

Trends in Tropospheric Humidity from 1970 to 2008 over China from a Homogenized Radiosonde Dataset

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ABSTRACT

Radiosonde humidity data provide the longest record for assessing changes in atmospheric water vapor, but they often contain large discontinuities because of changes in instrumentation and observational practices. In this study, the variations and trends in tropospheric humidity (up to 300 hPa) over China are analyzed using a newly homogenized radiosonde dataset. It is shown that the homogenization removes the large shifts in the original records of dewpoint depression (DPD) resulting from sonde changes in recent years in China, and it improves the DPD's correlation with precipitation and the spatial coherence of the DPD trend from 1970 to 2008. The homogenized DPD data, together with homogenized temperature, are used to compute the precipitable water (PW), whose correlation with the PW from ground-based global positioning system (GPS) measurements at three collocated stations is also improved after the homogenization. During 1970–2008 when the record is relatively complete, tropospheric specific humidity after the homogenization shows upward trends, with surface–300-hPa PW increasing by about 2%–5% decade^{−1} over most of China and by more than 5% decade^{−1} over northern China in winter. The PW variations and changes are highly correlated with those in lower–midtropospheric mean temperature ($r = 0.83$), with a dPW/dT slope of $\sim 7.6\text{ K}^{-1}$, which is slightly higher than the 7 K^{-1} implied by Clausius–Clapeyron equation with a constant relative humidity (RH). The radiosonde data show only small variations and weak trends in tropospheric RH over China. An empirical orthogonal function (EOF) analysis of the PW reveals several types of variability over China, with the first EOF (31.4% variance) representing an upward PW trend over most of China (mainly since 1987). The second EOF (12.0% variance) shows a dipole pattern between Southeast and Northwest China and it is associated with a similar dipole pattern in atmospheric vertical motion. This mode exhibits mostly multiyear variations that are significantly correlated with Pacific decadal oscillation (PDO) and ENSO indices.

1. Introduction

Water vapor is one of the most important greenhouse gases (GHGs) in the atmosphere (Held and Soden 2000). It also plays a key role in the atmospheric branch of the global hydrologic and energy cycle (Trenberth et al. 2007). As the climate warms up because of increases in

CO₂ and other GHGs, atmospheric water vapor and surface specific humidity not only have been reported to increase in the real world (Ross and Elliott 2001; Zhai and Eskridge 1997; Trenberth et al. 2005; Dai 2006; Willett et al. 2008; Berry and Kent 2009; Durre et al. 2009; McCarthy et al. 2009), but also are expected to increase in climate models (e.g., Held and Soden 2000; Dai et al. 2001; Meehl et al. 2007), which, in turn, greatly enhances the warming. Among various climate feedbacks, this water vapor feedback has the largest magnitude (Held and Soden 2000). The observed increases of surface specific humidity (Dai 2006; Willett et al. 2008) and atmospheric water vapor have been partly attributed to human-induced global warming in recent decades seen in the observations and model simulations (Willett et al. 2007; Santer et al. 2007;

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Willett et al. 2010). Consistent warming and moistening trends of the marine atmosphere were also seen from satellite observations (Wentz and Schabel 2000). Although the rate of increase in water vapor with respect to temperature approximately follows the Clausius–Clapeyron equation with a constant relative humidity at $\sim 7\% \text{ K}^{-1}$ (Trenberth et al. 2003, 2005), variations in relative humidity associated with changes in atmospheric circulation, surface evaporation, and other processes could induce additional changes in atmospheric water vapor content. Thus, monitoring long-term changes in atmospheric water vapor is still needed for better understanding and predicting future climate changes (Held and Soden 2000).

Historically, measurements of tropospheric humidity over land have been made primarily using radiosondes attached to air balloons (Wang et al. 2003; Rowe et al. 2008). The radiosonde humidity data not only provide the longest record for assessing long-term trends but also are an important resource for weather prediction, atmospheric reanalyses, and satellite calibration. There are, however, many spurious changes and discontinuities in the raw radiosonde records resulting from changes in instruments, observational practice, processing procedures, station relocations, and other issues (Angell et al. 1984; Gaffen 1993, 1996; Elliott and Gaffen 1991, 1993; Zhai and Eskridge 1996; Elliott et al. 1998; Wang et al. 2003; McCarthy et al. 2009; Dai et al. 2011). These discontinuities can greatly affect estimated long-term trends, and thus they must be removed or minimized before the data can be used for climate change analyses.

China has a radiosonde network of about 130 stations that have been launching radiosondes twice daily since the 1950s. As for other regions, the Chinese radiosonde records for temperature and humidity are known to contain significant discontinuities (Zhai and Eskridge 1996; Guo et al. 2008; Guo and Ding 2009; Dai et al. 2011). In particular, recent changes from the old Goldbeater's skin hygrometer to newer sensors have introduced large discontinuities in Chinese radiosonde records (Wang and Zhang 2008).

Recently, Guo et al. (2008) discussed the upper-air temperature trends and their uncertainties over eastern China using radiosonde records. Guo and Ding (2009) further used homogenized temperature records from 92 of the Chinese radiosonde stations to quantify long-term trends in tropospheric temperature from 1958 to 2005. Radiosonde humidity data from some of the Chinese stations have been used in previous analyses of Northern Hemispheric water vapor trends (Ross and Elliott 2001; Durre et al. 2009; McCarthy et al. 2009). In particular, Zhai and Eskridge (1997) selected relatively homogeneous records from 1970 to 1990 from 63 Chinese radiosonde stations to quantify the climatology and trends

in precipitable water (PW) over China. They found that PW increased from 1970 to 1990 over most of China during all seasons and the PW trends are positively correlated with long-term changes in precipitation and surface air temperature.

Dai et al. (2011) recently developed a new approach to homogenize the daily radiosonde humidity records from the global radiosonde network, including the Chinese stations. They focused on the homogenization approach and did not analyze long-term water vapor trends. In this paper, we first examine the impact of the homogenization on the long-term trends of tropospheric temperature (T) and dewpoint depression (DPD) over China and evaluate the homogenized radiosonde humidity data from Dai et al. (2011) using observed precipitation over whole China and the PW data from ground-based global positioning system (GPS) measurements at three collocated stations, and then use this dataset to further characterize and update the trends from 1970 to 2008 in tropospheric PW (up to 300 hPa) and humidity and their relationships with temperature changes over China.

In the following, we first describe the datasets and data processing used in this study in section 2. A brief description of the homogenization and its impact on the long-term trends of tropospheric temperature and DPD are presented in section 3. Comparisons between the radiosonde-derived PW and observed precipitation and the GPS measurements are also made in section 3. Long-term trends of tropospheric specific humidity (q), relative humidity (RH), and PW, and their relationship with temperature changes are analyzed in section 4. Section 4 also discusses two leading empirical orthogonal functions (EOFs) of the PW over China. A summary is given in section 5.

2. Data and analysis method

In this study, the tropospheric humidity is derived from radiosonde data of homogenized DPD from Dai et al. (2011) and T from Haimberger et al. (2008). As in most homogenization studies, uncertainty estimates for both the adjusted DPD and T are unavailable. This makes it impossible for us to provide an estimate of the uncertainty range for the estimated PW associated with the adjustments made to both the DPD and T . Instead, we focus on examining the impact of the adjustments on T , DPD, and PW through comparisons with other independent measurements for related variables such as precipitation and GPS PW.

a. Radiosonde data

The radiosonde data came from two sources. The first one is from the National Climate Data Center's (NCDC)

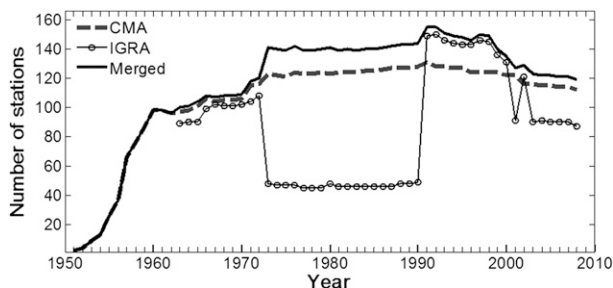


FIG. 1. Number of stations with reports during each year from 1951 to 2009 for the CMA, IGRA, and merged datasets.

Integrated Global Radiosonde Archive (IGRA) (Durre et al. 2006; <http://www.ncdc.noaa.gov/oa/climate/igra/index.php>). The second one is a radiosonde dataset compiled by the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). Figure 1 shows the number of stations with any valid DPD reports for each year from January 1951 to February 2009 for both the IGRA and CMA datasets. There are a total of 160 and 131 stations in the IGRA and CMA datasets, respectively. The two datasets have 125 stations in common, but six stations in the CMA dataset are not included in the IGRA. The IGRA stations not included in the CMA dataset are mainly located in western China often with short records (Fig. 2). However, the IGRA has no data before 1963 and has less than 50 stations during 1973–90.

The IGRA had undergone a series of quality control (QC) procedures (Durre et al. 2006). On the other hand, the data before 2002 in the CMA dataset were not quality controlled. Thus, we applied two QC procedures to the CMA data before 2002, a “limit check” and “climatological check.” For the limit check, each variable was checked to determine whether it falls within its possible limits based on Table 4 in Durre et al. (2006). The data outside the limits were removed. In the climatological check, the median and standard deviation (STD) of temperatures and DPD were computed at each station for each level, UTC time, month, and year. Any values that deviated by more than three (four) STDs from the median value for temperature (DPD) were removed. The use of a four-STD threshold for the DPD QCs was based on the consideration that DPD histograms are highly skewed (Dai et al. 2011), in contrast to those of air temperatures. These QC steps removed about 0.36% and 0.06% of data points for temperature and DPD, respectively. The QCed CMA data were compared with the IGRA data, and the two were found to be identical except small differences for a few reports that may resulted from differences in the QCs procedures or original data sources. To improve the coverage, we merged the two

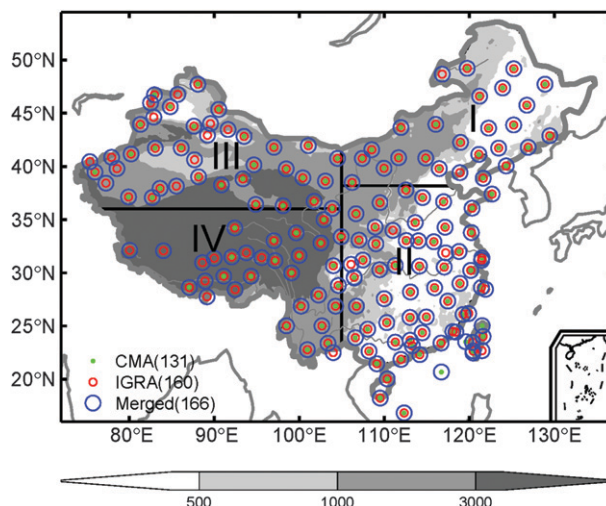


FIG. 2. Geographic distribution of all stations from the CMA (dots), IGRA (small red circles), and merged (big blue circles) datasets, and four subregions with topography (m). Region I means “Northeast China,” region II means “Southeast China,” and region III and IV are “Northwest China” and “Southwest China.”

datasets together to compile a new set of Chinese radiosonde data from 1951 to 2009. The IGRA was used as the starting point and was augmented by filling its missing data with QCed CMA data. The number of stations in the merged dataset increases quickly from one station (54511, Beijing, China) in 1951 to ~100 stations in 1960 (Fig. 1). In 1973 about 20 stations were added to the network that contained about 140 stations until 2000, thereafter it decreased to around 120 stations (Fig. 1). There are a total of 166 stations in the merged dataset, but not all stations have reports for any given year. Figure 2 shows their locations, with sparse stations in western China where high terrain and deserts are common and more stations in East China where elevations are lower. Most of the stations have less than 80% of the twice-daily reporting times with valid observations (referred to as the sampling rate below) of temperature and DPD for all levels (Fig. 3). In general, there are more missing reports for upper levels for both temperature and DPD and for years before 1970. At 50 and 100 hPa, the sampling rate for DPD is less than 15%. Therefore, in the trend analysis we only use the data at and below 300 hPa and focus on the period from 1970 to 2008.

b. Precipitation data

In our analysis, we found that mean precipitation over China is negatively correlated with tropospheric mean DPD, a measure of relative humidity. Here, we used the gridded monthly precipitation dataset from the Climate Research Unit (CRU; <http://badc.nerc.ac.uk/data/cru/>)

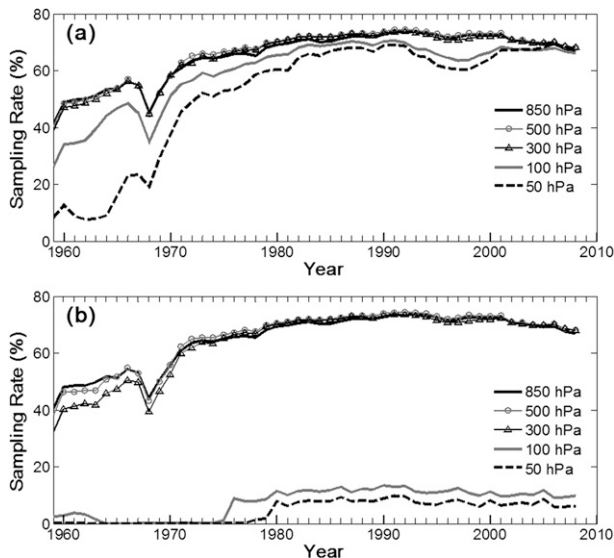


FIG. 3. The percentage of the twice-daily reporting times with valid data (sampling rate) for the 850-, 500-, 300-, 100-, and 50-hPa levels for (a) temperature and (b) DPD averaged over all the stations over China in the merged dataset.

(New et al. 1999; Mitchell and Jones 2005). It was constructed by interpolating monthly precipitation from over 19 000 gauge stations using a thin-plate spline technique. This dataset has recently been updated [CRU time series dataset (TS) 3.1] for the period 1901–2009. Here, we used this precipitation dataset to evaluate the impact of the homogenization made to the radiosonde DPD data.

c. GPS PW data

PW data from ground-based GPS measurements are often used to quantify biases in historical radiosonde humidity data because the GPS PW has continuous temporal sampling, high accuracy (<3 mm in PW), and long-term stability (Wang and Zhang 2008). Here we used the GPS PW data from Wang et al. (2007) at three collocated stations to validate the homogenization done by Dai et al. (2011).

We used the 2-hourly GPS PW data available from February 1997 to December 2008 produced by Wang et al. (2007) using the zenith tropospheric delay data from the International Global Navigation Satellite Systems (GNSS) Service (IGS) network. The IGS network includes more than 350 ground-based GPS stations around the globe, and there are a total of 130 stations matched with the IGRA stations (within 50 km and elevation differences less than 100 m), but only seven of these stations are located in China (Wang and Zhang 2008). The radiosonde PW was calculated by integrating specific humidity from the surface to 300 hPa. The GPS PW data within an hour of the radiosonde launch time

were used in the comparison. At the seven matched pairs of stations over China, only BJFS (54511, Beijing), WUHN (57494, Wuhan), and KUNM (56778, Kunming) had both GPS and radiosonde records over more than 7 years during 1997–2008. Thus, we made comparisons only at these three stations.

d. Analysis method

To ensure sufficient sampling, here we required a sampling rate of 50% or higher in deriving the monthly mean value for individual months and required at least 374 months (or 80% of the months) with data during 1970–2008. This reduced the number of stations to ~ 100 . Stations located above the 850-hPa level in western China were included only in the trend analysis of q and RH at higher levels.

Monthly means at 0000 and 1200 UTC were averaged to obtain monthly values. If the monthly means were available only at one of the two reporting times, the monthly value for the month was treated as missing. Monthly anomalies were computed as deviations from the long-term mean of the study period (1970–2008) for each month. Annual anomalies were then calculated from the monthly anomalies, requiring at least 10 months with data. Similarly, seasonal anomalies were formed for winter [December–February (DJF)], spring [March–May (MAM)], summer [June–August (JJA)], and fall [September–November (SON)] by averaging the monthly anomalies for the individual seasons, requiring at least two months with data. Trends and their statistical significance at individual stations were estimated using the pairwise method (Lanzante 1996) to minimize the effect of outliers and end points. To obtain regional mean values, the monthly anomalies were first interpolated onto a $1^\circ \times 1^\circ$ latitude–longitude grid using the Cressman interpolation technique (Cressman 1959), and then the gridded data were averaged using the gridbox area as weight to derive regional means.

3. Homogenization and its impacts

a. Homogenization of the radiosonde data

As part of a global dataset, the daily humidity data from the (merged) Chinese stations were homogenized by Dai et al. (2011). Here we briefly summarize this homogenization. Dai et al. (2011) focused on homogenizing daily DPD, which is the original archived humidity variable in the IGRA and CMA datasets. The DPD is much more stationary than q and PW, as the latter two increase with air temperature. This makes the DPD a better choice for statistical homogenization, which requires or prefers stationary time series.

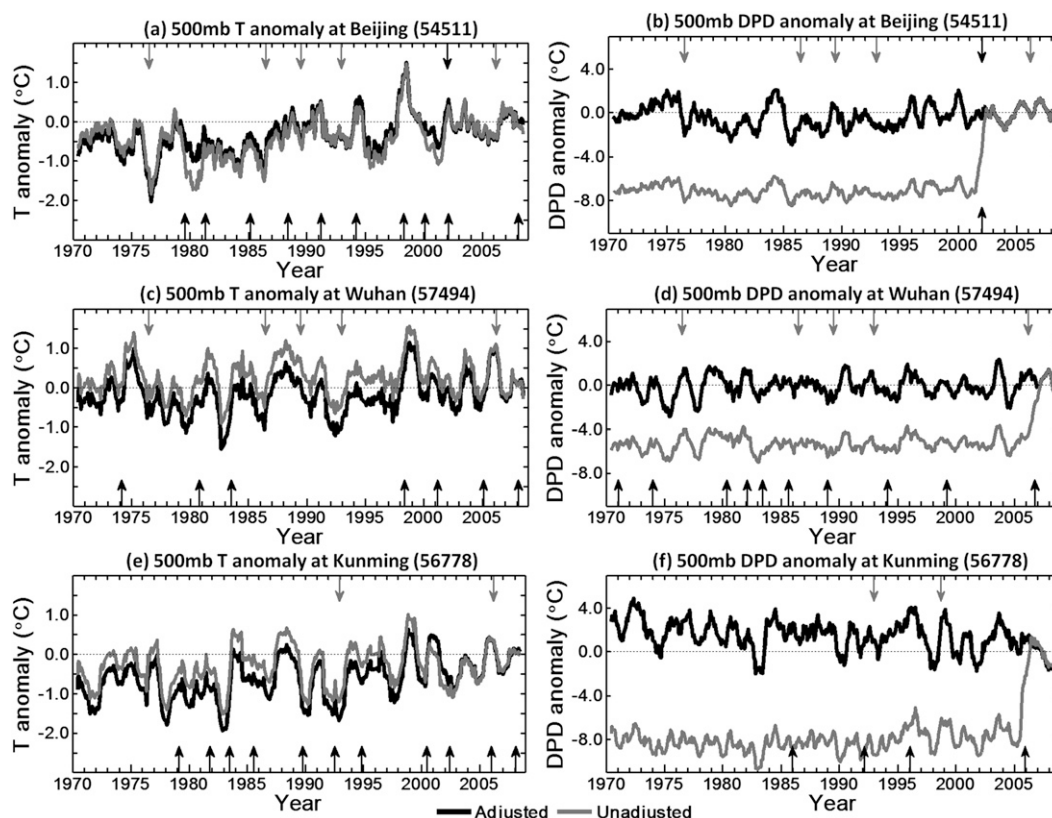


FIG. 4. Time series of 11-point-smoothed monthly anomalies of (left) temperature (T , $^{\circ}\text{C}$) and (right) DPD data ($^{\circ}\text{C}$) derived from daily data with (black) and without (gray) homogenization for 0000 UTC on 500 hPa at three stations for 1970–2008: (top) Beijing [World Meteorological Organization (WMO) id = 54511, 39.80°N , 116.47°E], (middle) Wuhan (id = 57494, 30.62°N , 114.13°E), and (bottom) Kunming (id = 56778, 25.02°N , 102.68°E). The anomaly data are relative to the monthly mean of the last segment. Arrows pointing upward show the locations of the statistically detected change points, and those pointing downward indicate instrumental (black) or observational (gray) changes based on available metadata.

Furthermore, the derived humidity variables, such as q and PW, contain different discontinuities resulting from both temperature and humidity sensors, which could make the discontinuities in q and PW more complex and thus make it more difficult to detect and remove them. On the other hand, many applications, such as atmospheric reanalyses, require homogenized T and DPD data, which are often used to derive the other humidity variables in most applications.

Dai et al. (2011) used two statistical tests to detect change points, which were most apparent in histograms and occurrence frequencies of the daily DPD: a variant of the Kolmogorov–Smirnov test for changes in distributions, and the Penalized Maximal F test for mean shifts in the occurrence frequency for different bins of DPD. Before applying adjustments, sampling inhomogeneity was first minimized by estimating missing DPD reports for cold ($T < -30^{\circ}\text{C}$) conditions from air temperature using an empirical relationship. The

sampling-adjusted DPD was then adjusted using a quantile-matching algorithm so that the earlier segments had histograms comparable to that of the latest segment.

Dai et al. (2011) showed that the adjusted daily DPD exhibits homogeneous histograms since the early 1970s, and much smaller and spatially more coherent trends during 1973–2008 than the unadjusted data. Combined with homogenized daily air temperature from radiosonde measurements from Haimberger et al. (2008), atmospheric specific humidity (q) and relative humidity (RH) and column-integrated PW (up to 100 mb) were derived and shown to have more spatially coherent trends than without the DPD homogenization (Dai et al. 2011). Using this new approach, a homogenized global daily DPD dataset, together with the homogenized daily temperature (T) from Haimberger et al. (2008) and derived daily q , RH, and PW, was created based on the IGRA, with additional data from the CMA and other archives. This study uses the homogenized DPD and

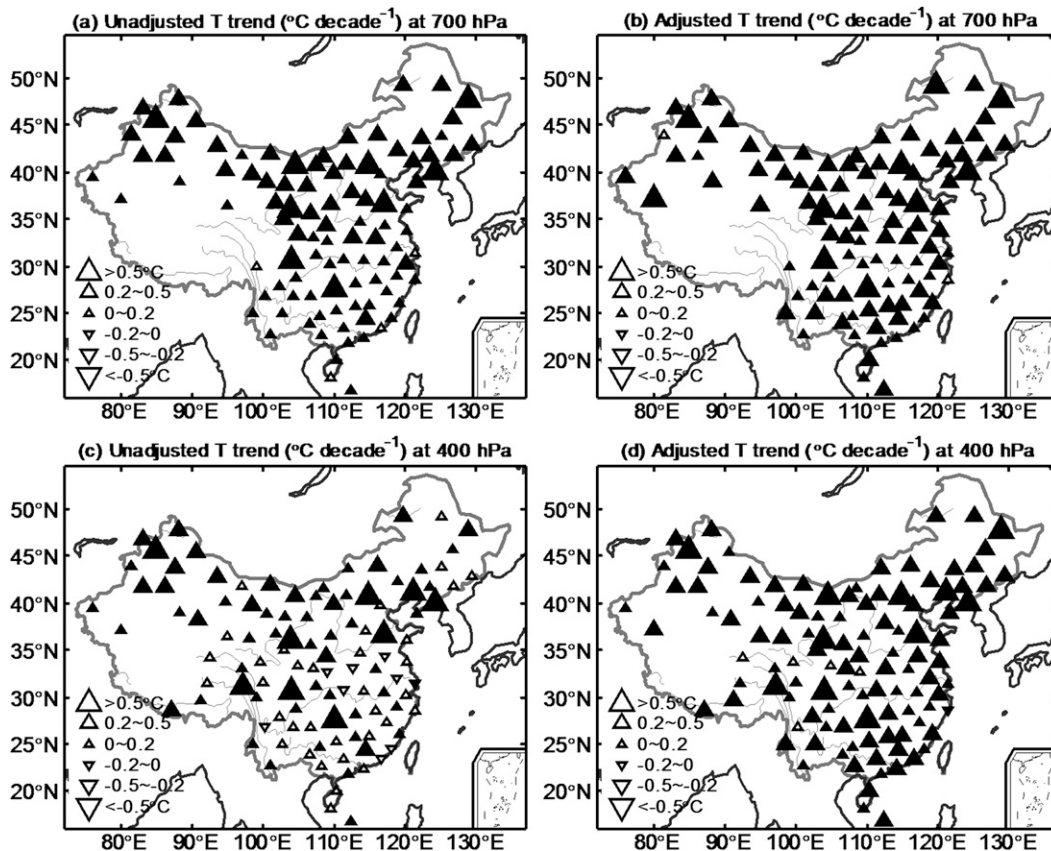


FIG. 5. Spatial distribution of T linear trends ($^{\circ}\text{C decade}^{-1}$) at stations with at least 80% of the months with data during 1970–2008 (left) with and (right) without homogenization for 0000 UTC at (a),(b) 700 and (c),(d) 400 hPa. The black triangles indicate that the trends are statistically significant at the 5% level. The trend and its significant level were estimated using the pairwise method of Lanzante (1996).

T and the other related humidity data for stations over the Chinese territory from this homogenized global dataset created by Dai et al. (2011).

Differences in the various versions of the homogenized daily T data from Haimberger et al. (2008) are relatively small, especially when compared with uncertainties in the homogenized DPD data. However, this does not mean that the homogenized T data do not contain spurious changes. This is especially true at low latitudes (outside of China) where the trends in the homogenized T data are less coherent spatially. Furthermore, it is hard to provide a true error bar for the adjusted DPD data, as we have no data on measurement errors and biases for most of the records. Accurate measurements of tropospheric humidity with observational uncertainty well quantified are also a major thrust of the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRAN; Seidel et al. 2009). There is, however, evidence (see Dai et al. 2011 and discussions below) suggesting that the adjusted humidity

data are more homogeneous and thus better for estimating long-term trends than the unadjusted data.

b. Impacts of homogenization on T and DPD long-term trends

Dai et al. (2011) assessed the global impact of the homogenization on DPD and related humidity variables. In this section, we present some examples over China to further illustrate the effects of the homogenization on the long-term trends of T and DPD. The time series of homogenized and original monthly T and DPD anomalies for 0000 UTC and 500 hPa for 1970–2008 at Beijing, Wuhan, and Kunming stations are compared in Fig. 4. These stations have collocated GPS PW data and are discussed further below. According to the IGRA metadata (available at <http://www1.ncdc.noaa.gov/pub/data/igra/igra-metadata.txt>), which are incomplete and were created from the original work of Gaffen (1996) by NCDC and the National Center for Atmospheric Research (NCAR) people by updating and adding new

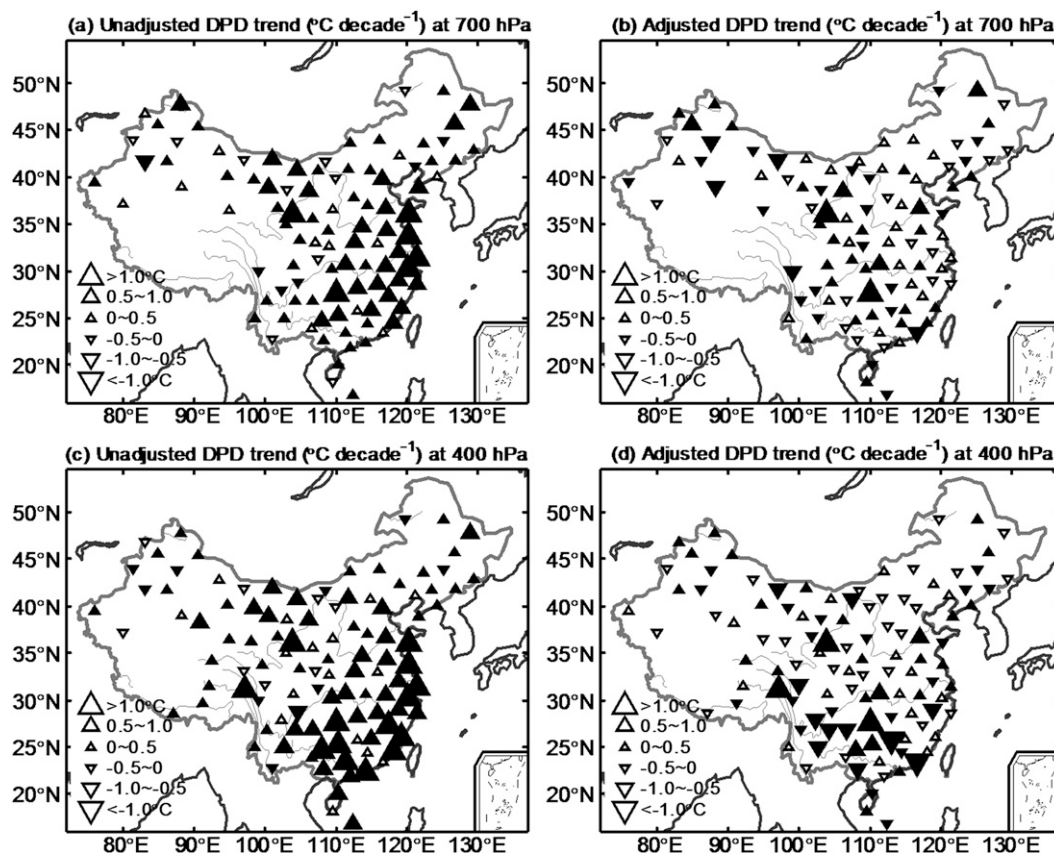


FIG. 6. As in Fig. 5, but for DPD.

information, there are a number of instrumental and observational changes as indicated by the downward-pointing arrows in Fig. 4.

Figure 4 shows that the adjusted and unadjusted T series both have similar variations and demonstrate consistent upward long-term trends at the three stations. In contrast, the switch from Shang-M to Shang-E sondes around the beginning of 2002 at Beijing station resulted in a large jump in the original monthly DPD, and thus a large upward (i.e., drying) trend throughout the period, especially in the middle and upper troposphere. This is consistent with what is known about the characteristics of Shang-M (slow response) and Shang-E (dry bias) humidity sensors (Wang and Zhang 2008; Bian et al. 2010). After the homogenization, those abrupt changes in the original series were greatly reduced, and the adjusted series become more homogeneous. A similar change also occurred at the Wuhan and Kunming stations during recent years that induced a large upward jump in the DPD series. The adjustment largely removed this discontinuity.

We analyzed and compared the original and adjusted T and DPD time series for other stations as well and

obtained similar results. They indicate that the discontinuities in the DPD series are much larger than those in the T records, and the change from Shang-M to Shang-E around 2001/02 as part of the Chinese radiosonde replacement project introduced the largest discontinuities in the radiosonde DPD records over China.

Figure 5 shows spatial distributions of linear trends from 1970 to 2008 in monthly T anomalies with and without the adjustments for 0000 UTC over China at 700 and 400 hPa. The unadjusted T data show significant upward trends of $0.2^{\circ}\text{--}0.5^{\circ}\text{C decade}^{-1}$ at most of the stations over central and North China at 700 hPa, but only at a small number of stations in North China at 400 hPa. After the homogenization, the significant trends of $0.2^{\circ}\text{--}0.5^{\circ}\text{C decade}^{-1}$ are seen at both pressure levels at most of the stations and they distribute more coherently in space. This indicates that the T homogenization improves the spatial coherence of the long-term trends, especially over South China in the upper troposphere.

The linear trends for monthly DPD anomalies with and without the homogenization for 0000 UTC at 700 and 400 hPa are shown in Fig. 6. The DPD data without

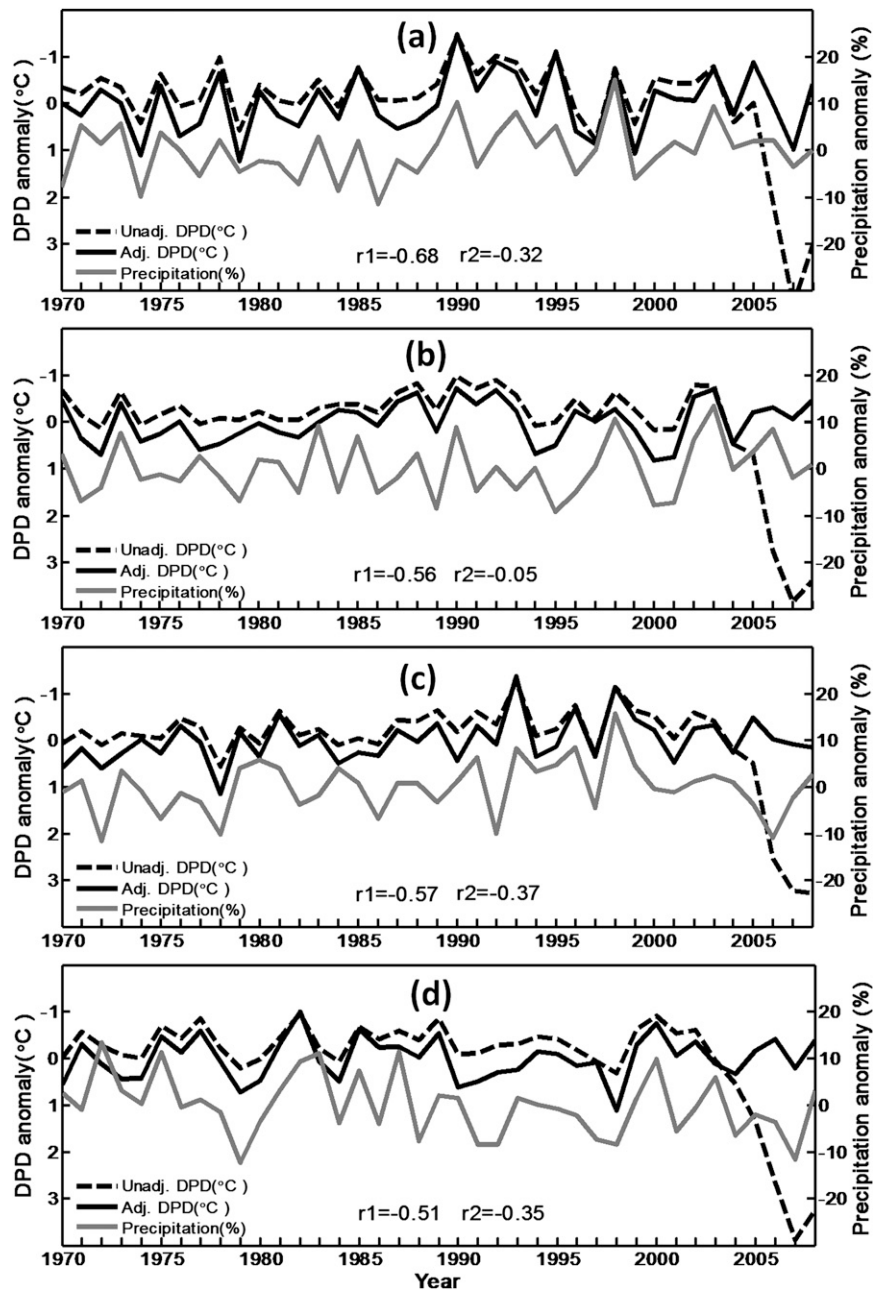


FIG. 7. The time series of the surface-to-300-hPa mean DPD anomalies ($^{\circ}\text{C}$) with (black dash line) and without adjustments (black solid line) and the precipitation anomaly from the CRU dataset (gray line, in % of the 1970–2008 mean) averaged across China for (a) winter, (b) spring, (c) summer, and (d) autumn. The r_1 and r_2 are the correlation coefficients of the DPD with and without adjustments with the precipitation series, respectively.

the homogenization show significant positive (i.e., drying) trends ranging from 0.5° to $1.0^{\circ}\text{C decade}^{-1}$ on both pressure levels at most of the stations. This large drying trend resulted primarily from the upward jump around 2001/02 (cf. Fig. 4) due to the sonde change from Shang-M to Shang-E. After the homogenization, the DPD trends

are reduced to within $\pm 0.5^{\circ}\text{C decade}^{-1}$ and become statistically insignificant at most of the stations.

c. Evaluation using precipitation data

To evaluate the impact of the homogenization on the DPD data, the time series of the surface-to-300-hPa

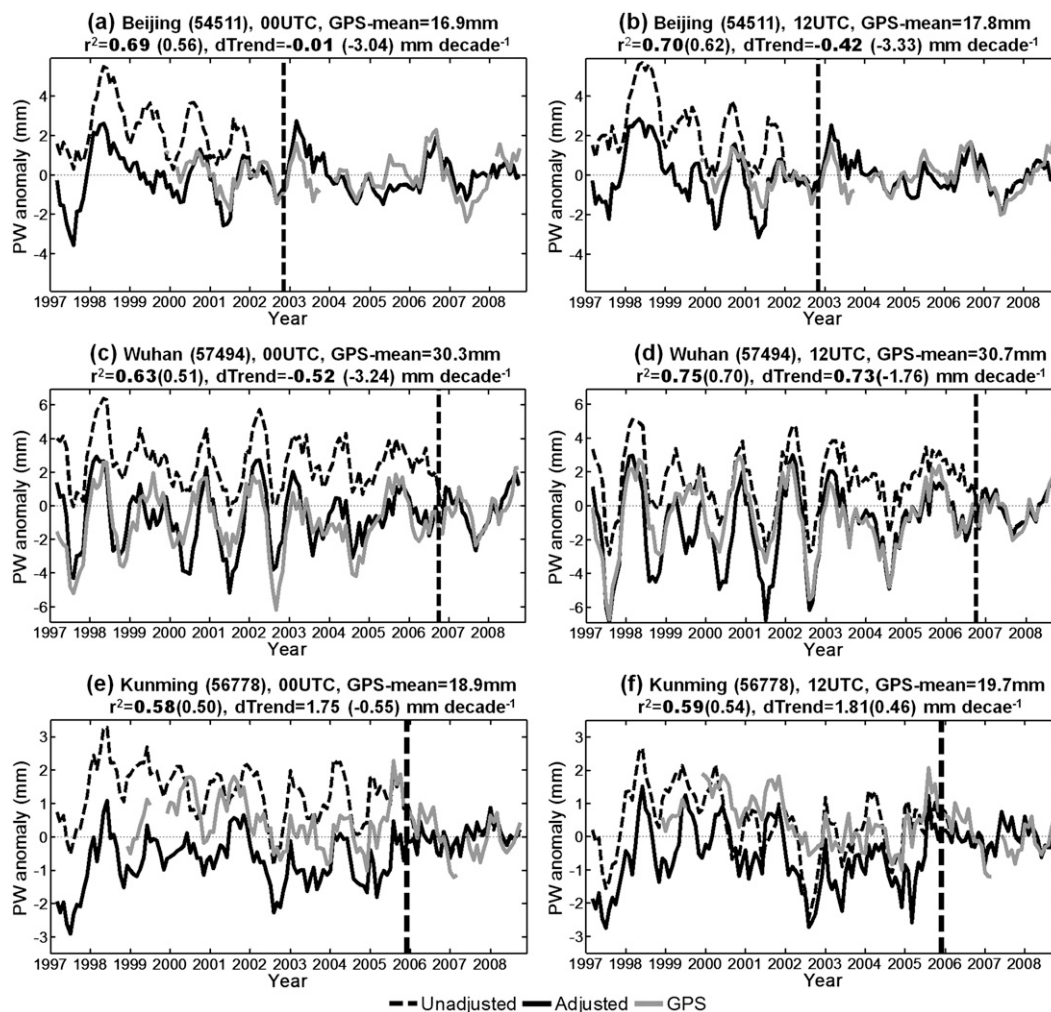


FIG. 8. Time series of 5-point-moving-averaged monthly PW anomalies (mm, relative to the monthly mean of the last segment) derived from radiosonde data and GPS observations for (left) 0000 and (right) 1200 UTC at the same three stations as shown in Fig. 4. The vertical dashed black line shows the location of the last change point for the DPD series. (top) The mean GPS PW (GPS-mean) over the compared time period, the squared correlate coefficient (r^2) between the adjusted radiosonde (Adj) and GPS PW anomalies and between the unadjusted radiosonde (UnAdj) and GPS PW anomalies (in parentheses), and the PW linear trend difference (dTrend) between the Adj and GPS PW and between the UnAdj and GPS PW (in parentheses) are shown. Numbers in bold indicate improvements by the adjustments.

mean DPD anomalies with and without the adjustments are compared with the precipitation anomaly from the CRU dataset averaged across China for the four seasons (Fig. 7). It is clear that variations in both the unadjusted and adjusted DPD series are similar before around 2002/03 but a sudden drop occur in the unadjusted series after that as seen in Fig. 4 because of the sensor change. The tropospheric mean DPD anomalies after adjustments correlates with the precipitation series much stronger than without the adjustment ($r = -0.5$ to -0.7 versus $r = -0.05$ to -0.4). Figure 7 shows that the DPD homogenization effectively eliminates the artificial

changes in the raw DPD series caused by the documented sensor changes during recent years, thereby improving its correlation with precipitation, which is physically related to tropospheric mean relative humidity or DPD.

d. Validation using GPS PW

Figure 8 shows the PW anomaly series from 1997 to 2008 from the unadjusted and adjusted radiosonde data and GPS observations at the three collocated stations with sufficient GPS data. The PW from the unadjusted radiosonde data at the Beijing station (Figs. 8a,b) has a moist bias of about 2 mm ($\sim 12\%$) before 2002. Such

a shift is a result of the switch from the old Shang-M to the newer Shang-E sonde at the beginning of 2002 (cf. Fig. 4). This moist bias before 2002 in the radiosonde data is effectively removed by the adjustment. The adjusted PW anomalies show improved correlation and better trend agreement with the GPS data at the Beijing station.

At the Wuhan station (Figs. 8c,d), there are two detected change points since 1997, and the last one (October 2006) is associated with the change from the Shang-M to Shang-E as found at the Beijing station (Wang and Zhang 2008). The unadjusted radiosonde PW shows a wet bias of about 2 mm ($\sim 7\%$) before about October 2006 (mainly for 0000 UTC). The adjusted PW anomalies show better agreement with the GPS data as reflected by the higher correlation and smaller trend differences between the radiosonde and GPS PW anomalies.

For the Kunming station (Figs. 8e,f), there is only one detected change point (December 2005) during 1997–2008, again associated with the switch from the Shang-M to Shang-E sonde. The adjustment removes the wet bias before December 2005 (mostly for 0000 UTC), resulting in improved correlation with the GPS PW anomalies. However, the GPS PW before 2002 at this station may contain a moist bias as a change occurred in 2002 in GPS data processing (Wang and Zhang 2008). This might explain the low correspondence between the radiosonde and GPS PW anomalies since 2006 and the lack of improvements in the trend difference by the adjustment at this station.

4. Humidity trends in the troposphere over China

a. Variations and long-term trends of q , RH, and T

Figure 9 shows time–height (pressure) cross sections of the nationwide-averaged annual anomalies (relative to the 1970–2008 mean) of q , RH, and T from the homogenized radiosonde data during 1970–2008. The q anomalies and changes in this paper are expressed as percentages of the 1970–2008 mean to make them more comparable spatially and easier to comprehend, although mm units are also included for regional trends listed in Table 1. However, RH anomalies and trends presented below are not normalized by its long-term mean. Figure 9 shows negative q anomalies before the mid-1980s and around the mid-1990s, but generally positive values after the late 1980s. The RH shows dry anomalies before the mid-1980s but generally wet anomalies thereafter at 700–300-hPa levels, while there are no obvious trends below 700 hPa (Fig. 9b). Trend maps for winter and summer revealed little seasonal variation (not shown).

Consistent with previous studies (e.g., McCarthy et al. 2009), most of the q variations over China appear to be

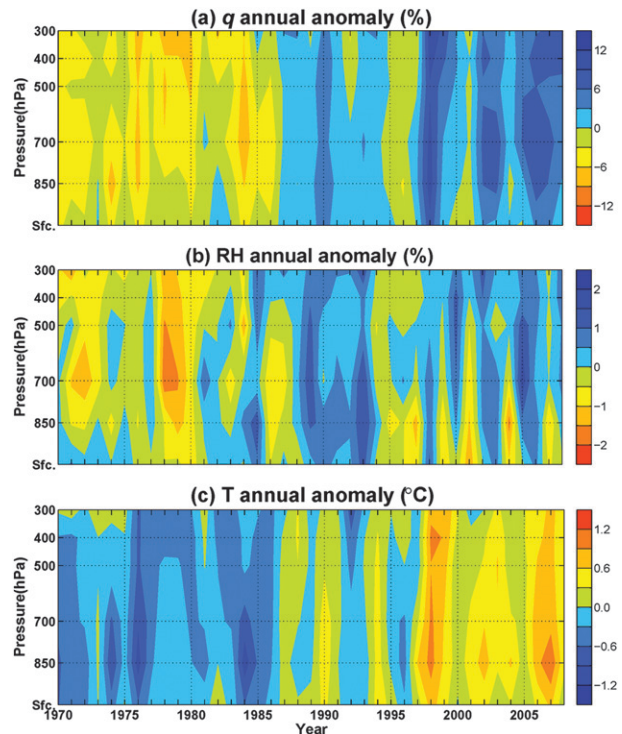


FIG. 9. Time–pressure cross sections of nationwide-averaged annual anomalies of (a) q (% of the 1970–2008 mean), (b) RH (%), and (c) T (°C) from the homogenized radiosonde data over China.

associated with accompanying temperature changes (Fig. 9c), which show steady warming from the surface to 300 hPa from 1970 to 2008. The cold temperature anomalies around 1991–93 were caused by the large volcanic eruption of Mount Pinatubo in June 1991 (Trenberth and Dai 2007), which also induced small decreases in q around 1991–93 above 600 hPa over China while RH shows small positive anomalies (Fig. 9b). The drop in q , RH, and T around 1995/96 appears to be a robust signal.

Figure 10 shows the vertical profiles of the linear trends of nationwide-averaged q , RH, and T with adjustments for each month from 1970 to 2008. The trends for both q and T are all positive and, especially for T , larger in the cold season [October–April, $\sim(0.3^{\circ}\text{C}–0.6^{\circ}\text{C}) \text{ decade}^{-1}$] than in the warm season [May–September, $\sim(0.1^{\circ}\text{C}–0.3^{\circ}\text{C}) \text{ decade}^{-1}$], whereas RH trends show both positive [$\sim(0.2\%–1.0\%) \text{ decade}^{-1}$, mostly in summer and above 850 mb] and negative (about -0.2 to $-0.4\% \text{ decade}^{-1}$, February–May in the lower troposphere; and September from the surface to 300 mb) values. These RH changes make the q trend patterns [$\sim(2\%–5\%) \text{ decade}^{-1}$] differ quantitatively from those of the T trends, which are much larger in the

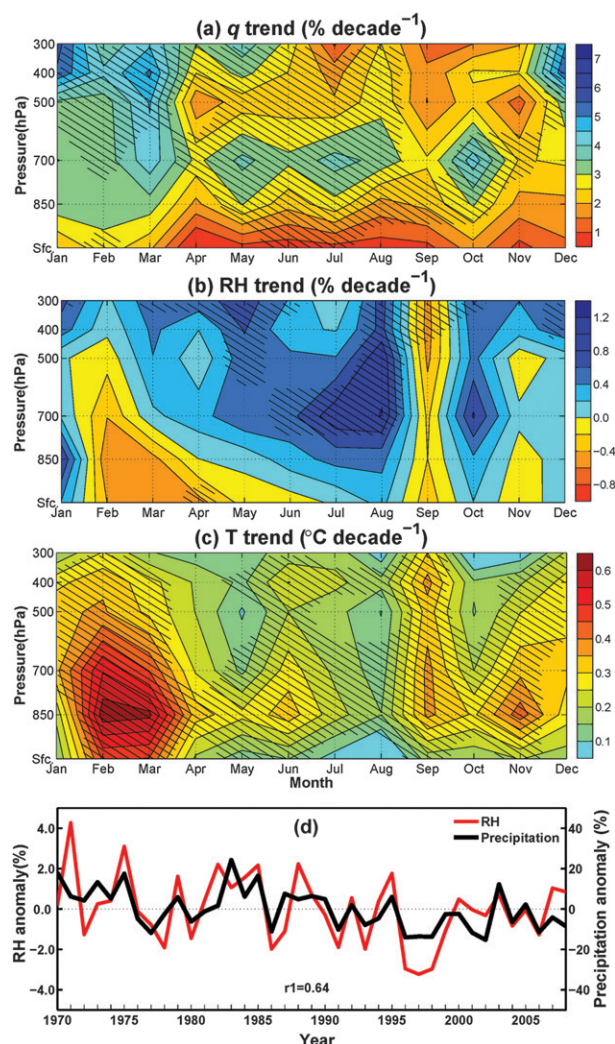


FIG. 10. Month–pressure cross sections of the monthly trends from 1970 to 2008 for (a) q ($\% \text{ decade}^{-1}$), (b) RH ($\% \text{ decade}^{-1}$), and (c) T ($^{\circ}\text{C decade}^{-1}$) with adjustments averaged over China. The stippled areas are statistically significant at the 5% level. (d) The RH (%), black) averaged from surface to 300 hPa and precipitation anomalies from the CRU dataset (red, in % of the 1970–2008 mean) for September over China are also shown. The correlation coefficient (r) between the RH and precipitation series is also shown in (d).

lower troposphere than at higher levels. The decreasing RH trend for September appears to be caused by large tropospheric warming in September (Fig. 10c) that is not accompanied by upward trends in specific humidity (Fig. 10a). The decreases in September RH are consistent with decreasing precipitation averaged over China (Fig. 10d), and thus are likely real. Trend patterns for tropospheric RH and precipitation are, however, only weakly correlated during summer and autumn ($r = 0.27$ and 0.24 , respectively). The q trends for 1970–2008

shown in Fig. 10a are consistent with McCarthy et al. (2009), who showed that tropospheric q increases from 1970 to 2003 are around $1\%–5\% \text{ decade}^{-1}$ in the Northern Hemisphere.

Spatial distributions of the linear trends for the homogenized annual q , RH, and T during 1970–2008 at 700, 500, and 300 hPa are shown in Fig. 11. The T trend is positive ($0.2^{\circ}–1.0^{\circ}\text{C decade}^{-1}$) and statistically significant at most of the stations in the lower and mid-troposphere, while the q ($2\%–10\% \text{ decade}^{-1}$) and RH (-2 to $+2\% \text{ decade}^{-1}$) trends are less coherent, although the q trends are mostly positive. In central East China, the temperature trend is relatively small and statistically insignificant at the 500- and 300-hPa levels. The q trend is also relatively small in this region. Over North China, both the T and q trends are large and positive. Thus, there exist some spatial correlations between the T and q trend patterns as expected. Our temperature trends during 1970–2008 are broadly consistent with Guo and Ding (2009), who showed mostly upward trends in air temperature at and below 400 hPa from 1979 to 2005 (but negative trends during 1958–78).

b. Variations and long-term trends of PW

Zhai and Eskridge (1997) concluded that the PW spatial variations in China are controlled by surface elevation and latitude. At stations with low elevations in East China, about 70%–75% of the PW is in the surface–700-hPa layer, 25%–30% in the 700–400-hPa layer, and only about 5% in the 400–200-hPa layer. For stations over the Tibetan Plateau, about 80%–90% of the PW is located in the 700–400-hPa layer, and 10%–20% in the 400–200-hPa layer. Hence, the following analysis focuses on the PW from surface to 300 hPa over China.

In our analysis, the percentage changes in PW were used in the trend maps since it is easier to compare spatially. Figure 12 shows the spatial distributions of the linear trends for annual, winter, and summer PW (up to 300 hPa) with and without the homogenization for T and DPD from 1970 to 2008 for the 97 individual stations over China with sufficient observations. The unadjusted data exhibit upward PW trends of $\sim 2\% \text{ decade}^{-1}$ at most of the stations, and statistically significant trends of $2\% \sim 5\% \text{ decade}^{-1}$ are sparsely distributed only at a third of the stations (Figs. 12a,c,e). After the homogenization, upward PW trends of $1\%–5\% \text{ decade}^{-1}$ are seen across most of China (Figs. 12b,d,f). About two thirds of the stations show significant positive trends for the annual and seasonal PW anomalies, but the largest trends ($>5.0\% \text{ decade}^{-1}$) are seen in winter in North China. Only a few stations in the South and Southwest China show small and insignificant negative PW trends (within

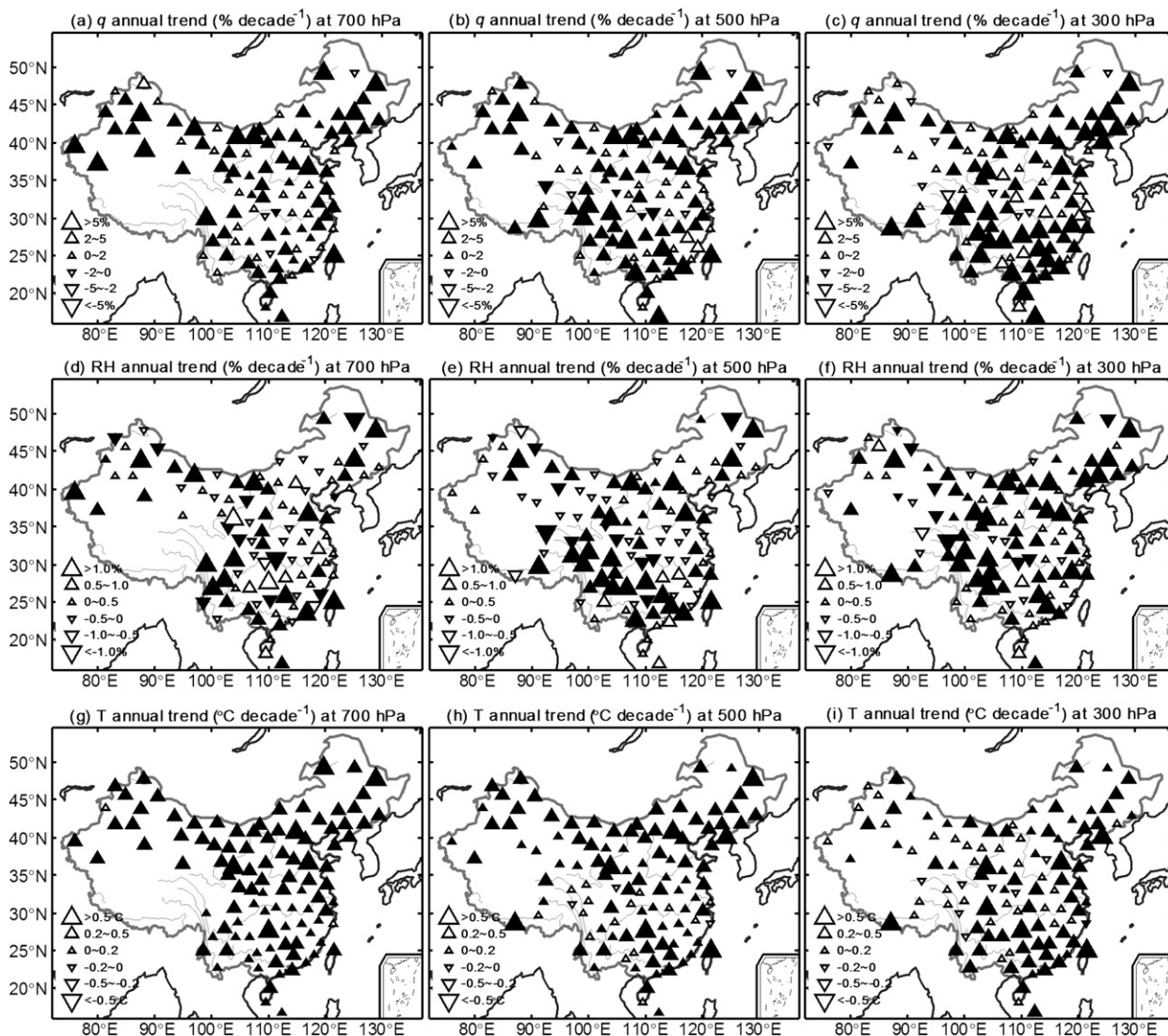


FIG. 11. Spatial distributions of the linear trends for annual (a)–(c) q ($\% \text{ decade}^{-1}$), (d)–(f) RH ($\% \text{ decade}^{-1}$), and (g)–(i) temperature ($^{\circ}\text{C decade}^{-1}$) from the homogenized radiosonde data during 1970–2008 at (left) 700, (middle) 500, and (right) 300 hPa over China. The filled black triangles indicate the trends are statistically significant at the 5% level.

0% to $-1\% \text{ decade}^{-1}$). The adjusted PW trend patterns shown in Figs. 12b,d,f are broadly consistent with the trend patterns from fewer stations for surface–200-hPa PW during 1970–90 reported by Zhai and Eskridge (1997), who used unadjusted records from select stations. The magnitude of the trends shown in Figs. 12b,d,f are broadly similar to that of Zhai and Eskridge (1997) but are more statistical significant for most stations over northern and southern China. Comparisons with trend maps for 1970–90 computed using our adjusted data yielded a similar conclusion. The slight magnitude difference is likely due to our use of adjusted data and more stations.

Table 1 and Fig. 13 present the annual and seasonal PW trends after the homogenization over whole China and the four subregions as shown in Fig. 2. They show that percentage-wise the PW trend is smallest (around $0.9\%–2.8\% \text{ decade}^{-1}$) in Southeast China (region II), and in absolute terms the PW trend in Northwest China (region III) is among the largest ($0.4–0.8 \text{ mm decade}^{-1}$). In Northwest China, the PW trend is largest for SON ($4.4\% \text{ decade}^{-1}$), while the DJF trend is largest for Southeast and Southwest China (regions II and IV). For China as a whole, the seasonal differences in the PW percentage changes ($2.2\%–2.8\% \text{ decade}^{-1}$) are small, with the DJF trend slightly larger.

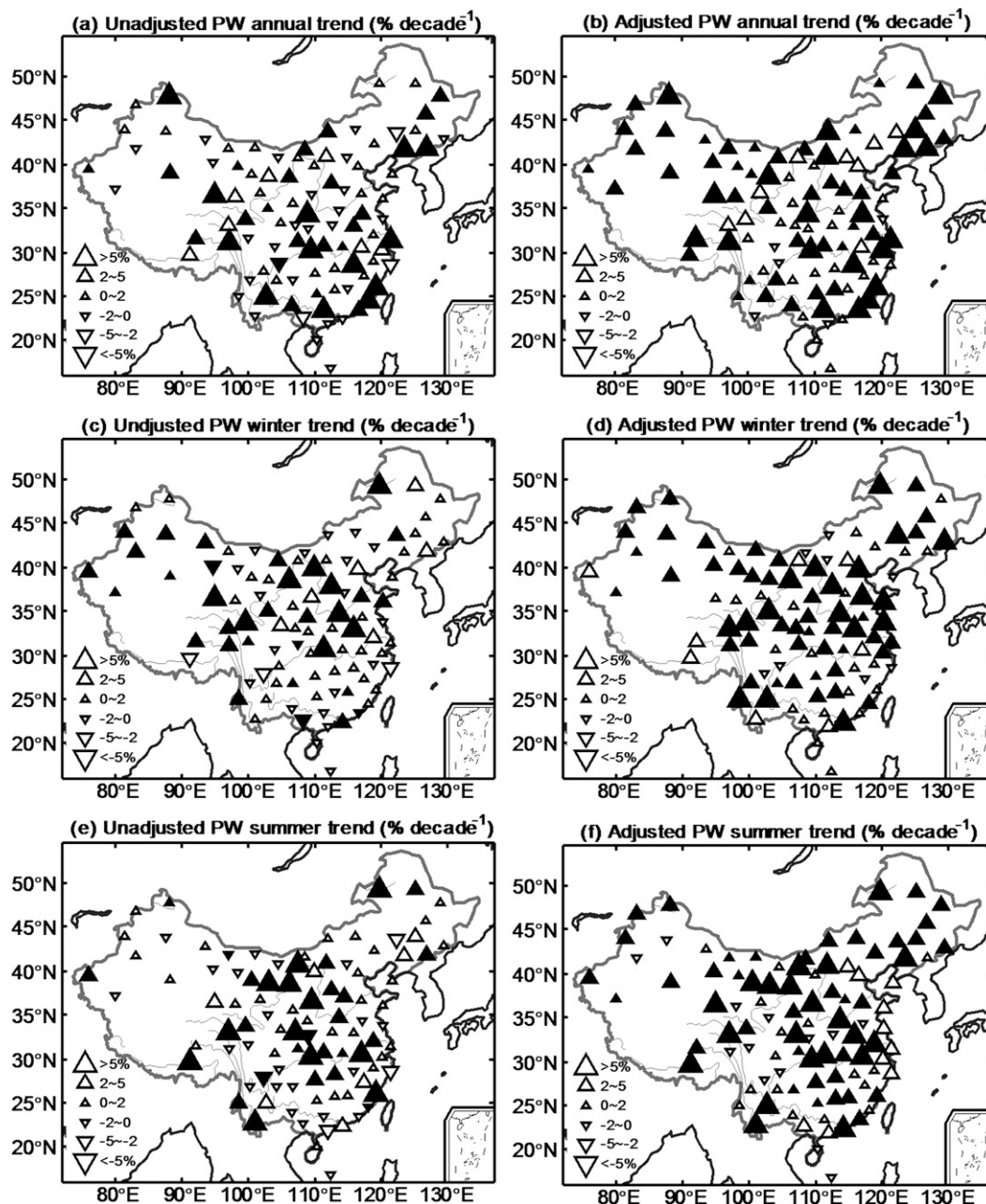


FIG. 12. Spatial distributions of the surface-to-300-hPa PW trend ($\% \text{ decade}^{-1}$) over China during 1970–2008 for (a),(b) annual, (c),(d) winter, and (e),(f) summer derived from the radiosonde T and DPD data (right) with and (left) without the homogenization. The black triangles indicate the trends are statistically significant at the 5% level.

c. Correlations with temperature

Because atmospheric water vapor provides a strong positive feedback to greenhouse gas-induced global warming, correctly simulating the relationship between the water vapor content and temperature is vital for climate models (Dai 2006). Some previous studies based

on sparse radiosonde data have examined the relationship between tropospheric water vapor content and surface air temperature (Gaffen et al. 1992; Zhai and Eskridge 1997; Wang and Gaffen 2001) but obtained complex results, presumably because tropospheric water vapor is coupled more directly to upper-air temperature rather than surface air temperature. Ross et al.

TABLE 1. Linear trends of regional PW (% decade⁻¹ and mm decade⁻¹ in parentheses) in the troposphere (up to 300 hPa) over China from 1970 to 2008. Numbers in bold are statistically significant at the 5% level.

	Annual	DJF	MAM	JJA	SON
Nationwide	2.32(0.29)	2.75(0.26)	2.41(0.44)	2.24(0.27)	2.29(0.21)
Northeast China	2.76(0.18)	3.54(0.10)	3.63(0.36)	2.15(0.13)	1.69(0.14)
Southeast China	1.60(0.20)	2.79(0.30)	0.86(0.18)	1.72(0.17)	0.92(0.16)
Northwest China	3.11(0.55)	3.01(0.43)	3.12(0.81)	3.18(0.51)	4.42(0.35)
Southwest China	2.03(0.26)	2.73(0.20)	1.90(0.16)	1.68(0.32)	1.47(0.19)

(2002) and Sun and Oort (1995) also examined correlations between atmospheric temperature and humidity based on unhomogenized radiosonde data and addressed the issue of constant relative humidity assumption. Here we examine the PW versus temperature relationship over China, with a focus on the correlation with tropospheric temperature.

As shown by Fig. 9, tropospheric specific humidity (q) over China is positively correlated with air temperature (T). To explore this further, in Figs. 14a,b we compare the smoothed time series of surface–300-hPa PW with water vapor–weighted mean temperature (T_m) and relative humidity (RH_m) in the same layer, together with surface air temperature (T_s) averaged over entire China. It can be seen that the PW, T_m , and T_s variations and long-term trends are highly correlated, with ~69% ($r = 0.83$) and 58% ($r = 0.76$) of the PW's variance being explained by T_m and T_s , respectively. The remaining part results mostly from RH_m variations ($r = 0.58$). In particular, both the PW and temperatures are stationary from 1970 to 1987; thereafter, both the PW and temperatures show increasing trends. Figures 14a,b show that recent changes in tropospheric water vapor over China are largely due to tropospheric warming, while changes in and contributions from RH are small.

Figures 14c,d show the scatter plots of the PW versus T_m and PW versus T_s anomalies as shown in Fig. 14a. The slope in the scatterplot suggests a dPW/dT_m of 7.6% K⁻¹, which is slightly higher than that implied by the Clausius–Clapeyron equation with a constant RH (Trenberth et al. 2003; Dai 2006). This result further suggests that annual PW variations and changes are mostly associated with tropospheric temperature changes approximately following the Clausius–Clapeyron equation, and that RH changes are relatively small over China during 1970–2008.

d. EOF analysis of PW

An EOF analysis of the gridded monthly PW anomalies was performed to identify the leading modes of variability. Figure 15 shows the four leading EOFs along with their corresponding principal components (PCs). The four EOFs explain, respectively, 31.4%, 12.0%, 11.7%,

and 9.0% of the total variance. These are substantial numbers; however, only the first two EOFs are statistically separated (and thus may be considered robust). The first EOF represents a quasi-monotonic upward trend seen over most of China, especially over central North China. The PC of this mode depicts the main feature of the nationwide-averaged PW anomalies shown in Fig. 14, which is largely related to the long-term changes in tropospheric temperatures (cf. Fig. 14a and Fig. 11).

The second EOF (Fig. 15b) displays a robust dipole (i.e., anticorrelated) mode between Southeast and Northwest China, with the temporal coefficient showing mostly multiyear variations (with decreasing amplitudes) and a small trend (Fig. 15f). A correlative analysis with Pacific decadal oscillation (PDO) and El Niño–Southern Oscillation (ENSO) indices revealed significant correlations ($r = 0.39$ with both PDO and ENSO) with the PC2 lagging the indices by six months. The distinct spatial pattern of this mode suggests that atmospheric PW variations tend to be out of phase or negatively correlated on multiyear time scales between Southeast and Northwest China.

We performed a correlative and regression analysis of the PC series with the atmospheric circulation fields from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (Kalnay et al. 1996). The

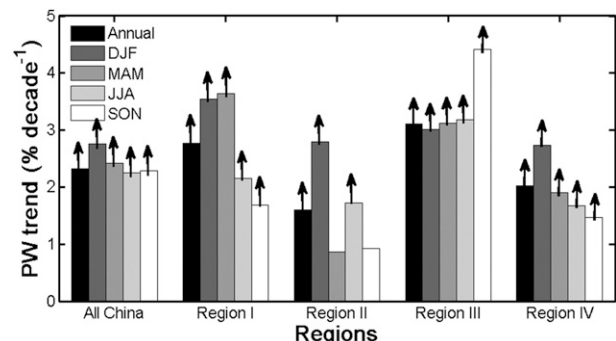


FIG. 13. Linear trends of the adjusted annual and seasonal PW (% decade⁻¹) from the surface to 300 hPa averaged over whole China and the four subregions shown in Fig. 2. The bars with an upward arrow are statistically significant at the 5% level.

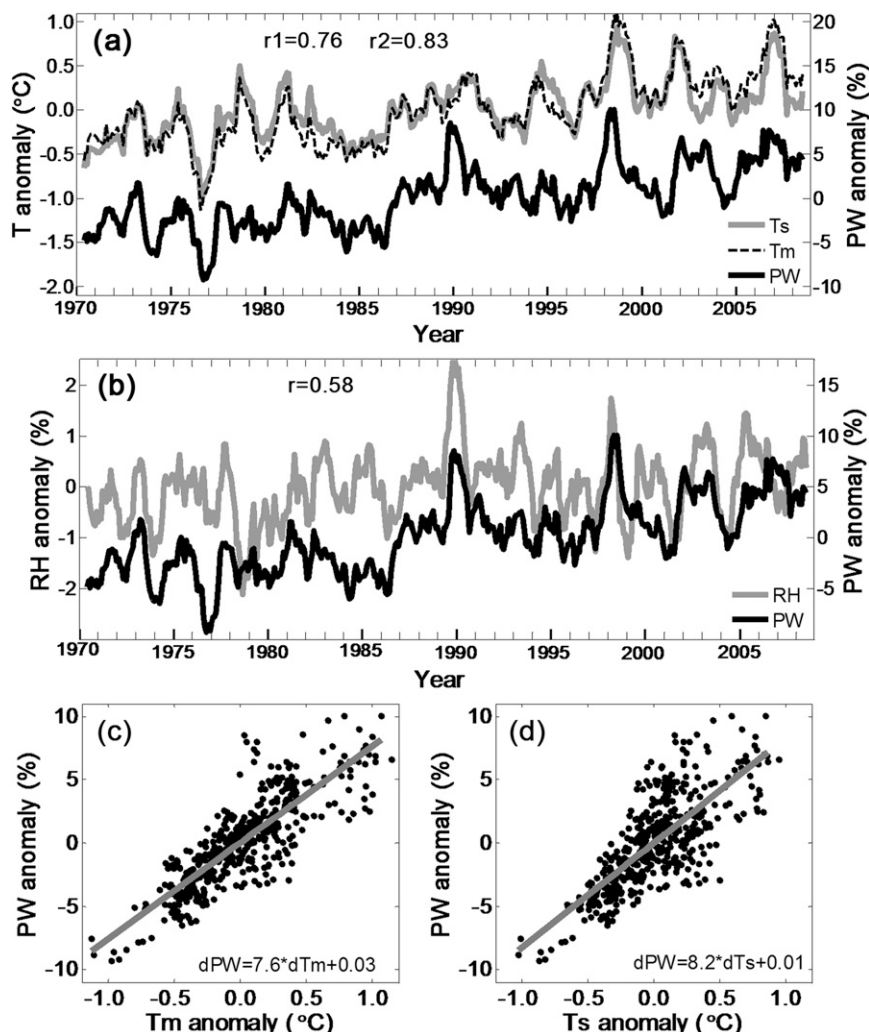


FIG. 14. (a) Time series of 11-point-moving-averaged PW (up to 300 hPa) anomalies (%), black line), surface temperature anomalies (T_s , °C, gray line) and the surface–300-hPa mean temperature anomalies (T_m , °C, thin black line) with the adjustments for China. (b) As in (a), but for PW anomalies (black line) and surface–300-hPa mean RH anomalies (%), gray line). The r_1 , r_2 , and r are the correlation coefficients between the smoothed lines of T_s and PW, T_m and PW, and RH and PW, respectively. Also shown are the scatterplots of (c) PW versus T_m and (d) PW versus T_s anomalies. Both the T_m and RH were derived using long-term mean water vapor content as the weight in the vertical averaging.

result (Fig. 16a) suggests that the PW pattern represented by its EOF 2 is linked to a large-scale dipole pattern of anomaly vertical motion, with air ascending (thus low-level convergence and higher PW) in Northwest and descending (thus drier air and lower PW) in Southeast China during the positive phase of the EOF 2.

The third EOF (Fig. 15c) shows three alternative patterns around the southwest–northeast direction, with its PC (Fig. 15g) exhibiting large multiyear variations with a small multidecadal shift around 1988. The fourth EOF (Fig. 15d) roughly represents a North–South China

dipole pattern with the largest, out-of-phase contributions from Southwest and central North China, while its PC (Fig. 15h) shows large multiyear variations together with a long-term trend that suggests moistening in South China and drying in North China from 1970 to 2008. Although these two EOFs are not well separated statistically, they appear to be associated with distinguishable circulation patterns (Figs. 16b,c) which could qualitatively explain the PW anomalies, given that ascending motion increases the PW and descending motion dries the column. For example, the ascending

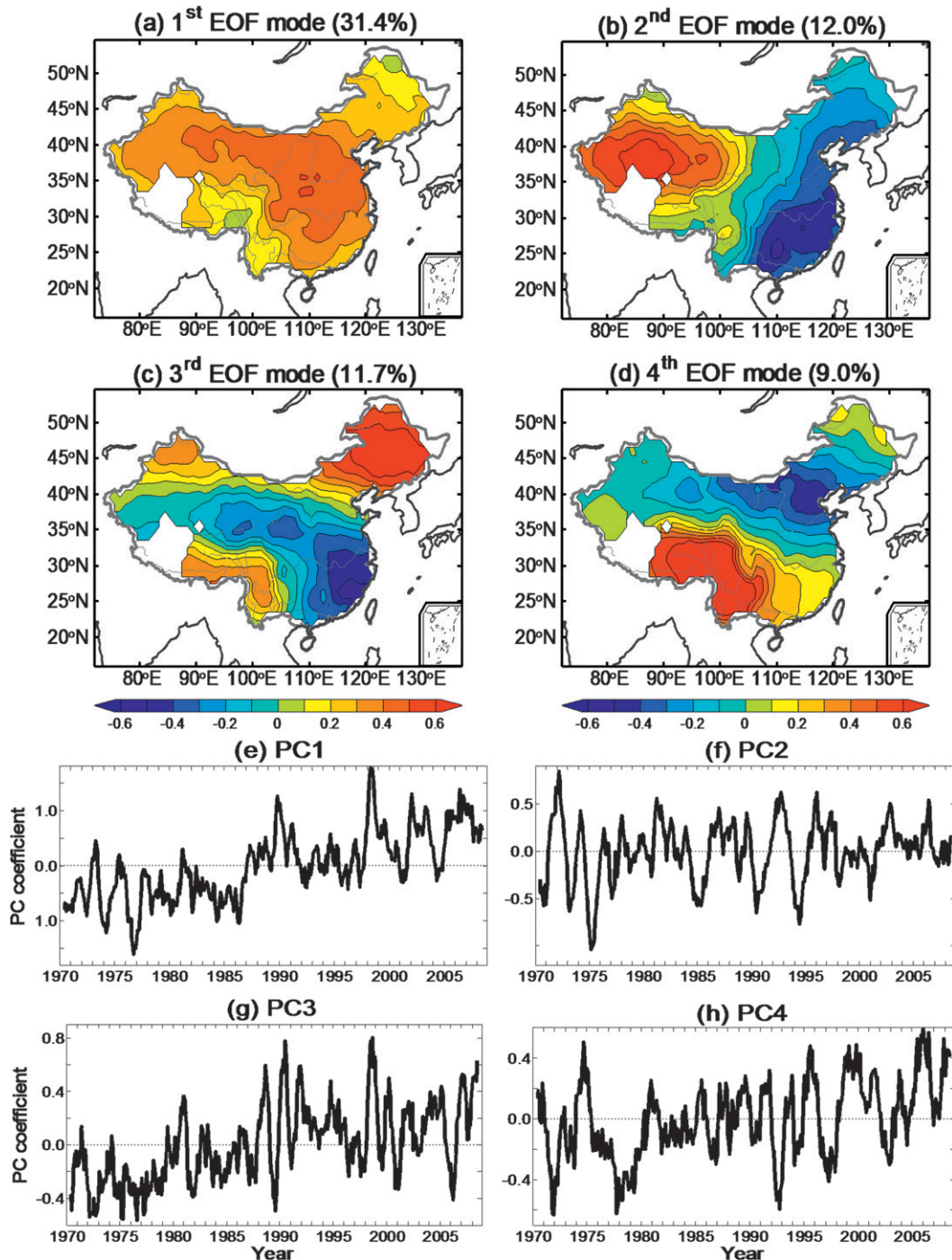


FIG. 15. (a)–(d) Four leading EOFs and (e), (f) their corresponding PC time series (11-point-moving averaged prior to plotting) of the monthly PW (up to 300 hPa) anomalies with the homogenization over China. The monthly PW anomalies were normalized by local standard deviation and multiplied by the square root of cosine of the latitude at each 1° grid box before the EOF analysis. (top) The explained percentage of the total variance is also shown in (a)–(d).

motion over Northeast and Southwest China and descending motion over Southeast and parts of central China (Fig. 16b) associated with a positive PC coefficient for EOF 3 could qualitatively induce the PW

anomaly patterns shown in Fig. 15c. The north–south dipole pattern of EOF 4 is also consistent with the ascending motion in South China and sinking motion in North China associated with this EOF (Fig. 16c).

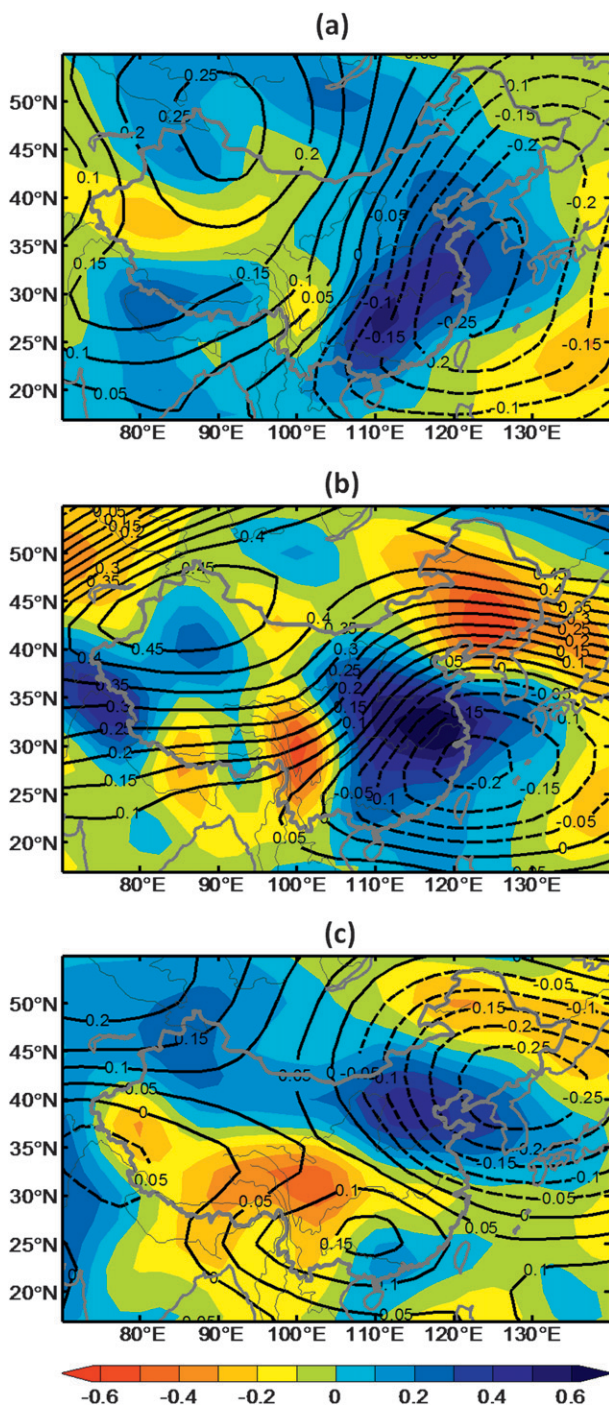


FIG. 16. NCEP-NCAR reanalysis vertical velocity anomalies (ω , colors, in P s^{-1} , warm colors for ascending motion and cold color for descending motion) at the 500-hPa level associated with (a) PC2, (b) PC3, and (c) PC4 of the PW. They are derived using linear regression and a PC coefficient value of 0.5. The contours are correlation coefficients (dashed lines for negative values) between 500-hPa geopotential height anomalies from the reanalysis and the PC time series shown in Fig. 15.

5. Summary

We have created a new Chinese radiosonde daily dataset from the 1950s to 2008 by merging two radiosonde archives, the IGRA and CMA datasets. The new dataset has improved spatial and temporal coverage, with a total of 166 stations and around 120 stations whose DPD and temperature records are 60%–70% complete since 1973. The daily DPD data were homogenized by Dai et al. (2011) using a new approach to minimize the discontinuities associated with changes to instrumentation and observational practices. Combined with the homogenized radiosonde daily temperature from Haimberger et al. (2008), the homogenized DPD data were used to derive specific and relative humidity and precipitable water (up to 300 hPa). Changes in tropospheric humidity and temperature over China from 1970–2008 have been analyzed using the homogenized data. The main findings are summarized below.

Both the raw radiosonde T and DPD monthly anomalies contain discontinuities at many Chinese stations. The discontinuities in the T data are relatively small during 1970–2008 compared with those in the DPD data, which show large discontinuities in recent years resulting from a change from the old Shang-M to the new Shang-E sondes. The Goldbeater's skin on the Shang-M radiosondes has a moist bias because of its slow response, while the Shang-E sondes bear a dry bias. The magnitude of the DPD jump varies from station to station and increases with height (e.g., from $\sim 4^\circ\text{C}$ at 850 hPa to $\sim 7^\circ\text{C}$ at 300 hPa at the Beijing station). Comparisons with recent ground-based GPS measurements of PW from three collocated stations show that the homogenization has removed this major discontinuity associated with this sonde change in recent years and improved the correlation with the GPS data. The homogenization also improves the correlation between the tropospheric mean DPD and precipitation over China.

Tropospheric (up to 300 hPa) specific humidity (q) over most of China shows upward trends during 1970–2008 that are largely related to tropospheric warming. As with air temperature, the increases in atmospheric water vapor occurred mostly after the middle 1980s. The trends in surface-to-300 hPa PW from 1970–2008 are upward and statistically significant across most of China, at about 2.0% – 5.0% decade $^{-1}$ (mainly after the middle 1980s) with larger percentage increases over North China and in winter and smaller percentage increases in central and Southeast China. These features are consistent with atmospheric warming patterns over China.

Tropospheric annual-mean relative humidity (RH) from the homogenized radiosonde data shows small (within $\pm 3\%$) variations over China, weak upward

trends (0.2% – 1.0% decade $^{-1}$) from 850 to 300 hPa and mostly in summer, and small downward trends (-0.2% to -0.4% decade $^{-1}$) in the lower troposphere during spring. Overall, the RH's contribution to the PW trend during 1970–2008 over China is relatively small.

The PW variations and long-term changes from the homogenized data over China are highly correlated with tropospheric water vapor–weighted mean temperature (T_m , $r = 0.83$) and surface air temperature ($r = 0.76$). Averaged over China, the dPW/dT_m slope is about 7.6% K $^{-1}$, which is slightly higher than the 7% K $^{-1}$ implied by the Clausius–Clapeyron equation with a constant RH (Trenberth et al. 2003).

An EOF analysis of the PW over China revealed several different patterns of variability, with the first EOF (31.4% variance) representing an increasing PW trend over most of China, especially in central North China, where tropospheric warming is largest. This mode reflects the warming-induced PW trend over China. The second EOF (12.0% variance) depicts a dipole pattern between Southeast and Northwest China, with mostly multiyear variations that are significant correlated with PDO and ENSO indices ($r = 0.39$). This PW mode results from a similar dipole pattern in atmospheric vertical motion, with anomaly ascending motion in Northwest China and descending motion in Southeast China during the positive phase of the PW mode. Two other different patterns of PW and their associated large-scale vertical motions were also identified.

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