Analysis of Upper-Air Temperature Variation Characteristics over Xinjiang - Postprint

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Abstract

Using reanalysis data (NCEP/NCAR), this study analyzed the characteristics of annual mean upper-air temperature changes in the Xinjiang region. Simultaneously, the stepwise regression method was employed to interpolate missing observed temperature data for cold months (January) and warm months (July) in the upper air over Xinjiang, and the accuracy of the interpolated data was assessed through cross-validation. Based on this, the characteristics of upper-air temperature changes in cold and warm months in the Xinjiang region were analyzed, and the interpolated/reconstructed upper-air observed data were used to validate the accuracy of the January and July reanalysis data (NCEP/NCAR). The results show that: (1) The interpolated data for missing upper-air observations in the Xinjiang region exhibit high accuracy and good performance, capable of reflecting the objective facts of upper-air temperature changes in Xinjiang. (2) Based on the analysis of cold-month, warm-month, and annual mean change trends in the troposphere (lower, middle, and upper) and lower stratosphere over the Xinjiang region, as altitude increases, the temperature change trend shifts from warming to cooling, and with increasing altitude, the warming rate decreases while the cooling rate increases; the higher the temperature in a given month, the higher the altitude at which the temperature change trend shifts with increasing height; after 2000, most years in the troposphere were warmer than normal, while most years in the lower stratosphere were colder than normal. (3) The turning points of annual mean temperature at 850 hPa and 700 hPa both occurred in 1996, shifting from cold to warm; at 100 hPa, it occurred during 1995-1997, shifting from warm to cold; at 500 hPa and 300 hPa, no significant abrupt change years were observed. (4) The correlation coefficients between the January and July reanalysis data (NCEP/NCAR) and observed data are mostly above 0.9, with relatively small overall errors.

Analysis of Upper-Air Temperature Change Characteristics in the Xinjiang Region

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Abstract

This study analyzes the characteristics of annual mean upper-air temperature changes in the Xinjiang region using NCEP/NCAR reanalysis data. Missing values in the measured upper-air temperature data for January (cold month) and July (warm month) were interpolated using stepwise regression, with the accuracy of the interpolated data verified through cross-validation. Based on this reconstructed dataset, we examined the characteristics of upper-air temperature variations during both cold and warm months, and subsequently validated the accuracy of the NCEP/NCAR reanalysis data against the interpolated observations. The results demonstrate that the interpolation method yields high-precision reconstructions that effectively reflect the objective reality of upper-air temperature changes in Xinjiang. Our analysis of temperature trends across the troposphere (lower, middle, and upper layers) and the lower stratosphere reveals that as altitude increases, the temperature trend shifts from warming to cooling, with the warming rate decreasing and the cooling rate increasing with height. Warmer months exhibit this transition at higher altitudes. After 2000, most years show warm anomalies in the troposphere and cold anomalies in the lower stratosphere. The turning point from cold to warm in the annual mean temperature occurred in 1996 at 850 hPa and 700 hPa, while at 100 hPa the transition from warm to cold occurred during 1995–1997. No significant abrupt changes were detected at 500 hPa or 300 hPa. Correlation coefficients between the NCEP/NCAR reanalysis data and measured data mostly exceed 0.9, with relatively small overall errors.

Keywords: upper-air temperature; climate change; Xinjiang region

1. Introduction

The upper atmosphere constitutes a crucial component of the climate system, and determining changes in upper-air meteorological elements represents an essential foundation for climate change research. Following the confirmation of global surface warming, increasing attention has been directed toward upper-air climate studies, particularly regarding temperature changes. For the Xinjiang region, which is located in the heart of the Eurasian continent and far from oceanic influences, upper-air observations can effectively represent the background of inland upper-air climate change. Previous studies have yielded valuable insights: Zhang Guangxing et al. analyzed upper-air temperature characteristics using radiosonde data and found that tropospheric temperature exhibited a "V-shaped" pattern of initial decline followed by increase, with relatively stable temperatures at the tropopause and in the lower stratosphere. Bai Ling et al., utilizing data from multiple radiosonde stations, identified a decreasing trend in stratospheric temperatures. Xue Deqiang et al., based on observations from 125 stations across China, concluded that the upper troposphere to lower stratosphere in Xinjiang showed cooling trends over 40 years, while the lower and middle troposphere exhibited warming, with cooling rates in the upper troposphere and lower stratosphere exceeding warming rates in the lower troposphere. Chen Fang et al., using 50-year observational data from 10 Xinjiang radiosonde stations, found temperature increases from the surface to 700 hPa and decreases from the upper troposphere to 10 hPa, particularly significant cooling at 50 hPa. Hou Linghong et al., employing Kashgar single-station radiosonde data, determined that upper-air temperature underwent a cold-to-warm transition in the mid-1980s, with increased positive anomalies and decreased negative anomalies after 2000. Zhang Jinfeng' s study of Harbin' s upper-air temperature revealed that seasonal variations become increasingly opposite with altitude, showing a single-peak pattern at 850–300 hPa and a double-peak pattern at 200–100 hPa.

However, several limitations exist in current research. First, temporal coverage remains incomplete; while global warming continues, long-term (1961–2017) temperature changes at different isobaric surfaces in Xinjiang are not well understood. Second, many studies have utilized limited stations with uneven spatial distribution, which cannot adequately represent regional upper-air temperature changes across Xinjiang. Third, Xinjiang' s radiosonde data contain numerous missing values, an issue not addressed in previous studies.

Given these data gaps, NCEP/NCAR reanalysis data, with its high spatiotemporal resolution, can compensate for missing observations in Xinjiang's upper-air stations. Zhi Xing et al. demonstrated that NCEP/NCAR data can effectively represent decadal variations in upper-air temperature. Zhou Shunwu et al. found NCEP/NCAR temperature data to be highly credible in interannual variability when compared with observational data. Therefore, this study employs NCEP/NCAR reanalysis data to analyze interannual variation characteristics of upper-air temperature in Xinjiang, while using stepwise regression to interpolate missing data for January and July, thereby providing a more comprehensive analysis of seasonal temperature variations.

2. Data and Methods

2.1 Data Sources

2.1.1 Radiosonde Data Daily upper-air temperature data at 00:00 and 12:00 UTC (08:00 and 20:00 Beijing Time) for nine pressure levels (850 hPa, 700 hPa, 500 hPa, and 300 hPa) were obtained from the Xinjiang Meteorological Information Center for the period 1961-2017. Statistical analysis revealed incomplete data at Tacheng, Karamay, Beitashan, and other stations (Table 1). To maintain temporal consistency, we selected 14 radiosonde stations with relatively complete records. The 850 hPa level represents the lower troposphere, 700 hPa the middle troposphere, 500 hPa the upper troposphere, and 300 hPa the lower stratosphere, with climatological means calculated for 1981-2010.

2.1.2 Reanalysis Data NCEP/NCAR reanalysis data were downloaded from https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html. This dataset was used to analyze interannual variation characteristics of upper-air temperature in Xinjiang. The reanalysis data have a temporal resolution of 6 hours and horizontal resolution of 2.5°$×$2.5°, covering 1948-2017. For this study, monthly mean temperature data from 1961-2017 were extracted for 850 hPa, 700 hPa, 500 hPa, 300 hPa, and 100 hPa levels.

2.2 Methods

2.2.1 Stepwise Regression Stepwise regression is a linear regression model for variable selection that introduces variables one by one based on significant partial regression sum of squares tests. After each new variable is introduced, existing variables in the model are re-examined, and non-significant variables are removed. This process continues until no new variables can be added, ensuring all remaining variables are statistically significant. We applied this method to correlate missing upper-air temperature data at target stations with data from other stations, selecting optimal station combinations as regression factors to establish models for interpolating missing values.

2.2.2 Cross-Validation Cross-validation was performed using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) to assess the accuracy of interpolated data. The formulas are:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i|$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$$

where x represents observed radiosonde data, y represents the data to be verified, and n is the sample size.

2.2.3 Mann-Kendall Test The Mann-Kendall test is a non-parametric statistical method that does not require normally distributed variables and is robust against outliers. We applied this test to detect abrupt changes in annual mean upper-air temperature.

2.2.4 Linear Trend Analysis Linear trends were calculated by establishing regression equations between temperature y_t and time t:

$$y_t = at + b$$

where a is the regression coefficient representing the trend (positive for warming, negative for cooling), and $a \times 10$ represents the temperature tendency rate in °C · $(10a)^{-1}$.

3. Results

3.1 Annual Temperature Variation Characteristics

3.1.1 Temporal Variation of Annual Mean Temperature Figure 1 shows annual temperature anomalies from 1961–2017. Linear fitting reveals warming trends in the lower and middle troposphere at rates of 0.16°C · $(10a)^{-1}$ (850 hPa) and 0.15°C · $(10a)^{-1}$ (700 hPa), respectively—both lower than the surface warming rate of 0.31°C · $(10a)^{-1}$. The upper troposphere (500 hPa) and lower stratosphere (300 hPa, 100 hPa) exhibit cooling trends at rates of -0.09°C · $(10a)^{-1}$, -0.10°C · $(10a)^{-1}$, and -0.37°C · $(10a)^{-1}$, respectively. The warming rate decreases with altitude while the cooling rate increases, consistent with Bai Ling et al.' s findings but with smaller magnitude due to differences in time series length, station selection, and data processing methods.

The troposphere shows alternating warm-cold patterns, while the lower stratosphere exhibits warm-cold transitions. After 2000, most years in the troposphere are warm anomalies, while the lower stratosphere shows cold anomalies. The warmest years occur in 2009 (lower/middle troposphere) and 2015 (upper troposphere/lower stratosphere), 1.4–1.6°C above normal. The coldest years occur in 1969 (lower/middle troposphere) and 1967 (upper troposphere/lower stratosphere), 0.8–1.7°C below normal.

Decadal analysis reveals distinct patterns: the lower troposphere shows warm-cold-warm-cold-warm sequences with strongest warming in the 2010s (+0.7°C) and strongest cooling in the 1960s (-0.6 to -0.8°C). The middle troposphere displays warm-cold-warm-cold-warm-cold patterns with maximum warming in the 2010s (+0.6°C) and maximum cooling in the 1970s (-0.9°C). The upper troposphere shows cold-warm-cold-warm-cold-warm patterns with peak warming in the 2000s (+0.5°C) and peak cooling in the 1960s (-0.8°C). The lower stratosphere exhibits warm-cold-warm-cold-warm-cold patterns with maximum warming in the 2000s (+0.3°C) and maximum cooling in the 2010s (-1.1°C).

3.1.2 Abrupt Change Detection Mann-Kendall tests detect significant abrupt changes at 850 hPa and 700 hPa in 1996 (cold-to-warm transition), with warming trends exceeding significance levels after 2000. At 100 hPa, a warm-to-cold transition occurs during 1995–1997, with significant cooling after 2000. No significant abrupt changes are detected at 500 hPa or 300 hPa.

3.2 Cold and Warm Month Temperature Characteristics

3.2.1 Data Interpolation and Error Analysis Although January and July data are relatively complete, missing values still exist, particularly at Hami and Kuqa stations (Table 2). Stepwise regression interpolation yields high-precision reconstructions, with multiple correlation coefficients mostly above 0.9 (significant at α=0.01) and errors within 2°C. Cross-validation confirms the reliability of interpolated data.

3.2.2 Interannual Variation Characteristics **Cold Month (January):** Linear trends show warming at 850 hPa (0.14°C $\cdot$ $(10a)^{-1}$) and cooling at 700 hPa (-0.11°C $\cdot$ $(10a)^{-1}$), 500 hPa (-0.20°C $\cdot$ $(10a)^{-1}$), 300 hPa (-0.08°C $\cdot$ $(10a)^{-1}$), and 100 hPa (-0.61°C $\cdot$ $(10a)^{-1}$). The troposphere exhibits alternating warm-cold patterns, while the lower stratosphere shows warm-to-cold transitions after the 1990s. The coldest years cluster around 1967, 2.4–5.2°C below normal.

Warm Month (July): Warming trends occur throughout the troposphere at rates of 0.13°C $\cdot$ $(10a)^{-1}$ (850 hPa), 0.17°C $\cdot$ $(10a)^{-1}$ (700 hPa), and 0.15°C $\cdot$ $(10a)^{-1}$ (500 hPa), while the lower stratosphere cools at -0.28°C $\cdot$ $(10a)^{-1}$. The transition from warming to cooling occurs at higher altitudes in summer. The troposphere shows warm-cold-warm patterns, while the lower stratosphere is predominantly cold after 2000. Warmest years appear in 1974 (lower/middle troposphere) and 2008 (upper troposphere), 0.9–1.4°C above normal.

3.2.3 Validation of Reanalysis Data Correlation analysis between NCEP/NCAR reanalysis data and interpolated observations shows coefficients mostly above 0.9 across all pressure levels (Table 3), all passing significance tests. Mean errors are generally within 1.0°C (Table 4), with the smallest errors at 300 hPa (0.29°C) and largest at 500 hPa (1.17°C). These results indicate that NCEP/NCAR data can reliably substitute for radiosonde observations in Xinjiang, though some stations (Kashgar, Hotan) show relatively weaker correlations at certain levels, possibly related to Xinjiang' s unique geography and terrain.

4. Conclusions

Using NCEP/NCAR reanalysis data and stepwise regression interpolation of missing values in radiosonde observations, this study analyzed upper-air temperature change characteristics in Xinjiang from 1961–2017. Key findings include:

1. **Vertical Structure of Temperature Trends:** Across the troposphere and lower stratosphere, temperature trends shift from warming to cooling with increasing altitude. The warming rate decreases while the cooling rate increases with height. Warmer months exhibit this transition at higher altitudes. After 2000, the troposphere predominantly shows warm anomalies while the lower stratosphere shows cold anomalies.
2. **Abrupt Changes:** Significant cold-to-warm transitions occurred in 1996 at 850 hPa and 700 hPa. At 100 hPa, a warm-to-cold transition occurred during 1995-1997. No significant abrupt changes were detected at 500 hPa or 300 hPa.
3. **Data Reliability:** NCEP/NCAR reanalysis data correlate strongly with observed data (mostly $r > 0.9$) in both January and July, with small errors, demonstrating their reliability for analyzing upper-air temperature changes in Xinjiang. The stepwise regression interpolation method produces high-precision reconstructions that accurately reflect actual temperature variations.

These results provide a more complete understanding of upper-air temperature changes in Xinjiang, addressing previous limitations in temporal coverage, spatial representation, and data completeness.

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