Near-surface air temperature lapse rates in the mainland China during 1962–2011

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[1] Land surface hydrological modeling is sensitive to near-surface air temperature, which is especially true for the cryosphere. The lapse rate of near-surface air temperature is a critical parameter when interpolating air temperature from station data to gridded cells. To obtain spatially distributed, fine-resolution near-surface (2 m) air temperature in the mainland China, monthly air temperature from 553 Chinese national meteorological stations (with continuous data from 1962 to 2011) are divided into 24 regional groups to analyze spatiotemporal variations of lapse rate in relation to surface air temperature and relative humidity. The results are as follows: (1) Evaluation of estimated lapse rate shows that the estimates are reasonable and useful for temperature-related analyses and modeling studies. (2) Lapse rates generally have a banded spatial distribution from southeast to northwest, with relatively large values on the Tibetan Plateau and in northeast China. The greatest spatial variability is in winter with a range of 0.3°C–0.9°C · 100 m^{-1}, accompanied by an inversion phenomenon in the northern Xinjiang Province. In addition, the lapse rates show a clear seasonal cycle. (3) The lapse rates maintain a consistently positive correlation with temperature in all seasons, and these correlations are more prevalent in the north and east. The lapse rates exhibit a negative relationship with relative humidity in all seasons, especially in the east. (4) Substantial regional differences in temporal lapse rate trends over the study period are identified. Increasing lapse rates are more pronounced in northern China, and decreasing trends are found in southwest China, which are more notable in winter. An overall increase of air temperature and regional variation of relative humidity together influenced the change of lapse rate.

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1. Introduction

[2] Quantifying the spatial distribution of temperature, especially the relationship between temperature and altitude, is essential for understanding hydrological processes and their variabilities. This is because those processes are sensitive to air temperature, especially in cryospheric regions, where air temperature influences the melting of snow, glacier, and permafrost, and controls exchanges of energy and water fluxes between land and atmosphere [*Blöschl*, 1991; *De Scally*, 1997; *Richard and Gratton*, 2001; *Zuzel and Cox*, 1975; *Singh and Singh*, 2001]. Correct measurement of spatial variability of air temperature has been recognized as a major constraint in snow modeling, and its introduction in these models can improve them somewhat [*Cazorzi and Fontana*, 1996]. Therefore, accurate modeling of air temperature is crucial to hydrological models, particularly for cryospheric hydrology studies [*Otto-Bliesner et al.*, 2006; *Ferguson*, 1999; *Minder et al.*, 2010; *Gardner et al.*, 2009; *Petersen and Pellicciotti*, 2011].

[3] In land surface hydrological models, the standard procedure for temperature input is interpolation from limited meteorological stations to gridded cells that cover the watershed [*Marshall et al.*, 2007; *Gardner et al.*, 2009; *Minder et al.*, 2010; *Jabot et al.*, 2012; *Kirchner et al.*, 2013; *Petersen and Pellicciotti*, 2011], which is often more important than other factors in those models in high mountain basins [*Charbonneau et al.*, 1981]. Lapse rate is often used to interpolate from point measurements to the grids, which highlights the importance of realistic lapse rates in the prediction of air temperature. The commonly used method is use of a fixed adiabatic lapse rate in the range 0.60°C to 0.65°C · 100 m^{-1} to create gridded temperature for hydrological models [*Singh et al.*, 2006; *Machguth et al.*, 2006; *Michlmayr et al.*, 2008; *Gardner et al.*, 2009; *Roe and O'Neal*, 2010; *Immerzeel*, 2012; *Gao et al.*, 2012]. This method is problematic [*Minder et al.*, 2010], especially on glacier surfaces [e.g., *Greuell and Böhm*, 1998; *Braun and Hock*, 2004; *Hanna et al.*, 2005;

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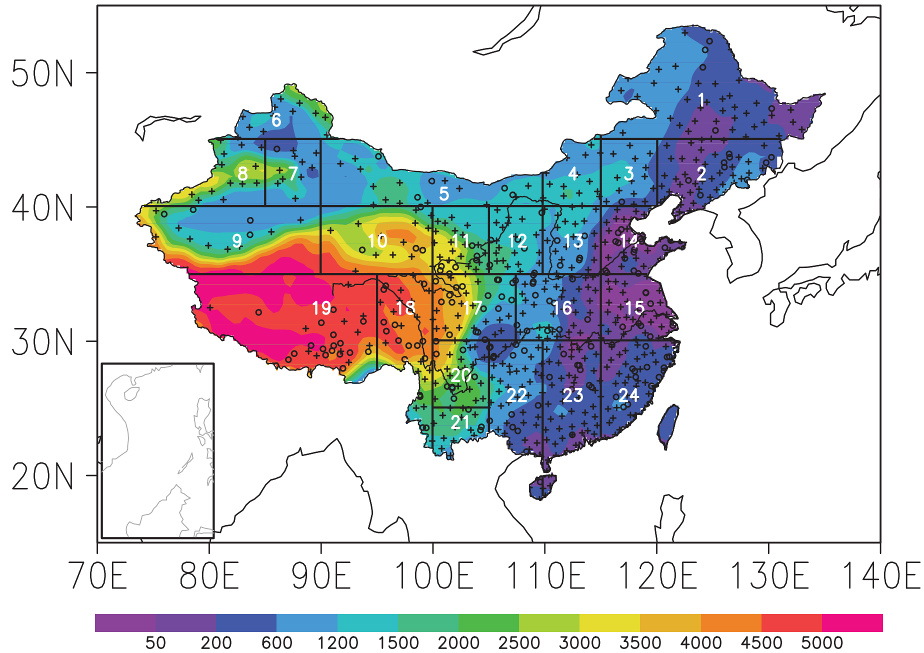

Figure 1. Distribution of the 754 Chinese national meteorological stations employed in this study. The 553 stations with plus sign and 24 groups denoted by the white numbers are for the lapse rates calculation, while the other 201 stations with open circle are for the lapse rates evaluation. The shades illustrate the elevation from Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (m).

Shea and Moore, 2010], because it implicitly assumes that terrain and surface processes are unimportant in determining surface temperature. This assumption is certainly not valid under real conditions. Therefore, a few studies produced time-varying lapse rates and stressed the importance of such variability in hydrological models [e.g., *Braun and Hock*, 2004; *Minder et al*., 2010; *Jabot et al*., 2012]. Some appreciable implications for hydrological modeling were found in these results. As an example, *Minder et al*. [2010] characterized lapse rates in the Cascade Mountains and emphasized the importance of their spatial variation and seasonality. It was found that using a realistic lapse rate could help reproduce mountain hydrology with regard to amplitude and phase of seasonality. Another example [*Marshall et al*., 2007] shows that different lapse rates could significantly change the amount of summer snowmelt or accumulation on the ice field.

[4] Near-surface temperature lapse rate varies on diurnal and seasonal time scales because of changes in sensible heat flux between the free atmosphere and underlying surface [*Gardner et al*., 2009], and it also varies spatially depending on macro topography [*Yoshino*, 1975]. Numerous studies have examined spatiotemporal variability of lapse rates over different regions, e.g., the Appalachian Mountains [*Bolstad et al*., 1998], Canadian Rockies [*Shea et al*., 2004], islands of northern Canada [*Marshall et al*., 2007], and Arctic glaciers [*Gardner et al*., 2009]. They all found that lapse rates are consistently weaker than the constant lapse rate as $0.65°\mathrm{C} \cdot 100\,\mathrm{m}^{-1}$ and have significant spatial and temporal features. For example, *Marshall et al*. [2007] found diurnal variability in the northern and southern sectors of the Prince of Wales Icefield, suggesting regional or synoptic-scale (rather than local) controls. *Petersen and Pellicciotti* [2011] found shallow lapse rates during night and morning hours when katabatic wind is present, while steeper lapse rates were typical of afternoon. Seasonal variability of lapse rates was examined before, such as in Arctic glaciers [*Gardner et al*., 2009] and mountain basin in south-central Idaho [*Blandford et al*., 2008]. Lapse rates are generally steeper in summer and more shallow in winter. In addition, *Rolland* [2003] found the spatial variation of lapse rates in Alpine regions, linked with latitude changes and topography.

[5] Similar spatiotemporal characteristics of lapse rates are found in the mainland China [*Fang and Yoda*, 1988; *Tang and Fang*, 2006]. However, very little has been done over the last two decades toward improving understanding of spatiotemporal variations of lapse rates in China. In recent years, some studies have suggested that near-surface air temperature at higher elevations is increasing more rapidly, especially on the Qinghai-Tibet Plateau [*Liu and Chen*, 2000; *Qin et al*., 2009; *Wang et al*., 2011; *Rangwala et al*., 2010]. *Pepin* [2001] pointed out that surface-based air temperature lapse rates may change in a warmer global climate. These studies motivated us to explore how the lapse rate, which is a variable connected with altitude, might vary under global warming. It is recognized that spatially distributed realistic lapse rates with fine spatial resolution are urgently needed for hydrological modeling studies of cryospheric regions.

[6] In this paper, we quantify the lapse rate of near-surface air temperature and examine geographic distributions of mean annual and seasonal lapse rates in the mainland China from 1962 to 2011. Our analysis gives long-term statistics and considers the influence of two important factors (air temperature and relative humidity) on lapse rate. With denser station networks and longer observations compared with previous studies, we expect to achieve more reliable estimates of the lapse rate.

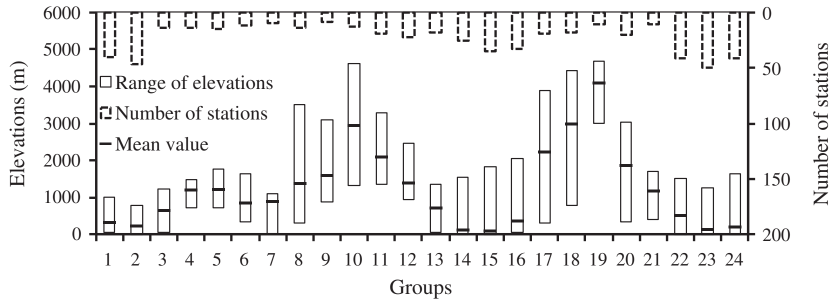

Figure 2. The range of station elevations for each of 24 groups (solid bar) and their mean station elevation (dash), as well as the number of stations in each group (dotted bar).

2. Data Set and Method

2.1. Data Set

[7] The data set used is derived from the "Monthly Surface Climate Variables of China" catalog (SURF_CLI_CHN_MUL_MON), issued by the National Meteorological Information Center of the China Meteorological Administration. This data set covers the period from January 1951 to the present and contains 756 stations distributed across China. Here we used 50 year data from January 1962 through December 2011. Two variables are included; one is near-surface air temperature (T_{air}), and the other is relative humidity. Two stations, one on an island in the South China Sea and one in Taiwan, are not included. Thus, the results are restricted to the mainland China and a total of 754 stations.

[8] The 754-station T_{air} was divided into two groups. One is for estimating lapse rates, and the other for evaluation of those lapse rates. Data from a station were removed if they were missing for more than 1 month. Ultimately, data from 553 stations, continuous from January 1962 to December 2011, were used in the estimation (Figure 1). The remaining discontinuous data set of 201 stations (also shown in Figure 1) were used to independently validate accuracy of the estimated lapse rates.

[9] A digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM; downloaded from http://srtm.usgs.gov/) with a resolution of 500 m was introduced to reproduce the topography in China shown in Figure 1 and elevations in equation (3) in the following section.

2.2. Method

2.2.1. Estimating Lapse Rate

[10] To estimate regional lapse rates, temperatures at 553 stations were divided into 24 groups (Figure 1). Numbers of the groups were determined such that they had similar regional climate settings and a reasonable number of stations (10–50), with some difference of elevation to allow for reliable lapse rate estimation. Figure 2 shows ranges and mean elevations as well as the numbers of stations for the 24 groups. Only three groups have a small range of elevations, between 760 m and 1000 m. The remainders have ranges greater than 1000 m.

[11] The multiple linear regression method [see *Du et al.*, 2010; *Fang and Yoda*, 1988] is adopted in our study, which includes the coactions of elevation, longitude, and latitude on lapse rate so that other factors (except elevation) such as latitude and continentality would not unduly influence lapse rate calculations.

[12] Lapse rates are estimated for each group using multiple linear regression by equation (1).

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3, \tag{1}$$

where Y is T_{air}; X_1, X_2, X_3 are longitude, latitude, and elevation of each station, respectively; a_0, a_1, a_2, and a_3 are the regression coefficients, and a_3 designates the estimated lapse rates for the time period corresponding to the averaged T_{air}.

2.2.2. Evaluation Approach

[13] The evaluation involves statistical comparison of the independent 201-station data (T_{air}) with the newly generated temperature (T_{new201}) at the corresponding stations, using the estimated lapse rates and elevations of the stations for the period January 1962 to December 2011.

[14] First, sea level temperatures for all stations were calculated by means of the estimated monthly mean lapse rates, station elevations, and $T_{\mathrm{air,}}$ using equation (2) for 1962–2011. Then, the sea level temperatures and lapse rates at the stations were interpolated to a regular 0.5° × 0.5° grid for generating T_{new} according to equation (3).

$$T_{\mathrm{sealevel}-sta} = T_{\mathrm{air}} + LR_{sta} \times Ele_{sta}/100 \tag{2}$$

$$T_{\mathrm{new}} = T_{\mathrm{sealevel-grid}} - LR_{\mathrm{grid}} \times \mathrm{DEM}/100, \tag{3}$$

where T_{air} and Ele_{sta} are the observed temperature and elevation at a station; LR_{sta} is the estimated lapse rate at the station; $T_{\mathrm{sealevel}\text{-}sta}$ is the sea level temperature at the station; $T_{\mathrm{sealevel\text{-}grid}}$, LR_{grid}, DEM, and T_{new} are the sea level temperature,

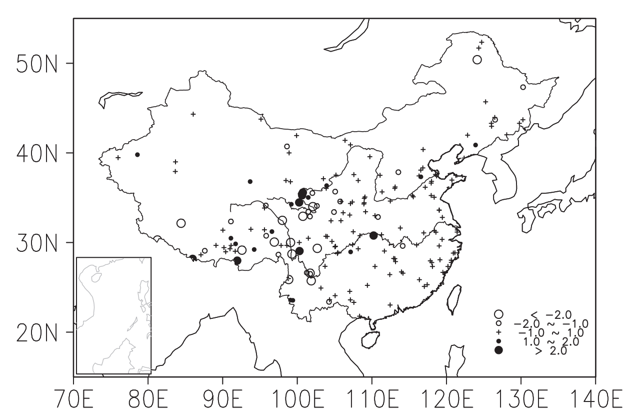

Figure 3. Distribution of BIAS (°C) between the station observations and the corresponding T_{new201} generated by the lapse rates and the altitude from independent 201 Chinese meteorological stations.

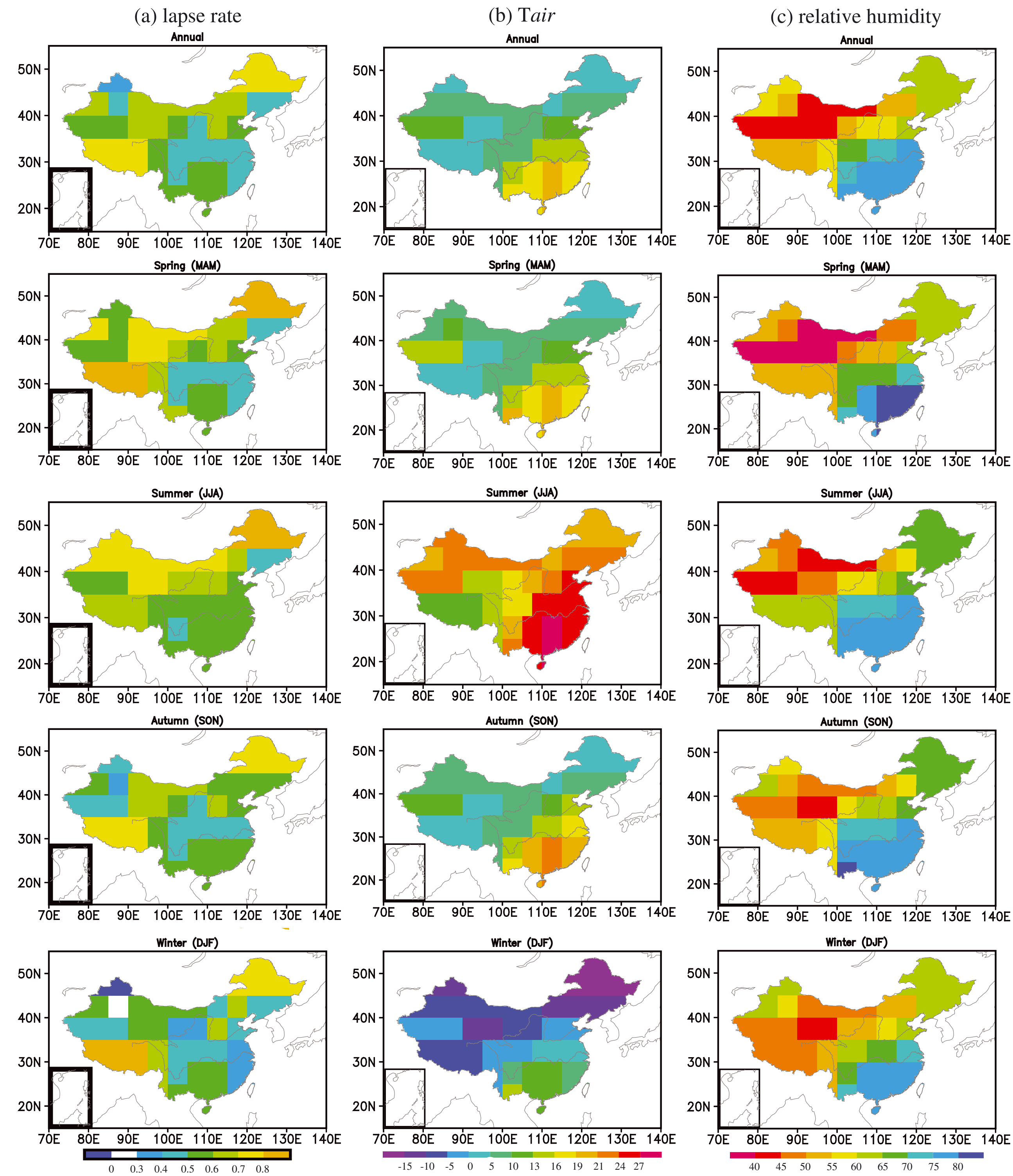

Figure 4. Spatial distribution of annual and seasonal mean lapse rate (°C · 100 m^{-1}), T_{air} (°C), and relative humidity (%) in the mainland China averaged over the period of 1962–2011.

lapse rate, elevation, and estimated near-surface air temperature, respectively, which were based on a grid cells. Thus, for all lapse rate estimates, all the stations in the same region share the same lapse rate (LR_{sta}), and there are totally 24 values in the mainland China; while the LR_{grid} is the interpolated grid values (0.5° × 0.5° for this study) from all LR_{sta}.

[15] Second, the lapse rates and sea level temperature at the 201 remaining stations were extracted according to equation (3). Then, the observed elevations at the 201 stations were used to calculate the estimated temperature (T_{new201}) from January 1962 to December 2011, by using the LR_{grid}. Finally, the estimated T_{new201} was verified with the observed T_{air} at the 201 stations.

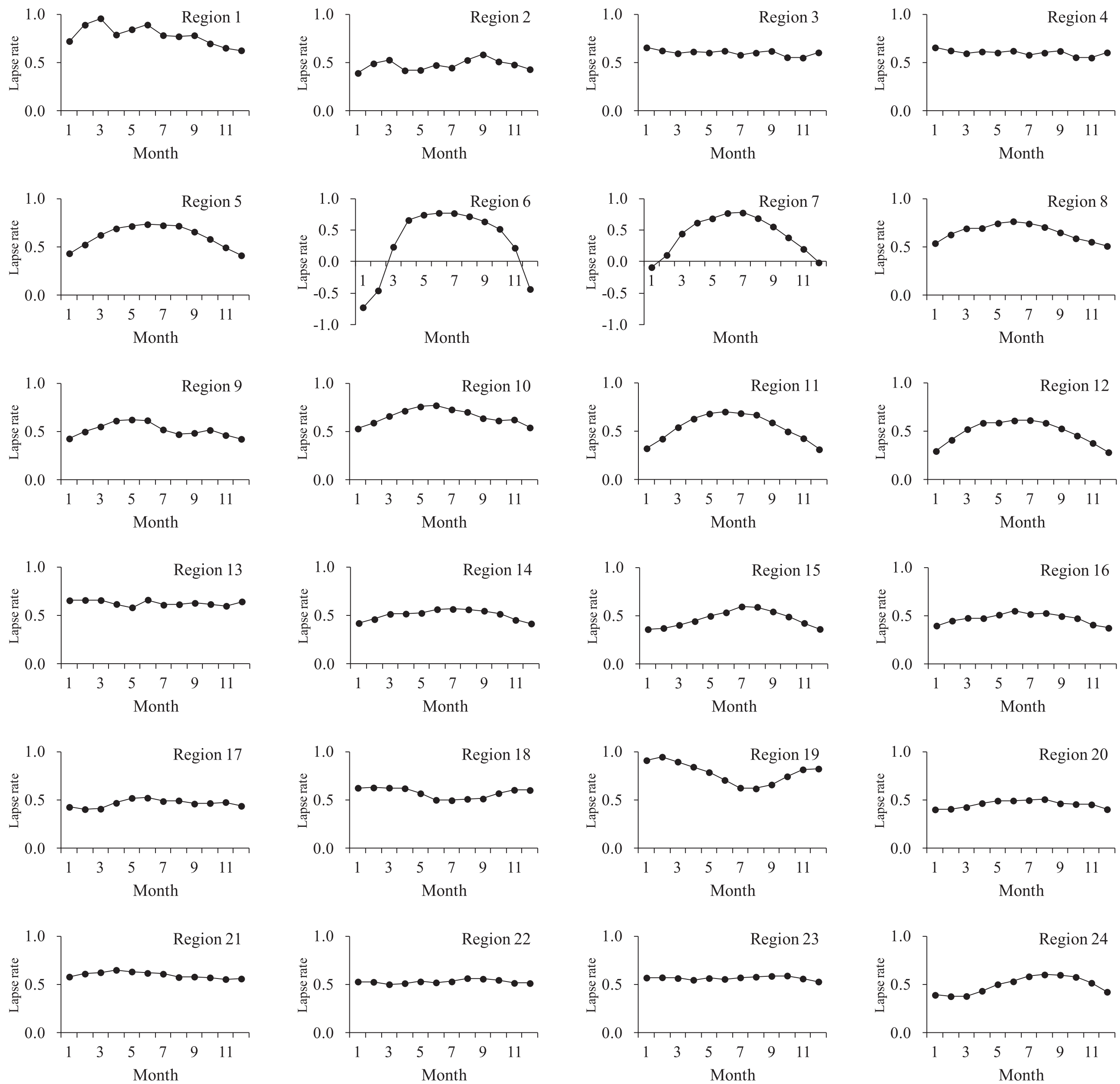

Figure 5. Monthly variation of lapse rates ($°C \cdot 100\,m^{-1}$) for 24 groups averaged over the period of 1962–2011.

2.2.3. Linear Regression

[16] To detect temporal trends for all time series data within the 24 groups, linear regression (least squares method) was used. Linear regression for 1962–2011 was done on the annual and four seasonal mean spatially distributed values.

[17] Four seasons were defined—spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

3. Results and Discussions

3.1. Evaluation of Estimated Lapse Rates

[18] To evaluate the utility of the estimated lapse rates for estimating surface air temperature, an independent validation was performed. This was based on the 201 validation meteorological stations not used in estimating the lapse rates. These stations are concentrated in the Yellow River and Yangtze River basins, and on the eastern Tibetan Plateau; there are fewer stations in northwest and northeast China (Figure 1).

[19] Bias error (BIAS) was used as evaluation criteria for performance of the estimated lapse rates. BIAS is defined as

$$\mathrm{BIAS} = \sum_{i=1}^{N} (T_{\mathrm{new201}} - T_{\mathrm{air}})/N \qquad (4)$$

[20] Here $N = 201$. Figure 3 shows BIAS between T_{new201} and T_{air} at 201 stations, based on the monthly mean values

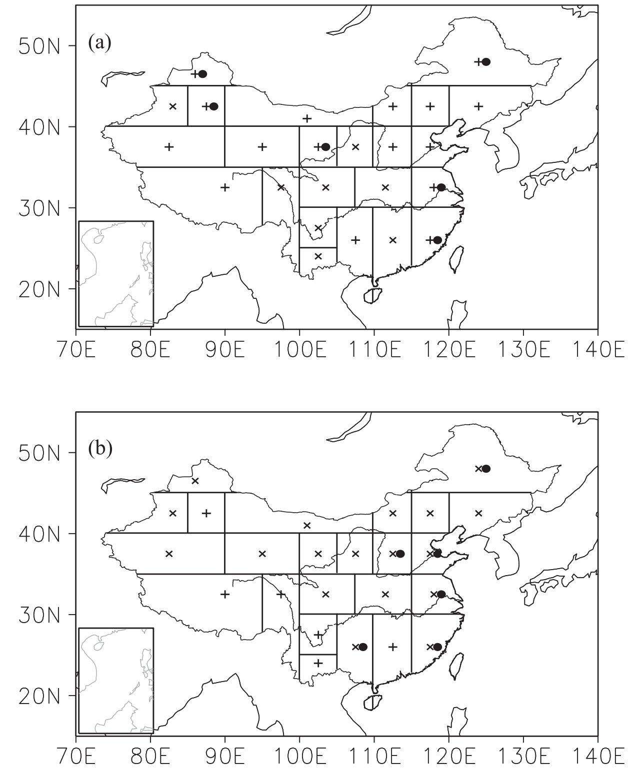

Figure 6. Statistical results (a) between annual mean lapse rate and annual mean air temperature and (b) between annual mean lapse rate and annual mean relative humidity for the period of 1962–2011 based on the 24 groups. The plus represents the positive correlations, while the cross represents the negative ones. The closed circle means the significant correlation at the 95% significant level.

from January 1962 to December 2011. It is found that the correlation coefficient between the two time series is over 0.95 which is statistically significant at the 99% significant level. There is both negative and positive bias, which indicates that there is no systematic error in the estimated T_{new201}. For most stations, BIAS lies within ±1.0°C, showing that the estimated lapse rates can be used to provide useful estimates for temperature at unsampled sites with reasonable accuracy. However, large BIAS value was found at some locations on the central and eastern Tibetan Plateau, which are most likely attributed to uncertainty in the estimated lapse rates because of the sparse distribution of meteorological stations, among other factors. Regions 18 and 19 are much larger than other regions, making application of the lapse rate concept less useful.

3.2. Spatial Distribution of Lapse Rates

[21] The spatial distribution of annual and four seasonal mean lapse rates are shown in Figure 4a. The lapse rates generally have a banded distribution from southeast to northwest and range from 0.3°C to 0.9°C · 100 m^{-1}, which agrees well with the results of *Fang and Yoda* [1988]. The spatial variability of lapse rates in winter was greater than in the other three seasons, with a range of 0.3°C–0.9°C · 100 m^{-1}, whereas the smallest variability was in eastern China during summer. Lapse rates on the Tibetan Plateau and northeast China were generally greater than in other regions, except for summer. Lapse rates in these two regions showed relatively small seasonal variability. On the plateau, the lapse rates ranged from 0.6°C · 100 m^{-1} in summer to 0.8°C · 100 m^{-1} in spring-winter, and in northeast China, they were within 0.7°C–0.9°C · 100 m^{-1}. It is interesting that an inversion phenomenon appears in the northern Xinjiang Province in winter, where there is steep topography and heavy snowfall. Processes in complex terrain include cold air accumulation in lower elevation locations and more exposure to warm airflow at higher elevation sites, which can form inversions.

[22] Except for the Tibetan Plateau, lapse rates over the mainland China always have a summer maxima and winter minima, consistent with previous results [*Pepin*, 2001; *Pepin and Kidd*, 2006; *Rolland*, 2003; *Tang and Fang*, 2006; *Marshall et al.*, 2007; *Blandford et al.*, 2008; *Gardner et al.*, 2009; *Minder et al.*, 2010]. This has to do with seasonal cycle of the solar heading. Moreover, it was found that estimated lapse rates over most regions were weaker than the commonly used environmental lapse rate (a constant value of 0.65°C · 100 m^{-1}). However, there are steeper values in the northeast, northwest, and Tibetan Plateau. This shows once again that the normally assumed constant value is not appropriate for China.

[23] The distinction between dry and wet conditions is extremely important in controlling the lapse rate near the surface [*Kattel et al.*, 2013]. Generally, lapse rates are weaker in humid conditions than in dry areas [*Pepin*, 2001; *Tang and Fang*, 2006; *Blandford et al.*, 2008; *Minder et al.*, 2010], which is due to the fact that humid air has a higher probability of heating by latent heat released from condensation at higher elevation. To further understand the relationship between lapse rate and water vapor in the atmosphere, Figures 4b and 44c show the spatial distribution of annual and seasonal mean T_{air} and relative humidity, averaged over 1962–2011. Both variables have a similar spatial distribution, dominated by a gradual decline from southeast to northwest. Interestingly, the two spatial distributions are nearly opposite. Greater lapse rates are always under much drier conditions, consistent with the theory and prior results.

[24] Specifically, on the Tibetan Plateau, relative humidity decreases from summer to winter, while the lapse rate has an opposite change. This demonstrates the importance of humidity to lapse rate on the seasonal scale.

3.3. Seasonal Variation of Lapse Rates

[25] Near-surface temperature lapse rate varies on seasonal time scales because of changes in sensible heat flux and different climate settings, which determines the diversity in the variation of lapse rates in China. Figure 5 show the mean monthly variation of lapse rates for 24 groups averaged over the period of 1962–2011. It is found that monthly variation is very different within 24 groups. In the Northeast China (regions 1–4), there is no obvious variation. In most of regions located in the northern region of the north of the Yangtze River (region 5–16), however, lapse rates are steeper in summer and more shallow in winter except for

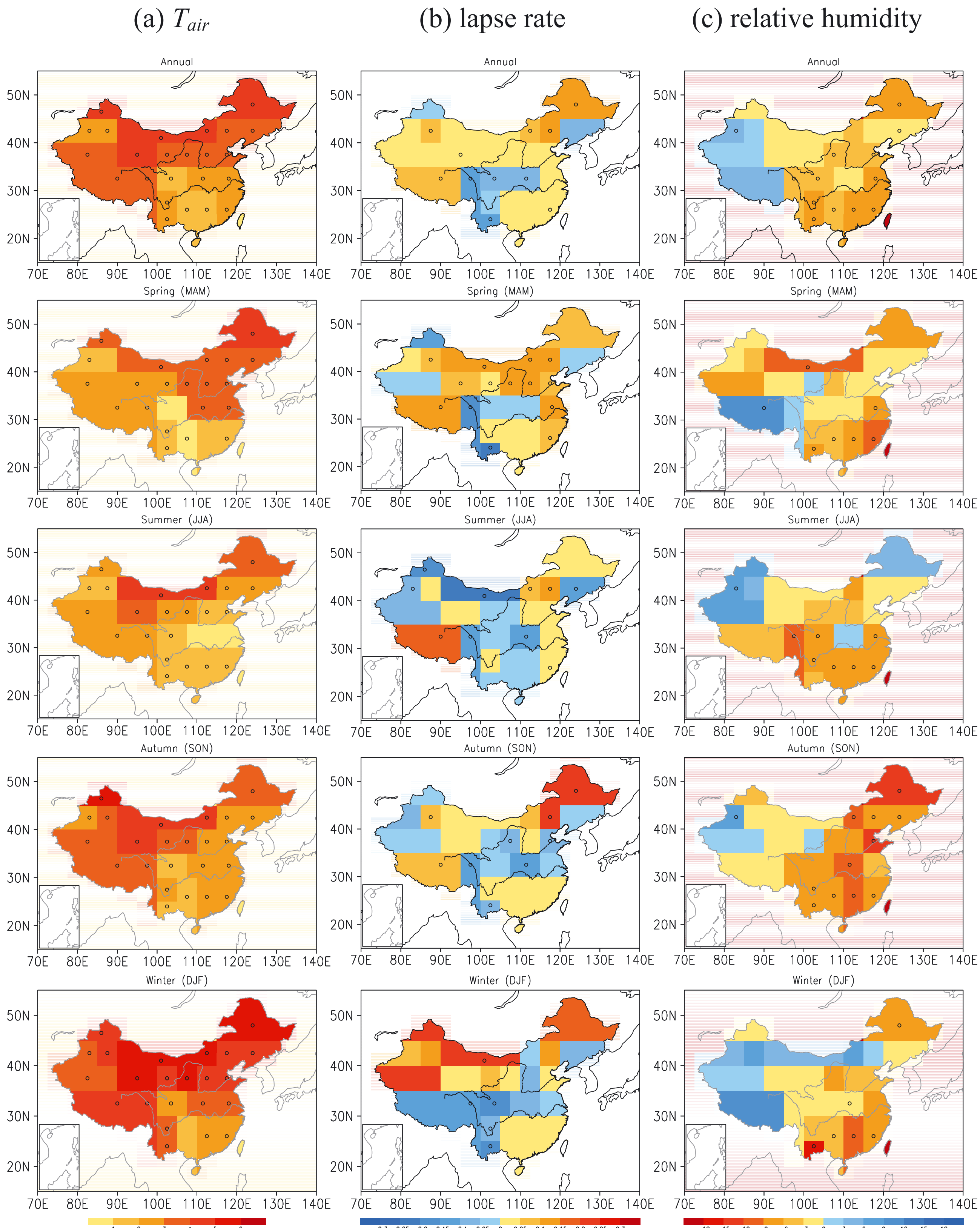

Figure 7. Linear annual and seasonal trends of T_{air} ($°\mathrm{C} \cdot 100\mathrm{a}^{-1}$), lapse rate ($°\mathrm{C} \cdot 100\,\mathrm{m}^{-1} \cdot 100\mathrm{a}^{-1}$), and relative humidity ($\% \cdot 100\mathrm{a}^{-1}$) over the period of 1962–2011. The marker of circle means the significance at the 95% significant level.MAM,March-April-May;JJA,June-July-August; SON, September-October-November; DJF, December-January-February.

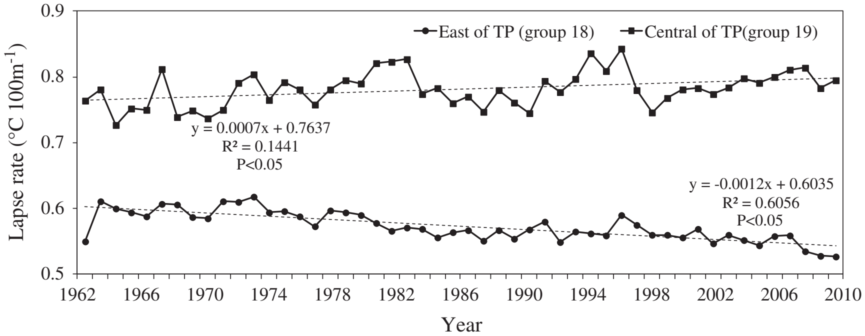

Figure 8. Time series of annual mean lapse rate ($°C \cdot 100\,m^{-1}$) in group 18 and group 19 on the Tibetan Plateau. The dotted lines represent the linear trend from 1962 to 2011.

regions 9 and 13. In region 9, the lapse rates display different monthly variation, with steeper lapse rates in spring and weaker values in summer, whereas in region 13 and region 17, the lapse rates have no obvious variation. Over the Tibetan Plateau (regions 18 and 19), lapse rate values are higher in winter and lower in summer. In the southern China (regions 20–24), the variability of lapse rate is smaller without obvious seasonal variation.

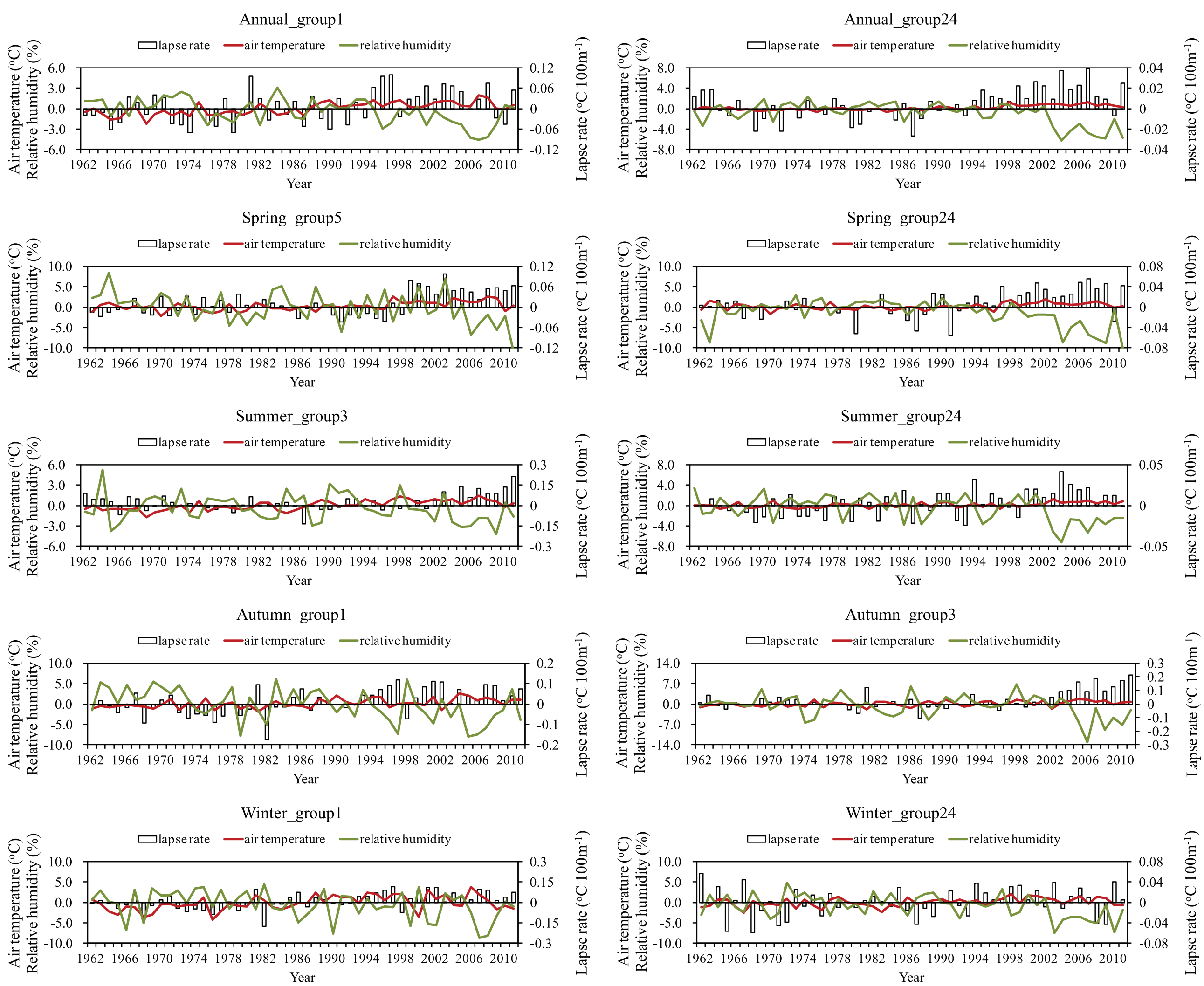

Figure 9. Time series of annual and seasonal mean lapse rate ($°C \cdot 100\,m^{-1}$), T_{air} (°C), and relative humidity (%) for the selected regions with significant linear trends in the past 50 years. All the values are anomalies relative to the 1971–2000 averages. Group 1 represents the Northeast China, and groups 3 and 5 means the most regions of Inner Mongolia, and group 24 is for the southeast coastal areas.

3.4. Lapse Rate in Relation to T_{air} and Relative Humidity

[26] To reveal the relationship between lapse rate, T_{air}, and relative humidity on the interannual scale, statistical analysis was made for annual and seasonal mean values based on the 24 groups from 1962 to 2011. All the values in the statistical analysis are anomalies relative to 1971–2000 averages. There is a consistently positive relationship between air temperature and lapse rate with 95% significance on annual, spring, and summer bases. This means that the warming in the past 50 years has probably supported the increase of lapse rate. On the contrary, the correlation between relative humidity and lapse rate is negative with 95% significance, except for autumn. The results are indicative of weaker lapse rates under warmer and more humid conditions, consistent with previous studies [*Pepin*, 2001; *Tang and Fang*, 2006; *Blandford et al.*, 2008; *Minder et al.*, 2010].

[27] Figure 6 shows the statistical results based on annual mean values. The positive relationship between lapse rate and air temperature is only valid in northern and eastern parts. The negative relationship between lapse rate and relative humidity appears in most groups, especially in eastern China where the significance level reaches 95%. The results indicate that both of relative humidity and temperature influence the lapse rates together, although their significantly influenced regions are different from each other.

3.5. Linear Trend of Lapse Rates

[28] Under the influence of global warming and regional climate change, how do lapse rates vary? Linear trends of annual and seasonal mean T_{air}, lapse rates, and relative humidity from 1962 to 2011 are shown in Figure 7. Linear regression was used to detect the trend. Figure 7a shows an obvious warming trend for all seasons and across all mainland China; however, lapse rates (Figure 7b) show trends with different signs, depending on season and region. This is expected, since lapse rates do not depend solely on temperature.

[29] Except southwest China and northern Xinjiang Province, most regions had increasing lapse rate trends, similar to spring and autumn. In summer, however, most regions had decreasing trends. In northern China and south of the Yangtze River during winter, lapse rates were increasing. On the country scale except for summer, higher surface air temperatures tended to be linked with increased lapse rate and thus less warming at higher elevations.

[30] The lack of full agreement between trends of T_{air} and lapse rate indicates that there must be factors other than surface air temperature that affect lapse rates. To clarify the reason for the lapse rate variability over the past 50 years and why these changes are distributed spatially, linear trends of relative humidity are shown in Figure 7c. This reveals that in most regions, relative humidity was decreasing. For most groups, the trends of lapse rate and relative humidity have opposite signs. This is especially true in the northern and southern parts as well as on the Tibetan Plateau, where there are either extremely dry or humid conditions (Figure 4).

[31] In particular, across the Tibetan Plateau region the lapse rates had an increasing trend in summer and autumn and a decreasing trend in winter over the past 50 years. This corresponds to the decreasing relative humidity in summer and autumn, and the increasing relative humidity in winter.

[32] Over the recent years, increased attention has been paid to elevation dependency of warming rates [*Rangwala and Miller*, 2012], although there has been no simplistic increasing of warming rates with elevation on the global scale [*Pepin and Lundquist*, 2008]. However, it was found that an elevation dependence of warming appears over the Tibetan Plateau [*Liu et al.*, 2009; *Qin et al.*, 2009], which was not detected in other research [*You et al.*, 2008, 2010]. In this study, regions 18 and 19 include most of the stations above 3000 m above sea level on the Tibetan Plateau. It is expected that a greater warming rate on the plateau leads to a decreasing lapse rate. However, lapse rates in those two regions (shown in Figure 8) had an opposite trend over the past 50 years, although both showed a similar warming trend with a value of 0.03°C per year (Figure 7a). The varying trends of relative humidity in Figure 7c, together with other factors, are likely responsible for the different change of lapse rate.

[33] To better examine the relationship between lapse rate and air temperature and the relationship between lapse rate and relative humidity, the interannual variability of annual and seasonal mean values is revealed in Figure 9 for a number of selected regions, where there are significant linear trends (shown in *n*) over the past 50 years (anomalies relative to the 1971–2000 averages). It is found that the lapse rates follow a distinct interannual variability with an increasing trend over most regions for most seasons, while the relative humidity shows an opposite tendency. At the same time, the temperature shows a consistent warming trend. For the 50 year period and on the interannual basis, there is a positive correlation between lapse rate and air temperature, and a negative correlation between lapse rate and relative humidity.

4. Summary and Conclusions

[34] We have characterized lapse rates for the mainland China in detail and shown their monthly, seasonal, interannual, and geographic variations. Observed monthly near-surface air temperatures from 1962 to 2011 at 754 stations were analyzed to estimate and verify the lapse rates.

[35] Lapse rates generally had a banded spatial distribution from southeast to northwest, which corresponds to the pattern of air temperature and relative humidity. The lapse rates have obvious annual and seasonal variation, ranging from 0.3°C to $0.9°\mathrm{C} \cdot 100\,\mathrm{m}^{-1}$. Winter had relatively large spatial variability, accompanied by an inversion phenomenon in the northern Xinjiang Province.

[36] For most regions, the lapse rates did have a statistically negative relationship with relative humidity, as expected from the theory, although there has been a rising trend of temperature over all China. This demonstrates the importance of relative humidity in determining lapse rate. Clearly, the changes in temperatures together with those of humidity influenced the lapse rate variations. Specifically, on the Tibetan Plateau (regions 18 and 19), similar warming rates but different variabilities of relative humidity together produced different lapse rate variability.

[37] In the Tibetan Plateau, it is found that similar mean warming rates bring about the different temporal trend of annual lapse rate, which may be linked to the debate on different warming rate at different elevations. The different trends in regions 19 and 18 may have been resulted from the facts (1) region 19 is much larger than region 18 while

the station density in the first is much sparser and (2) there can be a real difference with regard to regional elevation-dependent warming. A detailed seeking on the elevation-dependent warming remains to be investigated.

[38] Finally, it is worth pointing out several caveats of this study and issues that deserve future consideration. One of the limitations is that the estimated lapse rates have variable reliability, depending on the density of meteorological stations. This density in China is not evenly distributed; there are fewer observations in the western part of the country, especially in certain mountain regions such as the Tibetan Plateau. This sampling problem certainly impacts the quality of the estimates in these regions. In order to assess the rationality of our method, the goodness of the fits for all the regions and for all the time scales was looked at to test the sensitivity of the fits to the number of stations in regions with more stations. In general, it is found that the lapse rates are not so sensitive to the number of stations when the number is larger than a critical value. As an example, region 1 was chosen since it contains more stations and larger range of the elevations (not shown here). It is found that lapse rate stabilizes around a value of $0.8°\mathrm{C} \cdot 100\,\mathrm{m}^{-1}$ when derived using 16 stations or more. When the station number is less than the critical, the lapse rate estimated shows a great variation, indicating a larger uncertainty.

[39] Overall, the goodness fits for all lapse rate estimates show a satisfactory result, which is supported by the high multiple correlation coefficients (>0.85). This does confirm that our method and results are reasonable and useful.

[40] Another sampling problem is that there are few observations on the tops of mountains because of practical difficulties. This could make our estimates less representative for highly elevated areas. As an example, different slopes of a mountain range may have different lapse rates [e.g., *Tang and Fang*, 2006], indicating the importance of microclimatic conditions in determining lapse rate.

[41] It is interesting that the estimated lapse rates have both negative and positive temporal trends on the regional level over the past 50 years, under the background of regional warming and changing relative humidity. However, factors other than temperature and humidity that are behind these regional differences and the implication of these variabilities for hydrological processes at high altitudes, especially on the Tibetan Plateau, remain to be investigated.

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