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Abstract

The trends of the Cold-Point Tropopause (CPT) are presented using high-resolution radiosonde observations from 77 stations across China during 1979–2014. The latitude region from 18°N to 53°N is divided into 7 latitude zones at 5° intervals, and the spatial area of 18°N–53°N, 75°E–135°E is divided into 27 grids with 5°×10° resolution. The annual-mean values of Height-of-CPT (H-CPT) and Temperature-of-CPT (T-CPT) are obtained. First, using the least squares regression method, it is found that the H-CPT increases at a rate of 273 m/decade, while the T-CPT exhibits an overall significant cooling rate of -0.70 K/decade over China. Then, the trends and latitudinal distribution of H-CPT and T-CPT for each latitude zone are obtained. The change rates, and even the direction of change, of H-CPT show obvious latitudinal distribution characteristics. The characteristic differences of H-CPT across latitudinal distribution are decreasing year by year, while those of T-CPT are increasing. The H-CPT displays an uplift trend in the 28°N–53°N latitude region with positive change rates, while it exhibits a decline trend in the 18°N–28°N latitude region with negative change rates. The change rates of T-CPT are negative for all latitude zones. Third, the spatial latitude–longitude distribution of long-term trends of H-CPT and T-CPT for each grid is obtained. The change rates of H-CPT and T-CPT depend not only on latitude but also on longitude. Finally, the spatial structure of annual fluctuation of H-CPT and T-CPT for each grid is obtained. The fluctuation of standard deviations of T-CPT is related not only to spatial distribution but also to the economic belts of China.

Full Text

Distribution and Trends of the Cold-Point Tropopause over China from 1979 to 2014 Based on the Radiosonde Dataset

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Key Points: - Significant cooling rate of -0.70 K/decade for the T-CPT over China during 1979-2014 - The H-CPT over China shows a declining trend at low latitudes and an uplifting trend at high latitudes - Both the variation of H-CPT (T-CPT) and their change rates exhibit spatial distribution characteristics

Abstract

This study presents trends of the Cold-Point Tropopause (CPT) using high-resolution radiosonde observations from 77 stations across China during 1979-2014. The latitude region from 18°N to 53°N is divided into seven latitude zones at 5° intervals, and the spatial domain of 18°N-53°N, 75°E-135°E is partitioned into 27 grid cells using a 5°×10° grid. Annual-mean values of Height-of-CPT (H-CPT) and Temperature-of-CPT (T-CPT) are obtained. First, using the least squares regression method, we find that H-CPT increases at a rate of 273 m/decade, while T-CPT exhibits an overall significant cooling rate of -0.70 K/decade over China. Second, we examine the trends and latitudinal distribution of H-CPT and T-CPT for each latitude zone. The change rates (and even the direction of change) of H-CPT show clear latitudinal distribution characteristics. The characteristic differences in H-CPT among latitudes diminish year by year, while those for T-CPT enlarge. The H-CPT displays an uplifting trend in the 28°N-53°N latitude region with positive change rates, and a declining trend in the 18°N-28°N latitude region with negative change rates. The change rates of T-CPT are negative for all latitude zones. Third, we obtain the spatial (latitude-longitude) distribution of long-term trends of H-CPT (T-CPT) for each grid cell. The change rates of H-CPT (T-CPT) depend not only on latitude but also on longitude. Finally, we derive the spatial structure of annual fluctuation of H-CPT (T-CPT) for each grid cell. The fluctuation of standard deviations of T-CPT is related not only to spatial distribution but also to China's economic belts.

Index Terms and Keywords: Cold-Point Tropopause, Cold-Point Temperature, Cold-Point Height, Long-term trends, Change Rate, Radiosonde dataset

1 Introduction

The cold-point tropopause (CPT), a potentially important indicator of global climate change, represents one of the most fundamental structural features of Earth's atmosphere [?, ?]. The exchange of air mass, water vapor, trace gases, and energy between the troposphere and stratosphere occurs at the tropopause [?], and variations in tropopause structure are closely linked to climate change.

Over the past decades, it has become evident that the CPT is an atmospheric layer rather than a sharp surface, located between the troposphere and stratosphere with properties of both. Owing to its extreme sensitivity to climate variability and change, the CPT has attracted widespread research interest [?, ?, ?]. Growing evidence from various data sources suggests that the height of the CPT has increased [?, ?, ?], while a cooling trend in tropical T-CPT has existed in recent decades [?], closely associated with tropospheric warming and stratospheric cooling.

This study applies the CPT definition as the position of the coldest temperature in the vertical temperature profile between the troposphere and stratosphere for climatological statistics. We estimate long-term linear variation trends and spatial distributions of the CPT across China using radiosonde observations from IGRA v2beta (IGRA2), the beta release of version 2 of the Integrated Global Radiosonde Archive as NCDC's baseline upper-air dataset [?, ?, ?]. IGRA data offer substantially higher vertical resolution than reanalysis products and have much longer records than GPS radio occultation, thus enabling more accurate identification of the CPT from a climatic perspective [?, ?].

China's vast territory spans approximately 50° in latitude ($3^\circ 51'$ N– $53^\circ 33'$ N) and 62° in longitude ($73^\circ 33'$ E– $135^\circ 05'$ E), with most regions concentrated in subtropical and temperate zones. The Qinghai-Tibet Plateau, known as the third pole or the roof of the world, exhibits unique climate characteristics whose effects warrant study [?, ?]. With rapid industrial development, investigating its impacts on climate and environmental change within China is also essential. Analyzing temporal and spatial variations of regional climate in China holds significant importance for climate change research. Radiosonde data represent the most precise direct atmospheric sounding data available, spanning decades, making them optimal for CPT research. In this study, we determine the cold-point tropopause using sounding temperature profiles, processing nearly 36 years of radiosonde observations from 1979 to 2014 derived from IGRA2 sounding data to analyze temporal and spatial variation characteristics of the CPT over China.

Section 2 outlines the radiosonde data and methods of data processing and analysis. Section 3 describes long-term trends and spatial variation of CPT properties over China. Discussions and brief concluding remarks are provided in Section 4.

2.1 Data Source

The new beta release of version 2 of the Integrated Global Radiosonde Archive (IGRA2), which was in the documentation and review phase as a prerequisite for officially replacing IGRA1 as NCDC's baseline upper-air dataset, became publicly available in September 2014 [?, ?, ?]. IGRA1 quality assurance procedures include seven general categories: fundamental “sanity” checks, plausibility and temporal consistency checks of surface elevation, internal consistency checks, repetition of values checks, climatologically based checks, vertical and temporal consistency checks of temperature, and data completeness checks [?, ?, ?]. Compared to IGRA1, IGRA2 includes more soundings, longer records, and methodological changes [?, ?, ?]. Quality control algorithms have been applied to remove gross errors. Therefore, this investigation uses the IGRA2-derived sounding dataset, which contains 144 stations over China with records spanning from 1956 to present.

2.2 Methods for CPT Data Processing

To study long-term variation trends of CPT over China, we first identify H-CPT and T-CPT for each sounding profile based on the CPT definition. T-CPT is the minimum temperature determined from each sounding profile, and H-CPT is the corresponding minimum height for the T-CPT. Owing to some incorrect CPTs in sounding profiles, we preprocess radiosonde profiles by applying quality control to T-CPT for each sounding profile, with the flow chart shown in [Figure 1: see original paper]. For all 2,783,403 sounding profiles with valid data reports from 144 stations in China in the IGRA2-derived dataset during 1956-2014, we perform the following three steps.

First, we exclude sounding profiles with maximum heights below the 150 hPa level, as indicated by blue star symbols in [Figure 2: see original paper]. These cases likely occur when the sounding balloon fails to reach sufficient altitude, preventing effective determination of T-CPT and H-CPT. Second, we exclude sounding profiles where temperature does not rise above the H-CPT, as these represent ineffective records, indicated by black triangle symbols in [Figure 2: see original paper]. Finally, profiles indicated by red dot symbols in [Figure 2: see original paper] are considered effective CPTs, and the corresponding H-CPT and T-CPT meeting requirements are retained for analysis.

[Figure 1: see original paper] shows the flow chart of quality control for CPT data preprocessing to obtain effective H-CPT and T-CPT. [Figure 2: see original paper] presents examples of the CPT data quality control process for three sounding profiles at 1200 UTC in Beijing (stationID: CHM00054511). [Figure 3: see original paper] shows the number of sounding stations and distribution of available data in China for each year from 1956 to 2014 in the IGRA2-derived dataset. Original data are shown as black triangles, and effective data after quality control (as described in [Figure 1: see original paper]) for CPT processing are shown as red stars. After quality control, the total number of sounding

profiles decreases from the original 2,783,403 to 2,197,989 over China from 1956 to 2014.

As shown by black triangles in [Figure 3: see original paper], before 1978, the number of stations and sounding profiles in China was relatively small. After 1978, the number of sounding stations stabilized at more than 85 per year, with corresponding sounding profiles exceeding 50,000 annually. [Figure 3: see original paper] (red stars) also reveals that the number of effective radiosonde profiles in 1994 was approximately one-quarter less than in other years. Analysis shows that radiosonde profiles failing to meet CPT data process quality control requirements ([Figure 1: see original paper]) occurred mainly in June, July, and August of 1994. Therefore, to reduce effects on inter-annual CPT analysis, sounding profile data from December 1993 to November 1994 are excluded.

Based on this analysis, 77 stations (hereafter S77) from the 144 Chinese stations have usable sounding data from December 1978 to November 2014 for this investigation. In subsequent studies, we define December 1978–November 1979 as 1979 (winter, spring, summer, autumn), December 1979–November 1980 as 1980, and so on, to analyze seasonal variation impacts on CPT.

During 1979–2014, a total of 1,709,051 soundings remain for S77. According to relevant literature [?, ?, ?, ?], some abnormal values exist in H-CPT and T-CPT among these soundings, necessitating their removal. We adopt a three-standard-deviation threshold to eliminate abnormal values. Statistical analysis yields an average H-CPT of 16.32 km for 1,709,051 soundings, with a corresponding three-standard-deviation value of 8.37 km. The average T-CPT is 204.46 K, with a three-standard-deviation value of 22.94 K. Using the three-standard-deviation criterion, H-CPT values below 7.95 km or above 24.69 km are identified as abnormal, and T-CPT values below 181.52 K or above 227.40 K are identified as abnormal. A total of 5,355 sounding profiles are removed as outliers, leaving approximately 99.7% of the 1,709,051 soundings as normal values.

Finally, during 1979–2014, a total of 1,703,696 sounding profiles are adopted for S77 in subsequent investigations. [Figure 4: see original paper]a shows the distribution of H-CPT for 1,703,696 soundings in each integer height interval, and [Figure 4: see original paper]b shows the distribution of T-CPT in each integer temperature interval.

2.3 Methodologies for CPT Data Analysis

To investigate seasonal variation trends of CPT properties, we define four seasons as: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February of the following year). To examine latitudinal distribution of long-term CPT trends, we divide the latitude region from 18°N to 53°N into seven zones at 5° intervals, as shown in [Figure 5: see original paper]. The average H-CPT (T-CPT) for each latitude zone is calculated from sounding profiles of all stations within that zone. To investigate spatial (latitude-longitude) structure of long-term CPT trends, we divide the

China region (18°N-53°N, 75°E-135°E) into 27 grid cells using $5^{\circ}\times 10^{\circ}$ grids to ensure each cell contains sufficient samples, as shown in [Figure 5: see original paper]. Each cell is labeled with a number in the top-right corner. The average H-CPT (T-CPT) over all China is calculated from the corresponding averages of the 27 grid cells, and the average for each grid cell is calculated from H-CPT (T-CPT) values of sounding profiles from all stations within that cell.

In this study, we first calculate annual-mean and seasonal-average H-CPT (T-CPT) for the whole China region from the 27 grid cells. Using least squares regression, we obtain inter-annual variability regression coefficients of H-CPT (T-CPT) over China, yielding 10-year linear variation rates of average CPT temperature and height to analyze changing trends. Second, we calculate and analyze annual-mean and seasonal-average H-CPT (T-CPT) for each latitude zone using least squares regression to obtain latitudinal distribution characteristics. Third, for each grid cell, we analyze annual-mean H-CPT (T-CPT) using least squares regression to obtain spatial (latitude-longitude) structure characteristics of 10-year linear change rates. Finally, using 2014 sounding profiles from all stations within each grid cell, we analyze H-CPT (T-CPT) and their fluctuations using the standard deviation method to obtain the spatial structure of annual fluctuation.

3.1 Trends of the CPT over the Whole China from 1979 to 2014

The average height and temperature of CPT over China are calculated from the 27 grid cells. Using least squares regression, we obtain long-term evolution trends of H-CPT (T-CPT). [Figure 6: see original paper]a and [Figure 6: see original paper]b show annual-mean trends for CPT height and temperature during 1979-2014, computed from all grid annual-mean values over China. [Figure 6: see original paper]a presents a significant increase in H-CPT over China from 15,258 m to 16,558 m during 1979-2014, yielding a net rise of 273 m/decade over 36 years. [Figure 6: see original paper]b shows a significant decrease in T-CPT from 207.4 K to 204.5 K, yielding a net cooling of -0.70 K/decade.

[Figure 6: see original paper]c and [Figure 6: see original paper]d show seasonal-mean trends for CPT height and temperature during 1979-2014, computed from all grid seasonal-mean values. Summer CPT is the highest and coldest among all seasons over China. H-CPT shows increasing trends and T-CPT shows cooling trends in all four seasons during 1979-2014, though variation amplitudes differ by season. [Figure 6: see original paper]c reveals that winter H-CPT trends show the maximum change rate of 398 m/decade, while summer shows the minimum at only 86 m/decade. Summer H-CPT averages are highest (over 16 km) with the lowest annual change rate, indicating that summer H-CPT uplift contributes minimally to the whole China region. Correlation analysis yields coefficients between annual H-CPT trends and seasonal trends of 0.90, 0.90, 0.57, and 0.51 for winter, spring, summer, and autumn, respectively. Combined with [Figure 6: see original paper]c, this indicates that H-CPT uplift in China

is mainly driven by winter and spring uplift.

[Figure 6: see original paper]d shows T-CPT has an overall cooling trend in all four seasons during 1979–2014, with the largest change rate in winter (-0.78 K/decade) and the smallest in autumn (-0.60 K/decade). Differences in variation amplitudes among seasons are small. T-CPT averages are lowest in summer and highest in winter. Correlation coefficients between annual T-CPT trends and seasonal trends are 0.85, 0.92, 0.91, and 0.86 for winter, spring, summer, and autumn, respectively. Together with [Figure 6: see original paper]d, this suggests that annual cooling trends of T-CPT across seasons contribute similarly to the whole China region, indicating that seasonal CPT cycles are likely modulated by large-scale rather than small-scale local processes. Indeed, seasonality in the tropical lower stratosphere is largely controlled by upwelling driven by wave forcing in the extratropical lower stratosphere, which is stronger during summer than winter, resulting in higher H-CPT and colder T-CPT in summer.

3.2 Latitudinal Distribution of the Trends of CPT from 1979 to 2014

To study latitudinal distribution of long-term CPT trends, we calculate annual-mean and seasonal-mean H-CPT (T-CPT) for each 5° latitude zone from sounding profiles of all stations within that zone. [Figure 7: see original paper]a and [Figure 7: see original paper]b show annual-mean H-CPT and T-CPT for each latitude zone. [Figure 8: see original paper] and [Figure 10: see original paper] show seasonal-mean H-CPT and T-CPT. Using least squares regression, we obtain latitudinal distribution characteristics of change rates. [Figure 7: see original paper]c and [Figure 7: see original paper]d show 10-year change rates of H-CPT and T-CPT for each latitude zone. [Figure 9: see original paper] and [Figure 11: see original paper] show seasonal 10-year change rates.

[Figure 7: see original paper]a and [Figure 7: see original paper]b show annual-mean trends in CPT height and temperature by latitude zone during 1979–2014. H-CPT gradually decreases with increasing latitude, though in low-latitude zones (18°N – 33°N) over China, latitudinal distribution characteristics are not obvious, inter-annual variability is small, and annual-mean H-CPT trends are relatively stable. Conversely, in high-latitude zones (33°N – 53°N), latitudinal distribution characteristics are remarkable with large inter-annual variability. Combined with [Figure 7: see original paper]c, H-CPT uplift trends gradually increase with latitude within 28°N – 48°N during 1979–2014. T-CPT gradually increases with latitude, showing clear latitudinal distribution characteristics. Inter-annual variability is large in low-latitude zones and small in high-latitude zones. Combined with [Figure 7: see original paper]d, T-CPT cooling trends gradually decrease with latitude within 28°N – 53°N . Overall, T-CPT shows cooling trends in all latitude zones, with larger cooling trends in low-latitude zones.

[Figure 7: see original paper]c shows latitudinal distribution characteristics of 10-year linear change rates of H-CPT during 1979–2014. Change rates (and

even direction) show clear latitudinal distribution, generally decreasing from high to low latitude, varying from +499 m/decade in the high-latitude zone (48°N-53°N) to -19 m/decade in the low-latitude zone (18°N-23°N). H-CPT shows uplift between 28°N-53°N, with rates varying from 4 m/decade in 28°N-33°N to 499 m/decade in 48°N-53°N, and a maximum uplifting rate of 529 m/decade in 43°N-48°N. Conversely, H-CPT shows decline in low-latitude zones: -19 m/decade in 18°N-23°N and -29 m/decade in 23°N-28°N. This low-latitude decline has not been reported previously. Combined with [Figure 7: see original paper]a, the annual-mean difference in H-CPT between low and high latitudes shrinks yearly, reducing latitudinal distribution characteristics. The phenomenon of H-CPT becoming more similar from high to low latitudes is novel.

[Figure 7: see original paper]d shows latitudinal distribution characteristics of 10-year linear change rates of T-CPT during 1979-2014. Change rates show clear latitudinal distribution, generally increasing from high to low latitude, varying from -0.32 K/decade in the high-latitude zone (48°N-53°N) to -0.80 K/decade in the low-latitude zone (18°N-23°N), with a maximum cooling rate of -0.89 K/decade in 28°N-33°N. T-CPT shows cooling trends in all latitude zones. Combined with [Figure 7: see original paper]b, the annual-mean difference in T-CPT between low and high latitudes expands yearly, enlarging latitudinal distribution characteristics. The phenomenon of T-CPT differences between high and low latitudes gradually increasing is also novel.

We now focus on seasonal statistics of H-CPT for each latitude zone to further discuss distribution and seasonal-mean variation across seven latitude zones. Using time series smoothing of original sounding profiles from all stations within each latitude zone to reduce noise and increase statistical significance, we analyze seasonal-mean H-CPT for the seven zones. [Figure 8: see original paper] shows average H-CPT by season for each latitude zone during 1979-2014. H-CPT exhibits strong seasonal variation, with latitudinal distribution characteristics becoming increasingly obvious across seasons in the order: winter, spring, autumn, summer.

[Figure 9: see original paper] shows 10-year change rates of H-CPT by season for each latitude zone. From [Figure 8: see original paper]a, winter H-CPT shows the largest variation amplitudes (9.4-17.8 km), gradually decreasing with latitude. In low-latitude zones (18°N-33°N), winter H-CPT latitudinal distribution is not obvious, inter-annual variability is small, and trends are stable. In high-latitude zones (33°N-53°N), distribution characteristics are remarkable with large variability. Combined with [Figure 9: see original paper], winter H-CPT uplift trends increase with latitude within 28°N-43°N.

From [Figure 8: see original paper]b, spring H-CPT shows larger variation amplitudes (10.4-18.0 km). Latitudinal distribution is not obvious within 18°N-33°N but remarkable within 33°N-53°N. Combined with [Figure 9: see original paper], spring H-CPT uplift trends increase with latitude within 28°N-48°N.

From [Figure 8: see original paper]c, summer H-CPT shows the smallest varia-

tion amplitudes (13.3–17.4 km). Distribution is not obvious within 18°N–43°N with small inter-annual variability and stable trends. Within 43°N–53°N, distribution is remarkable with large variability. Combined with [Figure 9: see original paper], summer H-CPT uplift trends increase with latitude within 33°N–53°N.

From [Figure 8: see original paper]d, autumn H-CPT shows smaller variation amplitudes (10.9–17.4 km). Distribution is not obvious within 18°N–38°N but remarkable within 33°N–53°N. Combined with [Figure 9: see original paper], autumn H-CPT uplift trends increase with latitude within 33°N–53°N.

[Figure 9: see original paper] shows that 10-year change rates (and direction) of H-CPT exhibit clear latitudinal distribution characteristics across seasons. Generally, rates increase from low to high latitude each season. Winter H-CPT (black stars) shows uplift between 28°N–53°N, varying from 59 m/decade in 28°N–33°N to 315 m/decade in 48°N–53°N, with a maximum of 695 m/decade in 38°N–43°N. At low latitudes (18°N–28°N), winter H-CPT shows decline. Spring H-CPT (red dots) shows uplift between 28°N–53°N, varying from 48 m/decade in 28°N–33°N to 518 m/decade in 48°N–53°N, with a maximum of 639 m/decade in 43°N–48°N, and decline in 18°N–28°N. Summer H-CPT (blue triangles) shows uplift between 33°N–53°N, varying from 7 m/decade in 33°N–38°N to 465 m/decade in 48°N–53°N, with decline in 18°N–33°N. Autumn H-CPT (olive triangles) shows uplift between 33°N–53°N, varying from 33 m/decade in 33°N–38°N to 621 m/decade in 48°N–53°N, with decline in 18°N–33°N. The largest H-CPT uplift occurs in winter within the 38°N–43°N mid-latitude zone. Combined with [Figure 8: see original paper] and [Figure 9: see original paper], H-CPT differences between low and high latitudes shrink yearly for each season.

We now focus on seasonal statistics of T-CPT for each latitude zone. [Figure 10: see original paper] shows average T-CPT by season for each latitude zone during 1979–2014. T-CPT latitudinal distribution characteristics are very obvious each season, gradually increasing with latitude.

[Figure 11: see original paper] shows 10-year change rates of T-CPT by season for each latitude zone. In high-latitude zones (38°N–53°N), winter T-CPT distribution is not obvious with stable trends. In low-latitude zones (18°N–38°N), distribution is remarkable with large variability. Spring, summer, and autumn T-CPT averages increase with latitude, showing remarkable distribution characteristics.

[Figure 11: see original paper] shows latitudinal distribution characteristics of 10-year linear change rates of T-CPT by season during 1979–2014. Overall, T-CPT shows cooling trends in all seasons and latitude zones during 1979–2014. Winter T-CPT (black stars) shows clear latitudinal distribution, with rates increasing from high to low latitude, varying from -0.10 K/decade in 48°N–53°N to -1.09 K/decade in 18°N–23°N, and a maximum of -1.26 K/decade in 23°N–28°N. Combined with [Figure 10: see original paper]a, winter T-CPT differences between low and high latitudes expand yearly. Spring T-CPT (red

dots) shows rates varying from -0.26 K/decade in 48°N–53°N to -0.85 K/decade in 18°N–23°N, with a maximum of -0.98 K/decade in 28°N–33°N. Combined with [Figure 10: see original paper]b, spring T-CPT latitudinal characteristics enlarge yearly. Summer T-CPT (blue triangles) shows relatively stable rates across latitudes, from -0.55 K/decade in 48°N–53°N to -0.83 K/decade in 33°N–38°N. Autumn T-CPT (olive triangles) shows rates varying from -0.35 K/decade in 48°N–53°N to -0.68 K/decade in 18°N–23°N, with differences between high and low latitudes expanding yearly.

3.3 Spatial (Latitude-Longitude) Structure of the Change Rate of CPT during 1979–2014

To examine spatial (latitude-longitude) structure of long-term CPT trends, we analyze annual-mean H-CPT (T-CPT) using least squares regression for each grid cell, obtaining spatial distributions of 10-year linear change rates. [Figure 12: see original paper] and [Figure 13: see original paper] show 10-year linear change rates of H-CPT and T-CPT for each grid during 1979–2014.

[Figure 12: see original paper] shows 10-year change rates for H-CPT in each grid. The change rate exhibits clear spatial distribution characteristics. Under the same longitude zone (5° intervals), the change gradient gradually decreases from high to low latitude across China. Under the same latitude zone (5° intervals), the gradient increases from high longitude (east) to low longitude (west) in the region 95°E–135°E, 18°N–53°N (except grid 13). Combined with [Figure 12: see original paper]b, besides grid 13 (Sichuan Basin), all grids show H-CPT uplift between 28°N–53°N and decline between 18°N–28°N. This low-latitude decline has not been reported previously. The maximum uplifting rate of 664 m/decade occurs in grid 10 (Inner Mongolia Plateau).

[Figure 13: see original paper] shows 10-year change rates for T-CPT in each grid. The change rate shows clear spatial distribution characteristics. Under the same longitude zone (5° intervals), the change gradient increases from high to low latitude in 75°E–135°E, 33°N–53°N, and decreases from high to low latitude in 75°E–135°E, 18°N–33°N. Combined with [Figure 13: see original paper]b, under the same latitude zone, the change rate increases from high to low longitude in 28°N–53°N, 95°E–135°E (except grid 17). All grids show T-CPT cooling across China, with a maximum cooling rate of -1.08 K/decade in grid 24 (Qinghai-Tibet Plateau).

3.4 The Annual Fluctuation of the CPT Properties over China during 2014

To further discuss spatial (latitude-longitude) structure of annual CPT variation, we analyze 2014 data using the standard deviation method for each grid cell, obtaining spatial distributions of H-CPT and T-CPT fluctuations. [Figure 14: see original paper] shows average H-CPT and T-CPT for each grid during 2014.

[Figure 15: see original paper] shows standard deviations of H-CPT and T-CPT for each grid.

[Figure 14: see original paper] shows that average H-CPT and T-CPT exhibit clear spatial distribution characteristics. Under the same longitude zone (5° intervals), H-CPT average gradients increase from high to low latitude across China. Under the same latitude zone, gradients increase from high longitude (east) to low longitude (west) across China (except grid 12). Maximum H-CPT averages (~ 17.5 km) occur in low-latitude zones, while minima (~ 12.5 km) occur in high-latitude zones. Under the same longitude zone, T-CPT average gradients decrease from high to low latitude. Under the same latitude zone, gradients decrease from high longitude (east) to low longitude (west) (except grids 18 and 27). Maximum T-CPT averages (~ 214 K) occur in high-latitude zones, while minima (~ 191 K) occur in low-latitude zones.

[Figure 15: see original paper] shows that standard deviations of H-CPT and T-CPT exhibit clear spatial distribution characteristics. Under the same longitude zone, H-CPT standard deviation gradients decrease from high to low latitude. Under the same latitude zone, gradients decrease from high longitude (east) to low longitude (west) within 38°N - 43°N , and increase within 33°N - 38°N . Maximum H-CPT standard deviations (~ 3.5 km) occur in high-latitude zones, while minima (~ 0.7 km) occur in low-latitude zones. For T-CPT, standard deviation gradients decrease from the middle-latitude zone (33°N - 38°N) to both sides, aligning with China's rapid economic development belt. Under the same latitude zone, gradients decrease from high longitude (east) to low longitude (west) within 33°N - 53°N (except grid 21), and increase within 18°N - 33°N (except grid 24). Maximum T-CPT standard deviations (~ 4.7 K) occur in the 33°N - 38°N zone, possibly related to rapid industrial development, warranting further investigation.

4 Conclusions

This study presents the first long-term trends of cold-point tropopause height and temperature through analysis of 77 stations from the IGRA2 sounding dataset over China from 1979 to 2014. The analysis includes latitudinal and longitudinal distribution, seasonal cycles, annual fluctuations, and 10-year linear change rates of H-CPT and T-CPT.

A total of 1,703,696 sounding profiles were analyzed. Using least squares regression, we obtained 10-year linear change rates of average CPT temperature and height, finding H-CPT increases at approximately 273 m/decade and T-CPT shows a significant cooling rate of -0.70 K/decade across China. Summer CPT is the highest and coldest among all seasons, and H-CPT uplift in China is mainly driven by winter and spring uplift. Latitudinal distribution analysis reveals that change rates (and direction) of H-CPT and T-CPT show clear latitudinal characteristics. H-CPT shows uplift between 28°N - 53°N , with rates varying from 4 m/decade in 28°N - 33°N to 499 m/decade in 48°N - 53°N , and

decline between 18°N-23°N (-19 m/decade) and 23°N-28°N (-29 m/decade). T-CPT shows overall cooling in all latitude zones, with rates varying from -0.8 K/decade in 18°N-23°N to -0.32 K/decade in 48°N-53°N.

The following phenomena have not been reported previously: H-CPT decline with negative change rates at low latitudes; H-CPT differences between high and low latitudes shrinking yearly; and T-CPT differences between high and low latitudes expanding yearly.

Spatial (latitude-longitude) structure analysis for each grid cell reveals that H-CPT (T-CPT) change rates show clear spatial distribution characteristics, depending significantly on both latitude and longitude. The maximum uplifting rate of 664 m/decade occurs in the Inner Mongolia Plateau region, and the maximum cooling rate of -1.08 K/decade occurs in the Qinghai-Tibet Plateau region. The reasons for these changes warrant further study.

Analysis of annual fluctuation structure using the standard deviation method reveals that T-CPT annual fluctuations show clear spatial distribution characteristics. Maximum T-CPT standard deviations (~4.7 K) occur in the 33°N-38°N zone, decreasing gradually from the middle-latitude zone to both sides, aligning with China's rapid economic development belt. This relationship warrants further investigation.

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Figure Captions

Figure 1. The flow chart of the quality control for the CPT data preprocess: to obtain an effective H-CPT and T-CPT.

Figure 2. Examples of the CPT data quality control process: three sounding profiles at 1200 UTC in Beijing (stationID: CHM00054511).

Figure 3. The distribution of available data in China for each year from 1956 to 2014. (a) Number of sounding stations for each year where data are available before CPT quality control process (black triangle) and after CPT quality control process (red star). (b) Number of total sounding profiles for each year where data are available before CPT quality control process (black triangle) and after CPT quality control process (red star).

Figure 4. The distribution of H-CPT and T-CPT of 1,703,969 soundings after abnormal-value removal. (a) Number of total profiles of H-CPT for each integer height interval. (b) Number of total profiles of T-CPT for each integer temperature interval.

Figure 5. The spatial division and geographic distribution of the 77 stations over China: the red stars mark the location of S77, the blue numbers in the center of each grid represent the station count within that grid, and the black numbers in the top right corner of each grid represent the grid number.

Figure 6. The average variability in height and temperature of CPT. The solid lines are the corresponding linear trends during 1979–2014 using a least squares procedure. Change rates are shown at the top right of each diagram. (a) The annual-mean trends of H-CPT; (b) The annual-mean trends of T-CPT; (c) The seasonal-mean trends of H-CPT; (d) The seasonal-mean trends of T-CPT.

Figure 7. Latitudinal distribution of the annual-mean trends for CPT with 5° intervals during 1979–2014. (a) The annual-mean trends of H-CPT with respect to soundings in each latitude zone; (b) The annual-mean trends of T-CPT with respect to soundings in each latitude zone; (c) Latitudinal distribution of the 10-year-change-rate for H-CPT; (d) Latitudinal distribution of the 10-year-change-rate for T-CPT.

Figure 8. Latitudinal distribution of the seasonal-mean trends for H-CPT in each latitude zone during 1979–2014: (a) Winter; (b) Spring; (c) Summer; (d) Autumn.

Figure 9. Latitudinal distributions of the 10-year-change-rate of H-CPT with 5° intervals for four seasons.

Figure 10. The latitudinal distribution of the seasonal-mean trends for T-CPT in each latitude zone during 1979–2014: (a) Winter; (b) Spring; (c) Summer; (d) Autumn.

Figure 11. The latitudinal distribution of the 10-year-change-rate of T-CPT with 5° intervals for four seasons.

Figure 12. Maps of the 10-year-change-rate for H-CPT in each grid over 1979–2014. (a) Contour interval is 100 m/decade; (b) Numerical values are the 10-year-change-rate, positive in red and negative in blue. Each lattice is labeled with the digital number in the top right corner.

Figure 13. Maps of the 10-year-change-rate for T-CPT in each grid over 1979–2014. (a) Contour interval is 0.1 K/decade; (b) Numerical values are the 10-

year-change-rate, positive in red and negative in blue. Each lattice is labeled with the digital number in the top right corner.

Figure 14. Maps of the average H-CPT and T-CPT in each grid during 2014: (a) Contour interval is 646 m for H-CPT; (b) Contour interval is 3 K for T-CPT.

Figure 15. Maps of the standard deviations for H-CPT and T-CPT in each grid during 2014: (a) Contour interval is 390 m for H-CPT; (b) Contour interval is 0.32 K for T-CPT.

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