{Ta}$ and $\gamma_{Ts}$ have different sensitivity to local surface energy balance and large-scale energy transport and therefore they may have diverse spatial and temporal variability, which has not been clearly illustrated in existing studies. In this study, we calculated and compared $\gamma_{Ta}$ and $\gamma_{Ts}$ at ~2200 stations over China from 1961 to 2014. This study finds that $\gamma_{Ta}$ and $\gamma_{Ts}$ have a similar multityear national average (0.53 °C/100 m) and seasonal cycle. Nevertheless, $\gamma_{Ta}$ shows steeper multiyear average than $\gamma_{Ts}$ at high latitudes, and $\gamma_{Ta}$ in summer is steeper than $\gamma_{Ta}$ especially in Northwest China. The North China shows the shallowest $\gamma_{Ta}$ and $\gamma_{Ts}$, then inhibiting the vertical diffusion of air pollutants and further reducing the lapse rates due to accumulation of pollutants. Moreover, the long-term trend signs for $\gamma_{Ta}$ and $\gamma_{Ts}$ are opposite in northern China. However, the trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ are both negative in Southwest China and positive in Southeast China. Surface incident solar radiation, surface downward longwave radiation and precipitant frequency jointly can account for 80% and 75% of the long-term trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ in China, respectively, which provides an explanation of trends of $\gamma_{Ta}$ and $\gamma_{Ts}$ from perspective of surface energy balance.

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1. Introduction

Air temperature usually decreases with altitude over the vertical profile of the atmosphere, and the rate of this decrease is called the lapse rate ($\gamma$) [1–3]. The near-surface or surface $\gamma$, which is particularly important because it is a result of surface energy balance and determines atmospheric stability above the surface, has been calculated from near surface air temperature ($\gamma_{Ta}$) or land surface temperature ($\gamma_{Ts}$) from different weather stations with diverse surface elevation [4–9]. It is different from the free-air $\gamma$ because the free-air $\gamma$ is unaffected by the surface energy balance [10–12]. The actual lapse rate is variable [13], and how does it determine the stability of the atmospheric state? If the lapse rate of the environment ($\gamma_{e}$) is larger than the dry adiabatic lapse rate ($\gamma_{ad}$), which denotes that temperature will decrease with height at 0.98 °C/100 m when an ascending unsaturated air parcel does not exchange heat and moisture with its environment, the atmospheric state is absolutely unstable [13–16]. In contrast, if $\gamma_{Ta}$ is smaller than the moist adiabatic lapse rate ($\gamma_{ma}$) [16], the atmospheric state is absolutely stable. In the intermediate case when $\gamma$ is between $\gamma_{ad}$ and $\gamma_{ma}$, the atmospheric state is conditionally unstable [7]. The stable atmospheric state is not conducive to the diffusion and dilution of pollutants in the atmosphere due to the suppression of turbulent activity [17]. The nonuniform change in the vertical temperature profile may also introduce important lapse rate feedback to the global mean surface temperature [18–20].

The widely-used constant value in the range of 0.55 to 0.65 °C/100 m is gradually found to be unsuitable for application in hydrological models or geoscience studies, because $\gamma_{Ta}$ could vary with $\gamma_{Ta}$ temperature and local conditions and display large variabilities at different spatiotemporal scales based on observations [4–6.8.21–23]. In general, $\gamma_{Ta}$ is shallower under warmer and moister climatic conditions [15], where air has a higher probability of heating by higher saturation vapor pressure and latent heat released from condensation at higher elevation. Steeper lapse rate always occurs in spring or summer, but in winter, it is lower [9.24]. Moreover, $\gamma_{Ta}$ is steeper at high elevation, such as the European Alps, the Front Range of the Colorado Rockies, USA and the Tibetan Plateau [25–27].

Existing studies have mostly focused on the climatological variabilities of the lapse rates [5.6.28], while less focus has been given...
to the interannual and long-term changes of the lapse rate in China. Li et al. [29] divided China into 24 regional groups to estimate their $\gamma_{Ta}$ based on approximately 500 weather stations, and they indicated that lapse rates generally show a banded spatial pattern and a clear seasonal variation. However, their results could not display the local features at the edges of these regional groups [25]. In addition, previous studies have shown that the spatial variability of near surface lapse rate depends on terrain, distance from the coast and surface elevation that do not change with time [9], and is also related to the impacts of climatic factors (e.g., temperature, precipitation, cloud cover, relative humidity and wind) [7,21,30]. However, they have rarely concerned about the effects of climatic factors to the long-term trends of lapse rate.

The spatial variations in $\gamma_{Ta}$ have not been well characterized due to the sparse ground-based meteorological stations [25]. Satellite-derived land surface temperature data can provide comprehensive temperature data based on statistical methods [31,32], which from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used to calculate the lapse rate to replace $\gamma_{Ta}$ [33–35] at high temporal and spatial resolution. Zhang et al. [21] compared the lapse rate ($\gamma_{Ta}$) calculated from land surface temperature of MODIS with the observed $\gamma_{Ta}$ in the Tibetan Plateau and suggested that $\gamma_{Ta}$ from MODIS shows acceptable accuracies in the climatology. Nonetheless, satellite data are of limited duration and are available under only clear sky conditions. Moreover, the sensitivity of air temperature and land surface temperature to local and surface energy is different, and air temperature is more affected by large-scale energy transport [36].

In this study, we used the monthly mean near-surface 2-m air temperature and land surface temperature to estimate the lapse rates in China from 1961 to 2014 to investigate the spatial–temporal patterns and trends of $\gamma_{Ta}$ and $\gamma_{Ts}$. Meanwhile, the mechanisms of the spatial and temporal variations in $\gamma_{Ta}$ and $\gamma_{Ts}$ were analyzed and discussed from the perspective of surface energy budget and its partitioning.

2. Data and methods

2.1. Data

Monthly land surface temperature ($T_s$) and 2 m air temperature ($T_a$) were calculated from a suite of homogenized dataset [36,37] based on 2479 meteorological stations in China from 1961 to 2014 from the China Meteorological Administration (CMA, http://data.cma.cn/en/), excluding stations in Hong Kong, Macao and Taiwan. This suite of homogenized dataset has removed many of the spurious shifts in time series, which are likely due to station relocation and instrument changes (such as instrument replacement and aging); thus, the rational changes over the decadal to long-term variabilities can be revealed.

The surface incident solar radiation ($R_s$) that directly warms the land surface partly becomes the sensible heat flux that heats the air near the surface [38]. Sunshine duration, collected from the CMA at 2479 meteorological stations, was used to derive $R_s$ in this study, based on the revised Ångström–Prescott equation [39]. The derived $R_s$ from sunshine duration can accurately capture the impacts of both aerosols and clouds on $R_s$ by considering the absorption of water vapor and ozone and the effects of Rayleigh scattering and reproduce the interannual, decadal and long-term changes and trends on $R_s$ [40–42]. Moreover, the derived $R_s$ also has a great spatial-temporal coverage and suffers less from inhomogeneous issues due to instrument replacement and instrument sensitivity drift than the observations of $R_s$ in China [40]. See the Text S1 (online) for more details of the derived $R_s$ from sunshine duration.

The portion of the energy absorbed by the surface is released back to space as outgoing longwave radiation, which is partly reflected or scattered by clouds and atmospheric water vapor to further heat the air and then slow the cooling effect from the increase in altitude. This process can be quantified by the surface downward longwave radiation ($L_d$). See the Text S2 (online) for more details on the method of $L_d$ estimates.

Soil moisture can adjust the distribution of available energy to sensible and latent heat fluxes, but soil moisture datasets are usually not complete enough to be replaced by precipitation amount. Precipitation frequency could better quantify the variation in soil moisture over China compared with precipitation amount [36,37,43]. Because the precipitation amount exhibits a Gamma distribution and the relatively high one saturates the soil moisture, then there is a high correlation between the two. The number of monthly precipitation days ($N_p$, unit: d month$^{-1}$), i.e., precipitation frequency, is defined as days with over 0.1 mm daily precipitation per month.

For some reason (such as irregular observations), the raw data used in this study has missing data. Excluding stations with more than 30%, 20% or 10% of missing records, the results are not much different. To ensure enough available stations in the areas with sparse stations (such as the Tibetan Plateau) and satisfy the credibility of calculating lapse rate (see 2.2 Method), we selected 2168 stations with at least 70% of record length at all the time scales. The spatial distribution of the stations and the elevation over China is shown in Fig. S1 (online).

2.2. Method

The near-surface lapse rate can be estimated by a multiple linear regression between temperature and elevation, and the linear regression includes latitude and longitude to separate the effects of latitude and distance from the coast [7,9,30]. To show the detailed spatial distribution of lapse rates, we used up to 50 nearest stations inside a five-degree-circle (comparable to all the stations in two-degree circle over North China and Southeast China in Fig. S1 online) to estimate the lapse rate for each station that was excluded in the sequent analysis if <15 nearest stations (due to not well meeting the fitting requirement), by adopting multiple linear regression:

$$T = b_0 + b_1 \cdot Lon + b_2 \cdot Lat + b_3 \cdot Ele + e,$$

(1)

where $T$ is $T_s$ or $T_a$; $Lon$, $Lat$ and $Ele$ are the longitude, latitude and elevation, respectively; $b_0$ is the constant and $e$ is the regression residual; $b_1$, $b_2$, and $b_3$ are the regression coefficients, and $b_3$ denotes the estimated lapse rates, i.e., $\gamma_{Ta}$ or $\gamma_{Ts}$. The high partial correlation between $T_s$ ($T_a$) and elevation (Fig. S2 online) and the fit goodness of the regression (Eq. (1)) for each station (Fig. S3 online) show the reliability of the method for calculating the lapse rates. To quantify the contribution of $R_s$, $L_d$ and $N_p$ to the lapse rate trends from 1961 to 2014, the partial least-squares approach was also used:

$$\gamma = \gamma_1 = \sum \beta_i X_i + c + e,$$

(2)

$$C_{Ts} = \beta_1 T_s,$$

(3)

where $\gamma$ is the annual anomaly of $\gamma_{Ta}$ or $\gamma_{Ts}$ relative to the reference period of 1971–2000; $\beta_i$ is the partial regression coefficient for $R_s$, $L_d$ or $N_p$ against to the lapse rate; $X_i$ is the annual anomaly of $R_s$, $L_d$ or $N_p$; $c$ and $e$ are the contact and residual, respectively; $C_{Ts}$ is the contribution of $R_s$, $L_d$ or $N_p$ to the lapse rate trends; and $T_s$ represents the trend in $R_s$, $L_d$ or $N_p$ from 1961 to 2014 by using the least-square method.
3. Results and discussion

3.1. Spatial variations in lapse rates

Fig. 1a, b illustrates the spatial distribution of the multiyear average $\gamma_{Ta}$ and $\gamma_{Ts}$ on the annual and seasonal timescales in China from 1961 to 2014. The lapse rate based on $T_a$ has a similar multiyear regional average as $\gamma_{Ta}$ (0.53 °C/100 m), and they both show the largest values in Northeast China (0.64 °C/100 m for $\gamma_{Ta}$ and 0.67 °C/100 m for $\gamma_{Ts}$). Steep values commonly occur at high altitudes and high latitudes, which is consistent with previous results [17,29]. In the southern Tibetan Plateau, the lapse rates even reach 0.80 °C/100 m. Due to the limited meteorological stations in the western region of the Tibetan Plateau, the lapse rate estimated over the Tibetan Plateau in this study does not seem to represent the entire Tibetan Plateau. The estimates of the multiyear regional average $\gamma_{Ta}$ in Northwest China are both <0.25 °C/100 m in winter. An inversion phenomenon appears at some stations north of Northwest China (Fig. 1), which is in line with previous studies [28,29], so are $\gamma_{Ts}$ estimates. It may be due to the weak solar radiation absorption at the surface due to heavy snowfall in winter and nocturnal radiative cooling at the surface [8]. Furthermore, $\gamma_{Ta}$ maybe also driven by the motion of the air mass, i.e., cold air accumulating at low-elevation sites and warm airflow at high-elevation locations.

$\gamma_{Ta}$ and $\gamma_{Ts}$ over North China are much lower at all the timescales, and most of the values are below 0.2 °C/100 m (Fig. 1). Rapid urbanization and industrial development in North China have resulted in increased emissions of anthropogenic aerosols [44–46]. Large amounts of aerosols in the air scatter or absorb solar radiation to heat the atmosphere and then cool the surface because of declining absorption of solar radiation at the surface [47,48], thereby reducing the lapse rate followed by an increase in atmospheric stability. Enhanced atmospheric stability can inhibit the movement of air masses, which may exacerbate air pollution due to increasing aerosol concentrations and weakening diffusion of pollutants [49–52]. Moreover, the meteorological stations in North China are almost all located at low elevation. Wang et al. [53] revealed that air pollution is also largely related to terrain, because weak or calm winds occur at low elevation to trigger more frequent air stagnation and then to exacerbate pollution. The partial correlation coefficients between temperature and elevation and the variances ($R^2$) for the multiple linear regression are low in North China (Figs. S2 and S3, online), likely due to the effect of local climate [28].

The differences ($\gamma_{Ts}$–$\gamma_{Ta}$) in China have obviously diverse spatial and seasonal patterns, with a range from −0.2 to 0.2 °C/100 m (Fig. 1c). It is a remarkable fact that the multiyear average $\gamma_{Ts}$ values at high latitudes (i.e. in Northwest China and Northeast China) are always much larger than the $\gamma_{Ta}$ values (Fig. 1c(1–5)), especially in summer, where strong $R_a$ weak $L_a$ and low $N_p$ values are distributed (Fig. S4 online). In high altitude areas, such as the Tibetan Plateau, as $R_a$ increases, the temperature rises slower due to the mixing of the surrounding atmosphere [54], resulting in $\gamma_{Ta}$ being steeper than $\gamma_{Ts}$ (Fig. 1). In addition to landscapes and terrains, the climatology of lapse rates is subject to the surface energy budget, and $\gamma_{Ta}$ is more affected by atmospheric motion, which may be one of the causes for different spatial patterns between $\gamma_{Ta}$ and $\gamma_{Ts}$.

3.2. Seasonal cycle in lapse rates

Fig. 2a–h shows the monthly variations in $\gamma_{Ta}$ and $\gamma_{Ts}$ averaged from 1961 to 2014 for China and seven subregions. Generally, the estimations in the multiyear average $\gamma_{Ta}$ exhibit similar seasonal variations, with the maxima occurring in summer and the minima occurring in winter [5,6], so do the $\gamma_{Ts}$ estimates. However, different subregions show various seasonal cycles. In North China and Southeast China, both $\gamma_{Ta}$ and $\gamma_{Ts}$ show steeper values in summer and shallower values in spring. In Northeast China, $\gamma_{Ta}$ and $\gamma_{Ts}$ exhibit no obvious seasonal cycle (Fig. 2e). On the Tibetan Plateau, steeper values of $\gamma_{Ta}$ and $\gamma_{Ts}$ occur in spring and summer; and shallower values of them both appear in winter, which are not consistent with previous some studies that the lapse rate steeper in winter and shallower in summer [21,28,29,55]. Major reasons for the difference seem to be the spatial differences of lapse rates in different seasons on the Tibetan Plateau (Fig. 1) and uneven distribution of meteorological stations there (Fig. S1 online). For
example, in the southern Tibetan Plateau (near the Himalayan Mountains), steep $\gamma_{Ta}$ and $\gamma_{Ts}$ occur in winter and shallow ones occur in summer (Fig. 1b, a); while the seasonal variations of the lapse rates in the northern Tibetan Plateau are opposite (Fig. 1b, a), which is consistent with the studies of Qin et al. [17] and Kattel et al. [56].

Although the seasonal cycle in $\gamma_{Ts}$ is roughly the same as the seasonal cycle in $\gamma_{Ta}$, the differences between the monthly variations in $\gamma_{Ta}$ and $\gamma_{Ts}$ are still considered. Compared with $\gamma_{Ta}$, $\gamma_{Ts}$ estimates are steeper in summer in all areas except for North China (Fig. 2), probably because $\gamma_{Ts}$ is more sensitive to increased $R_s$ in summer, which largely determines the lapse rates from $T_s$ [15].

In North China, the monthly variations in $\gamma_{Ts}$ are lower than those in $\gamma_{Ta}$ are, and the differences between them are approximately equal to 0.08 °C/100 m (Fig. 2e, i). However, in Northwest China, especially in summer, the monthly variations in $\gamma_{Ts}$ are much larger than those in $\gamma_{Ta}$ are, resulting in steeper annual average values (Figs. S5c and S6c online).

3.3. Trend of lapse rates

3.3.1. China

Table 1 describes the trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ on annual and seasonal timescales over China from 1961 to 2014. There is a clear
difference between the $\gamma_{Ta}$ and $\gamma_{Ts}$ trends (0.05 vs. −0.04 °C (100 m)$^{-1}$ century$^{-1}$, $P < 0.05$) on the annual timescale in China (Table 1, Figs. 3a and 4a1, b1). In spring and summer, the trend signs in $\gamma_{Ta}$ are consistent with those in $\gamma_{Ts}$, with significant increasing trends in spring ($P < 0.05$) and nonsignificant decreasing trends in summer ($P$ greater than 0.10). However, $\gamma_{Ta}$ and $\gamma_{Ts}$ display opposite trend signs in winter (0.06 vs. −0.14 °C (100 m)$^{-1}$ century$^{-1}$, $P < 0.05$) and autumn (0.04 vs. −0.03 °C (100 m)$^{-1}$ century$^{-1}$, $P < 0.10$).

We further quantify the contributions of the $R_L$, $L_d$, and $N_p$ trends over China to the trends in $\gamma_{Ta}$ (Fig. 5a) and $\gamma_{Ts}$ (Fig. S7a online). In general, the variations in the three climatic factors could largely explain the long-term changes in $\gamma_{Ta}$ and $\gamma_{Ts}$ in China, $R_L$ contributes the increase of the trend in $\gamma_{Ta}$ except in summer, and the contribution of $R_L$ to the trend in $\gamma_{Ta}$ is the largest in winter (by 0.05 °C (100 m)$^{-1}$ century$^{-1}$), followed by that in autumn (0.01 °C (100 m)$^{-1}$ century$^{-1}$) and spring. For $\gamma_{Ts}$ trends, the contributions of $R_L$ to them are all negative on annual and seasonal timescales, and the value is also the largest in winter (−0.04 °C (100 m)$^{-1}$ century$^{-1}$), followed by that in summer (−0.02 °C (100 m)$^{-1}$ century$^{-1}$), autumn and spring (−0.01 °C (100 m)$^{-1}$ century$^{-1}$).

The contributions of $L_d$ to the trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ are consistent, resulting in declining lapse rates in winter (−0.04 °C (100 m)$^{-1}$ century$^{-1}$) but increasing rates in other seasons (approximately 0.01 °C (100 m)$^{-1}$ century$^{-1}$). $\gamma_{Ta}$ increases by nearly 0.02 °C (100 m)$^{-1}$ century$^{-1}$ from 1961 to 2014 due to the variations in $N_p$ on annual and seasonal timescales. Nevertheless, $\gamma_{Ts}$ decreases by −0.02 °C (100 m)$^{-1}$ century$^{-1}$ in winter and by −0.01 °C (100 m)$^{-1}$ century$^{-1}$ in autumn due to the effect of $N_p$.

### 3.3.2. Seven subregions

To further investigate its regional contrast, the interannual variability and spatial details in seven subregions are considered (Table 1, Figs. 4, S5, S6, and S8–S10 online). The spatial distribution of the trends between $\gamma_{Ta}$ and $\gamma_{Ts}$ shows apparent discrepancies on the annual timescale from 1961 to 2014 (Fig. 4). On an annual timescale, the trend signs for $\gamma_{Ta}$ and $\gamma_{Ts}$ are opposite except in Southeast China, Southwest China and Northwest China (Table 1, Figs. 4 and S5 online). In winter, the trends in $\gamma_{Ta}$ are negative except in Southeast China, with the largest downtrend in Northeast China of −0.42 °C (100 m)$^{-1}$ century$^{-1}$ ($P < 0.05$) (Table 1, Figs. 4 and S8 online). In spring, the change in $\gamma_{Ta}$ over China appears to be consistent with that in $\gamma_{Ts}$ (Table 1, Fig. 3). In summer, a significant downtrend in $\gamma_{Ta}$ appears in only Southwest China (−0.05 °C (100 m)$^{-1}$ century$^{-1}$, $P < 0.05$), where the variation of $R_L$ contributes −0.03 °C (100 m)$^{-1}$ century$^{-1}$ to $\gamma_{Ta}$ trend (Fig. 5). In autumn, the regional average of $\gamma_{Ta}$ appears to be declining in all subregions except in Southeast China, with the largest trend on the Loess Plateau (Table 1, Fig. S10 online).

The spatial differences in $\gamma_{Ta}$ ($\gamma_{Ts}$) trends mainly depend on their sensitivity of the lapse rate to climatic factors in different regions, and $R_L$, $L_d$ and $N_p$ could explain the contributions to the lapse rate trends. On the Tibetan Plateau, $R_L$, $L_d$ and $N_p$ could fully account for the weakened trends in $\gamma_{Ta}$ in winter and autumn (Fig. S5b); and all the factors could mostly explain the trends in $\gamma_{Ta}$ in summer (67%)}
**Fig. 4.** Spatial distribution of the annual and seasonal trends (unit: °C (100 m)⁻¹ century⁻¹) in $\gamma_T$ (a1–a5), $\gamma_s$ (b1–b5) and their differences ($\gamma_s - \gamma_T$, c1–c5) from ~2200 stations over China from 1961 to 2014. Large dots denote significant trends ($P < 0.05$). SCS denotes the South China Sea Islands.

**Fig. 5.** Contributions (unit: °C (100 m)⁻¹ century⁻¹) of three climatic factors, i.e., $R_s$ (in red), $L_d$ (in orange) and $N_p$ (in blue) to trends in $\gamma_T$ from 1961 to 2014 on annual and seasonal time scales over China and seven subregions.
and autumn (75%, Fig. S7b online). Over Northwest China, the increasing trends in $\gamma_{Ta}$ on the annual, summer and autumn timescales mainly result from the contribution of $L_d$ (by 0.04, 0.02 and 0.04 °C (100 m)$^{-1}$ century$^{-1}$, respectively), where the trends of $L_d$ show obvious increases (Figs. 5c, S11 online). However, $\gamma_{Ts}$ are principally influenced by $R_s$ and $L_d$ (Fig. S7c online). $R_s$ and $L_d$ can mainly account for most trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ in the western Plateau, North China and Northwest China (Figs. 5 and S7 online).

The three climatic factors jointly can better explain the trends in $\gamma_{Ts}$ and contribute a large proportion of its long-term trends. Over Northwest China and Southeast China, the trends in lapse rates are mainly explained by $N_p$. Moreover, $R_s$ also plays an important role in influencing the trends of $\gamma_{Ta}$ and $\gamma_{Ts}$ in Southwest China. Except in winter and summer over Southeast China, the three climatic factors contribute almost 70% of the variations in $\gamma_{Ta}$ and $\gamma_{Ts}$ in southern China.

4. Conclusions

This study investigated the climatology variations and long-term trends of $\gamma_{Ta}$ and $\gamma_{Ts}$ based on their different sensitivity to local surface energy balance and large-scale energy transport from 1961 to 2014 over China, and quantified the contribution of the climatic factors ($R_s$, $L_d$ and $N_p$) to the lapse rates from the perspective of the surface energy balance.

The lapse rate based on $T_s$ has the same multiyear average as $\gamma_{Ts}$ (0.53 °C/(100 m)), and they have similar seasonal cycles, but not all subregions follow the changes of the maxima appearing in summer and the minima in winter (such as Northeast China). Therefore, the constant value of the environmental lapse rate (0.65 °C/(100 m)) that is normally assumed is not appropriate for China. $\gamma_{Ta}$ due to stronger impact of the local surface energy, shows a steeper multiyear average than $\gamma_{Ts}$ at high latitudes. In North China, a shallow lapse rate may be caused by severe air pollution, which will be expected to introduce the aggravation of air pollution due to increasing the stability of the atmospheric state.

In addition, there is an obvious difference in trend between $\gamma_{Ta}$ and $\gamma_{Ts}$ (0.05 vs. −0.04 °C (100 m)$^{-1}$ century$^{-1}$, $P < 0.05$) from 1961 to 2014 over China. Especially in northern China, $\gamma_{Ta}$ and $\gamma_{Ts}$ appear the opposite signs in trends, with increasing $\gamma_{Ta}$ and declining $\gamma_{Ts}$. In southern China, $\gamma_{Ta}$ and $\gamma_{Ts}$ show the same sign in the long-term trends with increases in Southwest China and decreases in Southeast China. The long-term changes of $\gamma_{Ta}$ and $\gamma_{Ts}$ climatology are inseparable from the impact of surface energy budget. $R_s$, $L_d$ and $N_p$ can account for 80% and 75% of the long-term trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ in China, respectively. $R_s$ and $L_d$ largely account for the trends in $\gamma_{Ta}$ and $\gamma_{Ts}$ in northern China, and $N_p$ could explain the trends in southern China.

The lapse rate determines the stability of the atmospheric state and then affects the vertical dispersion of air pollutants. Improvement in the study of the lapse rate, including significant spatial discrepancies in the lapse rates and their long-term changes, will help to understand the changes of atmospheric stability with ongoing global warming and pollution episodes. In addition, the contribution of surface energy balance to the lapse rate will also benefit future researches on regional climate changes.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Key Research & Development Program of China (2017YFA0603601) and the National Natural Science Foundation of China (41525018 and 41930970). Meteorological data (i.e., sunshine duration, precipitation amount and cloud fraction) were obtained from the China Meteorological Administration (CMA, http://data.cma.cn/en/). Maps in this article were reviewed by Ministry of Natural Resources of the People’s Republic of China (GS(2020)1045).

Author contributions

Kaijun Wang proposed the study. Yanyi He and Kaijun Wang conceived the study. Yanyi He conducted the analysis and wrote the initial draft of the paper. All authors participated in interpreting and revising the paper.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.04.001.

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