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A New Method for Quality Control of Chinese Rawinsonde Wind Observations

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ABSTRACT

In 2006, the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA) developed its real-time quality control (QC) system of rawinsonde observations coming from the Global Telecommunications System (GTS) and established the Global Upper-air Report Dataset, which, with the NMIC B01 format, is generally referred to as the B01 dataset and updated on a daily basis. However, when the B01 dataset is applied in climate analysis, some wind errors as well as some accurate values with incorrect error marks are found. To improve the quality and usefulness of Chinese rawinsonde wind observations, a new QC method (NewQC) is proposed in this paper. Different from the QC approach used for B01 datasets, the NewQC includes two vertical-wind-shear checks to analyze the vertical consistency of winds, in which the constant height level winds are used as reference data for the QC of mandatory pressure level winds. Different threshold values are adopted in the wind shear checks for different stations and different vertical levels. Several typical examples of QC of different error types by the new algorithm are shown and its performance with respect to 1980–2008 observational data is statistically evaluated. Compared with the radiosonde QC algorithms used in both the Meteorological Assimilation Data Ingest System (MADIS, http://madis.noaa.gov/madis_raob_qc.html) of the National Oceanic and Atmospheric Administration (NOAA) and the B01 dataset, the NewQC shows higher accuracy and better reliability, particularly when used to judge successive observation errors.

Key words: quality control, rawinsonde observation, vertical-wind-shear check

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1. Introduction

Regardless of the rapid development of satellite-derived observations, rawinsonde temperatures, geopotential heights and winds continue to be the most accurate observations available. In China, rawinsonde wind data were partially automatically processed before 2003, and completely manually processed in the 1950s and 1960s when theodolites were used to observe the balloon's position and calculate horizontal winds. Many errors are found in these observations, and a large percentage is of "human" origin, including incorrect transcription, typewriting, computation and coding of the data. Until April 2011, all sounding stations deployed the L-band (1675 MHz) electronic radiosonde and wind-finding radar sounding system, replacing the old system (Tape 59-701 Mechanical Radiosonde and Secondary Wind-finding Radar). From that time, the processing of all rawinsonde data has become almost completely automatic.

Generally, operational numerical weather prediction systems or sounding datasets employ a quality control (QC) or quality assurance (QA) system, such as the radiosonde QC system (http://madis.noaa.gov/madis_raob_qc.html; DiMego et al., 1985) in the Meteorological Assimilation Data Ingest System (MADIS) of the National Oceanic and Atmospheric Administration (NOAA) (MADIS QC), the complex QC (CQC) system (Gandin, 1988) used in the Comprehensive Aerological Reference Data Set (CARDS) (Eskridge et al., 1995; Alduchov and Eskridge, 1996), and the QA system of the Integrated Global Radiosonde Archive (IGRA, Durre et al., 2006). Some data assimilation schemes use the variational QC (Var-QC) system (Anderson and Järvinen, 1999). In addition, some scientific experiments have established corresponding QC processes of upper-air data (Ciesielski et al., 2010). A detailed overview of these methods is given by Steinacker et al. (2011).

In 2006, the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA) began to develop a basic QC system to remove the errors involved in global rawinsonde data coming from the Global

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Telecommunications System (GTS) in real time. The NMIC has combined digitized paper-based monthly reports of Chinese upper-air data from before 1980 and global real-time upper-air reports of the GTS into a global upper-air report data archive, which uses the NMIC B01 format and is generally referred to as the B01 dataset. The basic QC idea (Wang et al., 2011) of the B01 dataset is similar to the QC method of the Navy Operational Atmospheric Database (Baker, 1992). However, the QC algorithm and threshold values in the B01 dataset have been adjusted several times from 2006 to 2011. Depending on data availability, the time series began as early as 1951 and continues until the present day. The algorithm of the wind shear check in the update process of the B01 dataset is given in the appendix.

Although the QC of rawinsonde winds in the B01 dataset (B01 QC) includes a validity check, internal consistency check of wind direction and speed, and vertical wind shear check of different mandatory pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa) (WMO, 2008), there are some errors in the wind data QC. First, the B01 QC only selects winds at one neighboring mandatory pressure level (MPL) as reference data to judge the checked wind data. When the reference data are incorrect or missing, the checked data can be incorrectly judged or unchecked. Second, the QC does not consider the differences in vertical wind distribution for different regions, applying the same threshold value for different vertical layers and sounding stations. Wind data containing such errors cause problems when used in analyses of climatological variation. Figure 1 shows monthly mean wind speed at 850 hPa at 0000 UTC November 1980–2008, which is calculated by the wind data marked “correct” in the B01 dataset. The value in 1992 is obviously lower than in other years caused by six errors which include three “1 m s^{-1}” and three “2 m s^{-1}”. All the corresponding actual observations are larger than 8 m s^{-1}. In order to improve the quality of rawinsonde observation winds, this paper makes an attempt to develop a new QC (NewQC) method of radiosonde-derived winds, which is a sequential QC (SQC) method. Only those data that have passed previous QC are used in the following QC. Compared with B01 QC, NewQC makes more careful vertical wind shear checks and selects more observation wind data as supplementary data in the QC system. In addition, NewQC gives different QC threshold values for different layers and stations. It could be applicable to historical and operational data QA systems in real time.

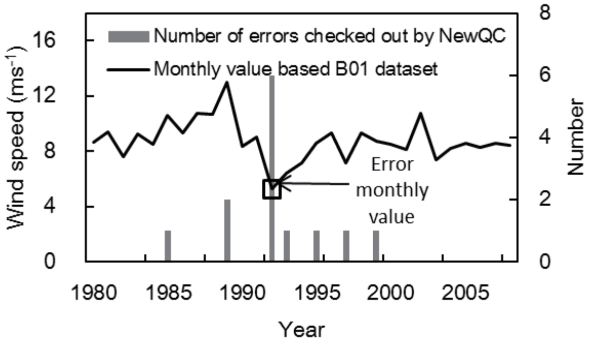

Fig. 1. Monthly mean wind speed (m s^{-1}, solid line) at 850 hPa calculated by the wind data marked “correct” in the B01 dataset and the number of errors (histogram) identified by NewQC at 0000 UTC November 1980–2008. The station is 54776, Shan Tung, China, at (37.40°N, 122.68°E).

The details of NewQC are introduced in section 2. Statistical results for the period 1980–2008 and several examples are given in section 3, including comparisons among NewQC, B01 QC and MADIS QC. A summary is provided in section 4.

2. Data and methodology

2.1. *Data*

According to the observation manuals of the CMA (CMA, 1976, 2010), observers calculate the wind direction and speed at MPLs and constant height levels (CHLs) from the original observation records. The observations at MPLs are coded into real-time upper-air reports in alphanumeric code form (WMO, 1995) and transmitted through the GTS to various regional and national meteorological centers around the world once obtained. The NMIC began to decode historical upper-air reports and those archived in the B01 dataset in 2006. The target of the QC system described in this paper is the MPL winds of Chinese real-time upper-air reports in the B01 dataset. The time range of the controlled data is from 1980 to 2008.

The CHLs are 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 7, 8, 9, 10, 10.5, 12 and 14 km, and then up to the top observation level at 2 km intervals (CMA, 2010). As described by WMO (1995), when pressure measurements are not available, wind data should be reported using geopotential approximations of the standard isobaric layers. Therefore, some CHLs are just reported in the GTS by winds-only stations, because of the lack of pressure observations (WMO, 1995). The reported levels are 1.5, 3, 5.5, 7, 9, 10.5, 12, 14, 16, 18, 20, 24, 26 and 30 km. In this paper, we define these CHLs as geopotential approximation levels (GALs). The corresponding mandatory levels are 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa (CMA, 1976). IGRA and CARDS have archived these observations and consider them as MPL winds, such as the observations at 850, 700 and 500 hPa of LETING (station ID: 54539) before April 2010 and HOBOKSAR (station ID: 51156) etc. The other CHLs, comprising approximately one third of all CHLs, are reported in the GTS (WMO, 1995) for all sounding stations in the GTS.

From 1951 to present, the wind observations at all the MPLs and CHLs have been recorded in paper form as “daily reports of Chinese upper-air data”, and observations at all CHLs have been recorded in paper form as “monthly reports of Chinese upper-air data”. In 2013, the NMIC finished capturing the CHL data in digital form by scanning and digitizing the paper-based monthly reports from 1951 to 2010. A strict

QA process has been applied to correct any errors caused by the digitization process. Most of the suspect or incorrect data have been checked and corrected manually. In this paper, the digitized CHL observations are used as reference data in the QC of MPL winds.

Recently, we obtained the digitized observations at MPLs from the meteorological administrations of 31 provinces in China. Before recording the observations into paper reports, some incorrect observations had been manually corrected by the observers. No errors caused by coding, transmission and decoding are included in those paper-based daily reports. The quality of the digitized MPL data is regarded as better than the GTS MPL data and are used for evaluating data for the QC effects. In order to improve the credibility of evaluating the data, a strict QA process is applied. The suspect and incorrect data in the digitized MPL data are rejected before being used as evaluating data. In addition, the IGRA (Durre et al., 2006) and CARDS (Eskridge et al., 1995) are applied to assist in the analysis of the reason behind the errors.

2.2. *Methodology*

2.2.1. *Principle*

The main idea of CQC is to combine simple QC methods (i.e., CQC components) through a decision-making algorithm (DMA) whose working logic would be similar to that of a human being (Alduchov and Eskridge, 1996). The CQC components contain geostrophic and thermal relationships, which are inappropriate for the winds of CHLs and winds-only stations since the pressures and temperatures are absent.

NewQC adopts a sequential QC method. It generally includes four steps, which are validity checks, internal consistency checks of speed and direction, and first and second vertical-wind-shear checks. The first step is to eliminate gross errors (Gandin, 1988; Baker, 1992; Steinacker et al., 2011) that might affect the performance of subsequent algorithms. Plausibility limits used in the validity checks cite the validity ranges of Wang et al. (2011). The second step is to find those observations that do not meet two criteria: (1) that wind direction value must be zero if and only if speed value is zero; and (2) that wind direction value can't be zero when wind speed value isn't zero. The wind is marked "suspect" if it does not pass the internal consistency check.

Data passing the validity check and internal consistency check are then examined by the double vertical-wind-shear checks. Different from the vertical wind shear algorithms of MADIS QC (DiMego et al., 1985) and B01 QC (Baker, 1992; Wang et al., 2011), this new algorithm includes two vertical-wind-shear checks. Figure 2 presents a flowchart illustrating the automatic QC process.

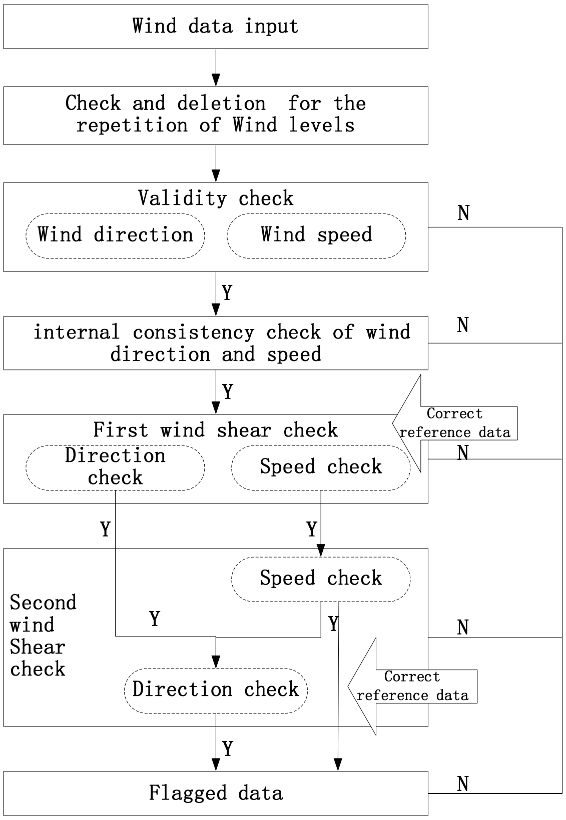

Fig. 2. Flowchart illustrating the quality control process.

2.2.2. *Definition of vertical wind shear*

Generally, vertical wind shear is defined as the local variation of the wind vector or any of its components in the vertical direction (Markowski and Richardson, 2006). This is described by $\partial \boldsymbol{V}/\partial P$, where P is the pressure (used here as the vertical coordinate), and $\boldsymbol{V}$ is the horizontal wind. Considering that the distances of neighboring levels have changed little since rawinsonde wind levels were fixed as stationary MPLs or CHLs, the vertical "speed shear", $\Delta S_{i,j}$, between levels i and j is simply defined in this paper as the speed difference between two levels. The directional wind shear, $\Delta A_{i,j}$, indicates the changing of the angle of the wind velocity vector between levels i and j. If the wind direction of level i has a clockwise rotation corresponding to level j, the directional wind shear is considered as positive shear. Otherwise, it is regarded as negative shear. S_i and A_i are the wind speed and direction on level i, and levels i and j could be MPLs or CHLs.

All MPL and CHL winds are combined into a single array before QC. Figure 3 shows schematically the relationship between the checked MPL level and neighboring levels. The vertical-wind-shear checks start from the bottom wind level and continue to the top wind level. Using the check of level m as an example, several vertical wind shears related to this level are obtained. Here, level m is an MPL. In the first vertical-wind-shear check, $\Delta S_{m,l}$ and $\Delta A_{m,l}$ are obtained using the winds of checked level m and level l, which is the GAL near to level m. In the second vertical-wind-shear check, $\Delta S_{m,l-1}$, $\Delta A_{m,l-1}$, $\Delta S_{m,l+1}$, $\Delta A_{m,l+1}$, $\Delta S_{m,m-1}$, $\Delta A_{m,m-1}$, $\Delta S_{m,m+1}$ and $\Delta A_{m,m+1}$ are obtained using the nearest neighboring MPLs or CHLs, except level l. This means that at least one and, at most, five neighboring levels of winds are selected as reference levels in NewQC, and the influence of a lack of reference data is avoided as much as possible.

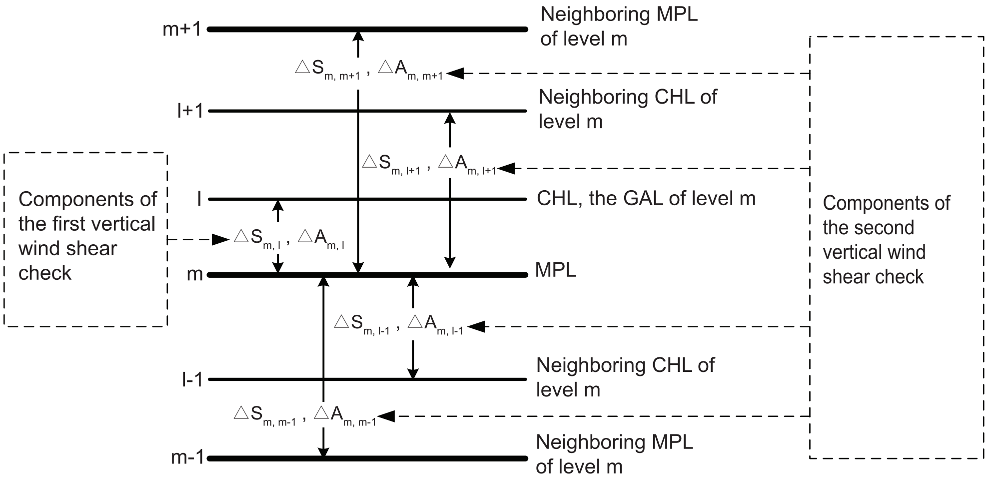

Fig. 3. Schematic diagram of the distribution of MPLs and CHLs used in the two vertical-wind-shear checks, performed at the MPL m.

2.2.3. *First vertical-wind-shear check*

The target of the first vertical-wind-shear check is to reject those wind speed and direction values that are outside the confidence intervals or deviate from the threshold values obtained from GALs near to the checked MPLs. In other words, the first vertical-wind-shear check is designed to check whether the MPL winds are close to those at the nearest GAL.

The confidence intervals or thresholds of speed and direction shear ($\Delta S_{m,l}$ and $\Delta A_{m,l}$) are given based on the root-mean-square error (RMSE), which is usually used to measure the differences between estimations and the values actually observed. In this paper, the GAL winds are used as the estimations of the winds at the corresponding MPL (WMO, 1995). For each station and each MPL, the bias, $\bar{e}_\mathrm{s}$, and RMSE, E_slm, of vertical speed shear, $\Delta S_{m,l}$, are given by

$$\bar{e}_\mathrm{s} = \frac{\sum_{i=1}^{N} e_{\mathrm{s}i}}{N} \tag{1}$$

and

$$E_\mathrm{slm} = \sqrt{\frac{\sum_{i=1}^{N} (e_{\mathrm{s}i} - \bar{e}_\mathrm{s})^2}{N-1}}\ . \tag{2}$$

The bias, $\bar{e}_\mathrm{a}$, and RMSE, E_alm, of vertical directional wind shear, $\Delta A_{m,l}$, are given by

$$\bar{e}_\mathrm{a} = \frac{\sum_{i=1}^{N} e_{\mathrm{a}i}}{N} \tag{3}$$

and

$$E_\mathrm{alm} = \sqrt{\frac{\sum_{i=1}^{N} (e_{\mathrm{a}i} - \bar{e}_\mathrm{a})^2}{N-1}}\ , \tag{4}$$

where $e_{\mathrm{s}i}$ and $e_{\mathrm{a}i}$ are the vertical wind shears, $\Delta S_{m,l}$ and $\Delta A_{m,l}$, for the ith observation, respectively, and N is the number of total samples during 1980–2008. The bias and RMSE are calculated using the samples from the historical data during 1980–2008. The samples pass the validity checks and internal consistency check, and are marked "correct" in the B01 datasets. The number of samples must be greater than 500. Statistical results show small bias and RMSE of vertical wind shear between the GALs and corresponding MPLs at different levels. The distribution of E_slm has regional characteristics. E_slm is larger in southern China than in northern China. At 850 hPa and 700 hPa, E_slm in high-elevation regions is larger due to the weakly stability of wind near the ground.

We check whether or not the vertical wind shears, $\Delta S_{m,l}$ and $\Delta A_{m,l}$, fall within the confidence intervals:

$$0 \leqslant |\Delta S_{m,l} - \bar{e}_\mathrm{s}| < fE_\mathrm{slm}\ ; \tag{5}$$

$$0 \leqslant |\Delta A_{m,l} - \bar{e}_\mathrm{a}| < fE_\mathrm{alm}\ . \tag{6}$$

If $\Delta S_{m,l}$ satisfies Eq. (5), then the corresponding wind speed data, S_m and S_l, pass the first vertical-wind-shear check, as do the wind direction data, A_m and A_l, if $\Delta A_{m,l}$ satisfies Eq. (6). If the average of the speeds at the checked MPL and the corresponding GAL is lower than 6 m s^{-1} (according the Beaufort scale), which means horizontal wind in the atmosphere layer is calm air, light air, light breeze or gentle breeze, the wind direction is not checked.

To choose the f for appropriate thresholds values, sensitivity experiments using various values of f between 3 and 7 are conducted to investigate what value of f would make the algorithms neither remove too many values within the normal range nor fail to remove a few values that are clear outliers. In these sensitivity experiments, the digitized MPL observations with strict QC are considered as "good observations". Taking into account the bias of data processing in difference data sources, the GTS MPL records and digitized MPL records are regarded as matching each other well if the difference falls within the similarity thresholds, which are selected as 2 m s^{-1} and 10° for wind speed and wind direction, respectively, according to Durre et al. (2006). If a GTS MPL record matching the corresponding digitized MPL record is rejected, it is a wrong rejection; otherwise, it is a good judgment. When a GTS MPL record not matching the corresponding digitized MPL record is rejected, it is a good judgment; otherwise, it is a lost rejection.

Figure 4 gives the percentages of wrong rejection, lost rejection and good judgment using various f values between 3 and 7 in the first vertical-wind-shear check. It can be seen that the percentage of wrong rejection decreases when the value of f increases from 3 to 6. On the other hand, the percentages of lost rejection and good judgment data increase following an increasing value of f. The percentages of wrong rejection and good judgment with $f = 6$ and $f = 7$, respectively, are very close. However, the percentage of lost rejection data with $f = 7$ is larger than that with $f = 6$. Therefore, $f = 6$ is selected.

If $\Delta S_{m,l}$ or $\Delta A_{m,l}$ do not fall within the confidence intervals, the corresponding wind is regarded as incorrect data not to be examined in the second vertical-wind-shear check. If the GAL winds are missing or incorrect, the first vertical-wind-shear check is not conducted and the MPL winds would enter the second vertical-wind-shear check directly.

2.2.4. *Second vertical-wind-shear check*

The second vertical-wind-shear check analyzes whether the winds are vertically consistent between the checked MPL and its neighboring MPLs or CHLs, except the GAL. It uses as many reference data as possible to avoid removing an accurate value caused by errors in the reference data. In the algorithm of the second vertical-wind-shear check, at least one level below the checked level and one level up from the checked level are selected as reference levels. It is easy to detect incorrect turning points using this algorithm. In addition, it is effective in controlling the quality of the MPL winds when corresponding GAL winds are missing. For example, there are no corresponding GAL winds at 1000 hPa and 925 hPa, and thus the second vertical-wind-shear check is the only way to check the vertical consistency between these two levels and other neighboring levels. In addition, the distance between the reference wind level and the checked wind level must be less than 3 km, which is the same as in MADIS QC.

In the second vertical-wind-shear check, the vertical levels are not of uniform distribution compared with those in the first vertical-wind-shear check. In addition, the distances between the checked level and reference levels are greater than in the first vertical-wind-shear check. Due to these reasons, the criterion of the first vertical-wind-shear check is unsuitable for the second vertical-wind-shear check. The final QC judgment by the second vertical-wind-shear check is made through a simple DMA that combines the credibility of all vertical wind shears between the checked level and its neighboring levels.

Marking the thresholds for level m as $\Delta S_{\mathrm{T},m,m-1}$, $\Delta S_{\mathrm{T},m,m+1}$, $\Delta S_{\mathrm{T},m,l-1}$ and $\Delta S_{\mathrm{T},m,l+1}$, the DMA regards S_m as an incorrect observation if more than half of the following inequalities are true:

$$|\Delta S_{m,l-1}| > \Delta S_{\mathrm{T},m,l-1} \, , \tag{7}$$

$$|\Delta S_{m,l+1}| > \Delta S_{\mathrm{T},m,l+1} \, , \tag{8}$$

$$|\Delta S_{m,m-1}| > \Delta S_{\mathrm{T},m,m-1} \, , \tag{9}$$

$$|\Delta S_{m,m+1}| > \Delta S_{\mathrm{T},m,m+1} \, . \tag{10}$$

Otherwise, S_m is assumed to be correct. The DMA controls the quality of A_m in a similar way. $\Delta S_{\mathrm{T},i,j}$ and $\Delta A_{\mathrm{T},i,j}$ are determined using the empirical cumulative distribution function, $F(x)$. The empirical cumulative distribution function is used for statistical inference of climate extremes (Ma et

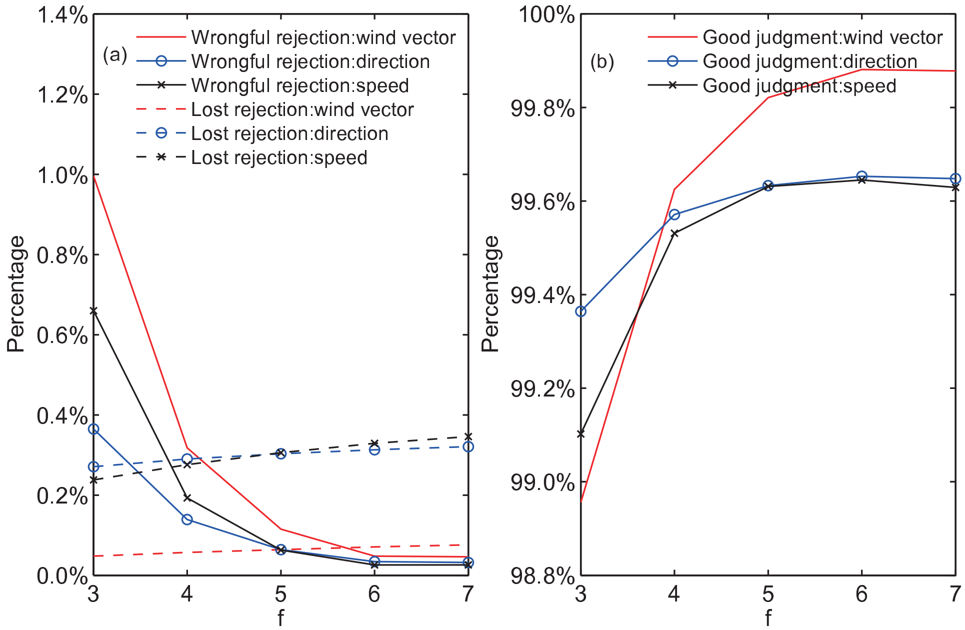

Fig. 4. Percentages of wrong-rejection, lost-rejection and good-judgment data using various values of f between 3 and 7 in the sensitivity experiments for the first vertical-wind-shear check.

al., 1993), such as the probability of exceeding a given wind speed in a tropical cyclone (Darling, 1991) and analysis of extreme heat events (Oswald and Rood, 2013). It is calculated based on the cumulative frequency of each $|\Delta S_{i,j}|$ (or $\Delta A_{i,j}$), i.e., the percentage of samples with values no larger than $|\Delta S_{i,j}|$ (or $\Delta A_{i,j}$) in all samples during 1980–2008. When calculating the threshold value using the historical data of 1980–2008, at least 500 values should be available for any station and level. Similar to the first vertical-wind-shear check, the samples must pass the validity checks and internal consistency check, which are marked "correct" in the B01 datasets. Referring to Barker (1992), the thresholds for directional shears are defined as a function of the average speed of two neighboring levels, i.e., $\Delta A_{\mathrm{T},i,j}$ is a function with respect to $\overline{S_{i,j}}$. Here, $\overline{S_{i,j}}$ is the average wind speed of level i and level j. Similar to the determination of f in the first vertical-wind-shear check, the value of $F(x)$ is chosen to be 99.5%.

The spatial distribution of the threshold value for the vertical wind speed shear between two neighboring mandatory levels in the second vertical-wind-shear check are shown in Fig. 5. Threshold values in the lower troposphere and stratosphere are lower than at other levels.

3. Results

In this section we present some examples of rawinsonde wind errors with different types of QC. The temporal and vertical distributions of errors determined by NewQC, B01 QC and MADIS QC are compared. The differences among the three QC methods are discussed.

3.1. *Examples*

Figure 6 shows the errors of the wind direction and speed at 0000 UTC 30 September 1998 from station 52203, Hami, China, at (42.82°N, 93.52°E), which are rejected by both NewQC and B01 QC. Several errors that B01 QC fails to identify are successfully removed by the validity check, first vertical-wind-shear check, and second vertical-wind-shear check in NewQC. The wind direction at 850 hPa shown as 580° and the wind speed at 500 hPa with the value 318 m s^{-1} are obviously gross errors. In the paper-based daily report, the corresponding values are 82° and 18 m s^{-1}, respectively. The wind direction at 300 hPa (235°) is rejected because the vertical directional wind shear between this level and the corresponding GAL at the altitude of 9 km, which is 37°, is beyond the threshold value (32.6°). Figures 7a–c show the spatial distribution of wind vectors, speed and direction shear at 300 hPa and 9 km. The vertical directional shear of station 52203 is significantly larger than the directional shear of its neighboring stations. The wind direction at 300 hPa is corrected by the value at the same vertical level (275°) in the paper-based daily report, which is very close to the value (272°) at the corresponding GAL.

The incorrect wind speed of 42 m s^{-1} at 925 hPa is found

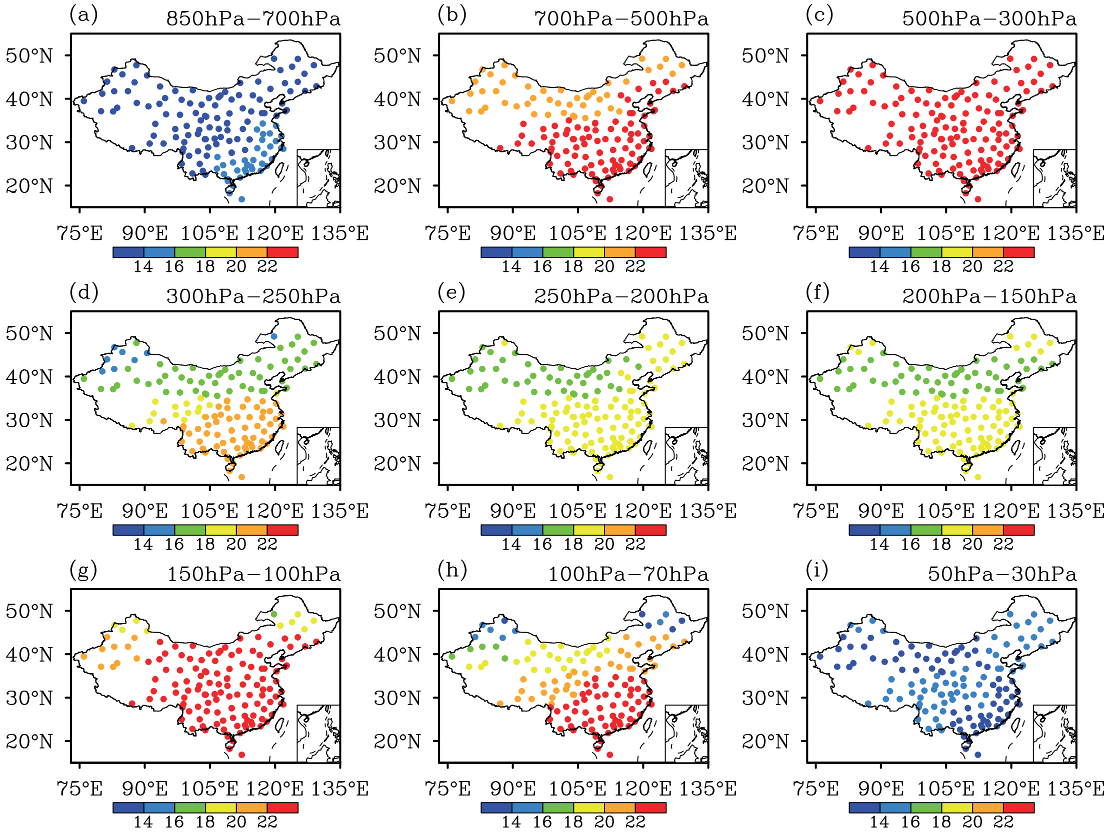

Fig. 5. Spatial distribution of the threshold values for the vertical wind speed shear (m s^{-1}) between two neighboring mandatory levels in the second vertical-wind-shear check.

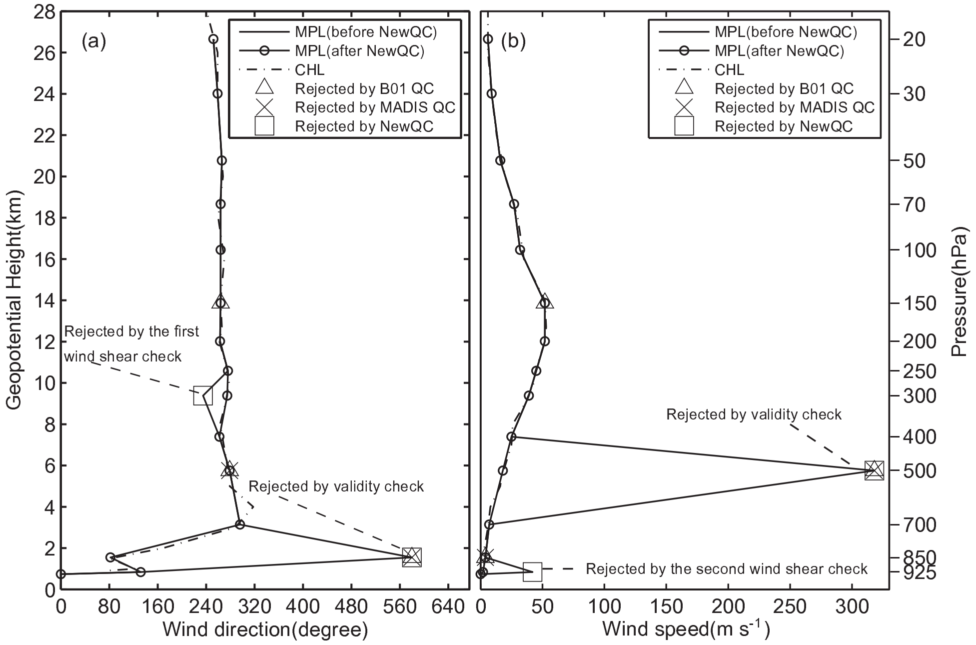

Fig. 6. Vertical profiles of (a) wind direction (°) and (b) speed (m s^{-1}) of MPL winds before NewQC (solid lines), MPL winds after NewQC (solid lines with circles), CHL winds (dashed-dotted lines), and observed values rejected by NewQC (squares), B01 QC (triangles) and MADIS QC (crosses), respectively. The case is 0000 UTC 30 September 1998 at station 52203, Hami, China, at (42.82°N, 93.52°E). After NewQC, the errors are corrected according to the paper-based daily reports of Chinese upper-air winds.

by the second vertical-wind-shear check. The correct observation value at the same vertical level in the paper-based daily report is 2 m s^{-1}. The B01 datasets and IGRA do not reveal the errors at 300 hPa and 925 hPa. These errors even pass the MADIS QC owing to the much larger wind shear threshold value it uses. The observation values at 925 hPa of the B01 datasets, IGRA and CARDS are compared in this case. The data sources for these three datasets are real-time GTS. At 925 hPa, the wind direction in the B01 and IGRA databases are 132° and 130°, which are the same as or close to the correct wind direction of 132°. Conversely, the wind direction in CARDS is erroneous (330°) at 925 hPa, while the wind speed is correct. It is possible that the irregular wind reports in GTS lead to the decoding differences among the three datasets. It is worth mentioning that the B01 datasets incorrectly mark the winds at 150 hPa as errors. These incorrect results may be due to the QC algorithm of B01. It only selects one neighboring MPL as the reference level to control the checked MPL. In this case, the larger wind speed difference between 150 hPa and 100 hPa causes the incorrect judgment in the B01 dataset.

Figure 8 shows another special case, at station 50527, Hailar, China at 1200 UTC 07 September 2001. In this case, five direction values and six speed values are rejected by the first vertical-wind-shear check. We checked the original GTS alphanumeric codes archived at the NMIC and found that all the geographical heights, temperatures, humidity values and winds of the station at that time in the GTS are the same as the observation reports at 1200 UTC 07 August 2001 for this station. It is thus supposed that observer wrongly imported the data file of 1200 UTC 07 August 2001 when compiling and transmitting the observation reports for 1200 UTC 07 September 2001. Therefore, the values in the IGAR are also incorrect. It is very difficult to establish this type of error if the GAL data are not used as reference data, since there is good vertical consistency among the MPLs of the wrong wind reports at that time.

In the MPL winds of 1980–2008, only 0.005% of wind direction data and 0.006% of wind speed data are rejected by the second vertical-wind-shear check, which is much less than those rejected by the first vertical-wind-shear check. This is because many of the errors identified by the first check would not be repeated. On the other hand, if the differences between incorrect data and corresponding GAL data are no larger than, but close to the threshold value in the first vertical-wind-shear check, these errors will probably be identified in the second vertical-wind-shear check, which uses more neighboring-level data as reference data. Figures 7d–i show one case in which the error is found in the second vertical-wind-shear check. The observational time is 0000 UTC 09 December 1993, and the station is 58424, Anqing, at (30.52°N, 117.03°E). The rejected wind speed at 500 hPa is 4 m s^{-1}, which is 14 m s^{-1} lower than the speed at the corresponding GAL. The difference of the speed between the checked level and the GAL is lower than the threshold value of 16 m s^{-1} in the first vertical-wind-shear check. At 500 hPa, the wind speed is significantly lower than at the neighboring stations. This does not happen at 5.5 km. The speed shear of station 58424 between 500 hPa and 6 km is larger than at neighboring stations. The wind speed of 58428 at 500

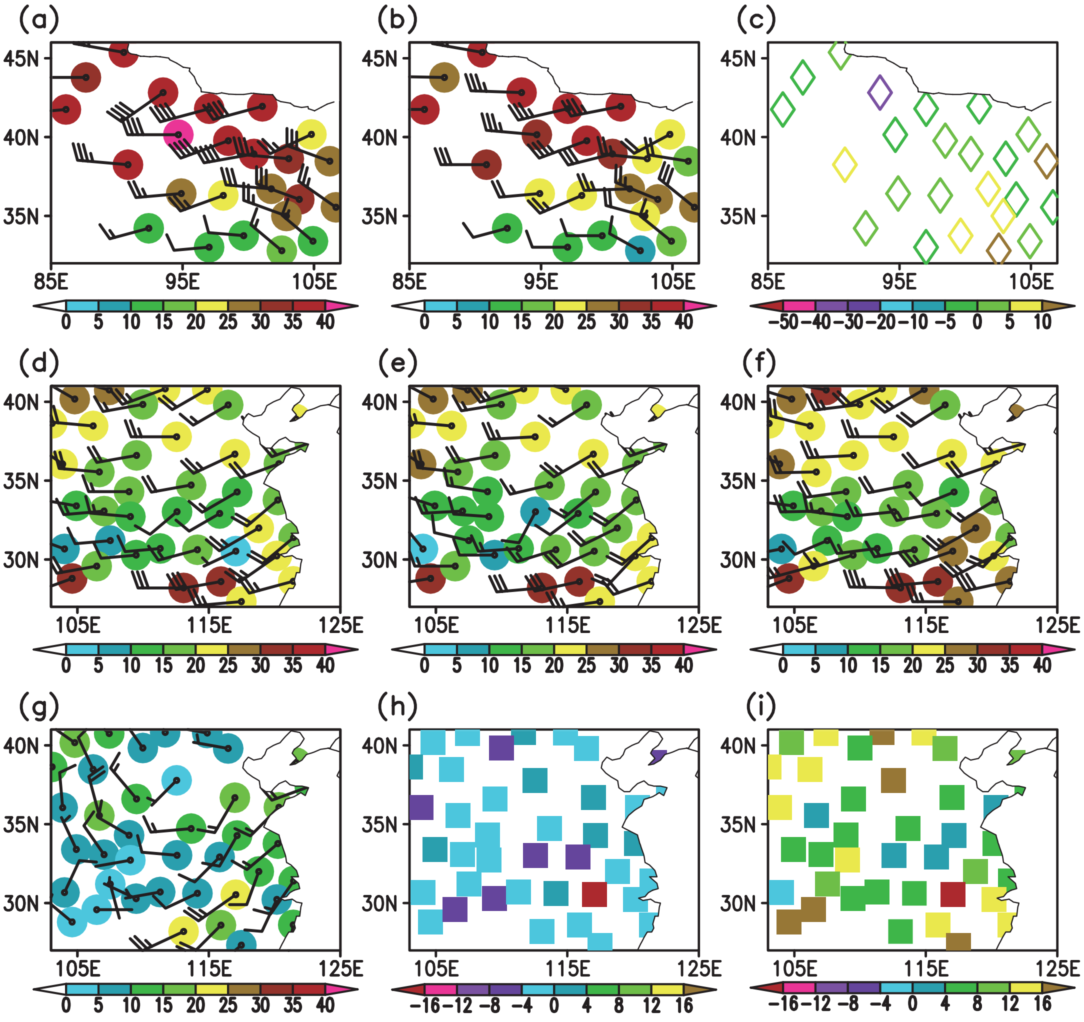

Fig. 7. Wind vectors (shafts), wind speed (solid circles, m s^{-1}), directional shear (diamonds, °) and speed shear (solid squares, m s^{-1}). The observations of (a), (b) and (c) are at 0000 UTC 30 September 1998, and the others are at 0000 UTC 9 December 1993. (a) 300 hPa; (b) 9 km; (c) directional shear between 300 hPa and 9 km; (d) 500 hPa; (d) 5.5 km; (f) 6 km; (g) 700 hPa; (h) speed shear between 500 hPa and 6 km; (i) speed shear between 500 hPa and 700 hPa. The erroneous observations are marked by triangles.

hPa is slower than the speed at 700 hPa, which is just the opposite for the neighboring stations.

3.2. *Statistics*

Next, NewQC is used to perform the QC process for the MPL winds during the period 1980–2008, and Table 1 shows the percentage of removed MPL winds from 1980 to 2008. Overall, 0.347% of the MPL winds during this period are rejected. 0.025% of the direction data and 0.031% of the speed data can be seen to possess gross error (Table 1). Approximately 0.053% of the wind data are rejected in the validity check, and 0.285% and 0.009% are removed by the first and second vertical-wind-shear checks, respectively. Wind direction and speed data are rarely all wrong in the rawinsonde observations.

Figure 9a shows the percentages of errors rejected by sev-

Table 1. Percentage of rejected MPL winds in the non-missing rawinsonde observations from 1980 to 2008.

	Error ratio		
Description	Rejected wind direction	Rejected wind speed	Rejected wind reports
Validity check	0.025%	0.031%	0.053%
First wind shear check	0.088%	0.207%	0.285%
Second wind shear check	0.005%	0.006%	0.009%
Total	0.118%	0.243%	0.347%

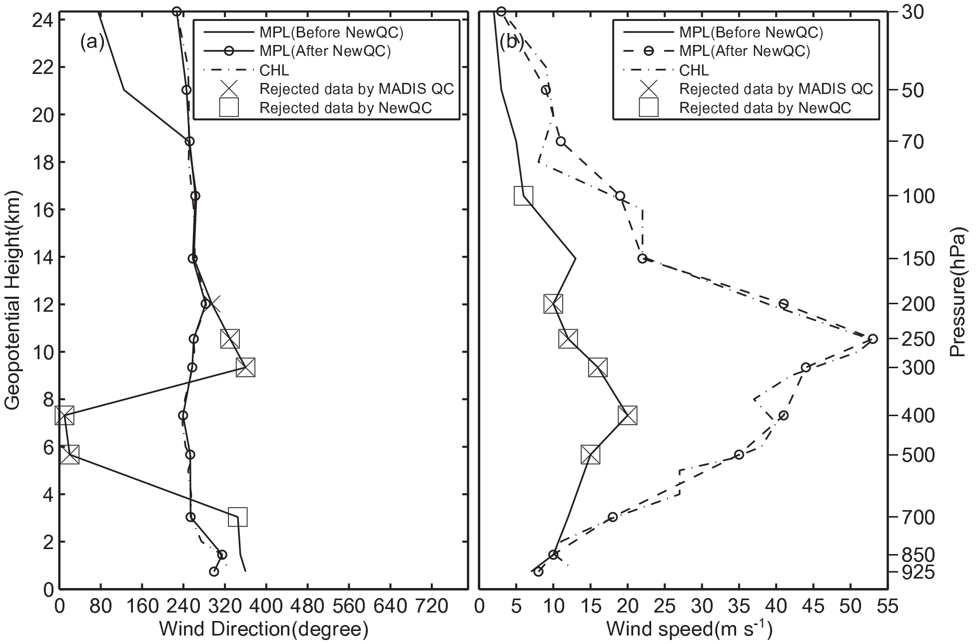

Fig. 8. The same as Fig. 6, except for the case at 1200 UTC 07 September 2001 of station 50527, Hailar, China, at (49.216°N, 119.750°E). This station is one of GCOS (Global Climate Observation System) Upper-Air Network stations. No observational value is rejected by the B01 QC in this case.

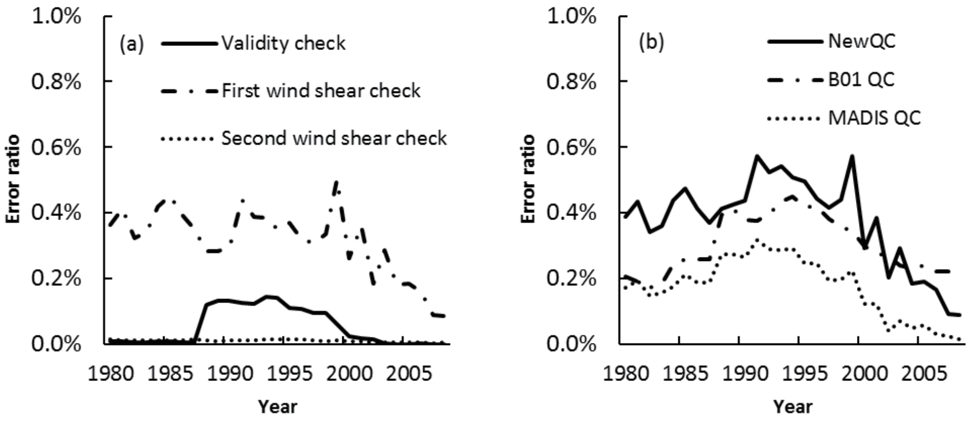

Fig. 9. Percentages of errors from 1980 to 2008 identified by (a) the validity check (solid line), first vertical-wind-shear check (dashed line), and second vertical-wind-shear check (dotted line) of NewQC, and (b) NewQC (solid line), B01 QC (dashed line) and MADIS QC (dotted line).

eral check steps in NewQC year by year. Almost all of the sounding data were processed manually in the 1980s. The automated upper-air sounding operation systems (PC-1500) were not applied until the end of the 1980s. However, the lack of basic QA in coding and decoding caused a large number of "gross errors", which couldn't even pass the validity check in the 1990s. At the end of 1990s, the CMA began to implement the Tape 59-701 sounding computer system to replace the PC-1500 computer systems. Correspondingly, the percentage of gross errors decreases rapidly in our results. From 2003, the CMA implemented an upper-air sounding system replacement program and deployed the L band (1675 MHz) electronic radiosonde and wind-finding radar sounding system as a new sounding system to replace the old system (Tape 59-701 Mechanical Radiosonde and Secondary Wind-finding Radar). Subsequently, we find the percentage of gross errors to be close to zero. Moreover, the vertical consistency has been improved and the percentages of errors established by vertical-wind-shear checks can be seen to decrease yearly since computer systems replaced manual calculation at the end of the 1980s.

3.3. *Comparison with other QC methods*

In this section, we compare NewQC with two others QC methods, i.e., MADIS QC and B01 QC. For the comparisons, the percentages of data marked "error" by B01 QC and

MADIS QC were calculated, and in this discussion of the results we focus on comparing their vertical-wind-shear check algorithms. In the validity check, both NewQC and B01 QC use the same threshold values, while MADIS QC adopts different ones. In order to avoid the influence of different validity check thresholds, the validity check thresholds of MADIS QC were modified to be the same as those used in NewQC and B01 QC. For further details about B01 QC and MADIS QC, please refer to the appendix and the website http://madis.noaa.gov/madis_raob_qc.html.

Figure 9b presents the yearly changes of the percentages of errors established by NewQC, MADIS QC and B01 QC. The three QCs show similar trends of error ratio, especially after 1994. Overall, the number of errors identified by NewQC is more than that by MADIS QC.

Figure 10 shows the vertical distributions of the percentages of errors established by the three QC methods. In MADIS QC, the wind shear check selects the nearest wind level as the reference level, similar to the first vertical-wind-shear check in NewQC. The distribution of the error rate marked by MADIS QC is similar to that by NewQC from 50 hPa to 400 hPa. However, the error rates controlled by the two methods are apparently different in the lower troposphere and stratosphere. MADIS QC identifies more errors in the mid–high troposphere than in the lower troposphere and stratosphere. Because NewQC allows larger vertical wind direction change when the wind speed is slower, and avoids checking the wind direction when the wind is classified as “breeze” or less, few data are rejected near to 50 hPa, which is a quasi-zero wind layer (QZWL) of the stratosphere. The winds at neighboring levels below and above the QZWL have opposite directions in general, and the meridional wind is weak in this layer (Xiao et al., 2008).

In B01 QC, the data not passing the internal consistency check would be marked “error”. Meanwhile, there is no internal consistency check in MADIS QC. There are two different selections. Considering the calm wind at the near-surface level, NewQC cautiously marks those data as “suspect” in the internal consistency check. Thus, the error rate revealed by B01 QC method is much greater than that by MADIS QC and NewQC at 700 hPa, 850 hPa and 925 hPa.

The wrong-rejection, lost-rejection and good-judgment rates of NewQC, MADIS QC and B01 QC are given in Table 2. The results show that NewQC has the highest good-judgment rate among the three methods. This is due to the separate judgment of wind direction and speed in NewQC, which reduces the lost-rejection rate.

The first vertical-wind-shear check finds a large number of errors in rawinsonde observations at 850 hPa, with 1 m s^{-1} and 2 m s^{-1} wind speed. Table 3 presents the statistical results of NewQC, B01 QC and MADIS QC for station 54776, Shan Tung, China, at (37.40°N, 122.68°E). The results show that NewQC finds 163 errors in rawinsonde observation winds at 850 hPa, which amounts to 1.04% of total observations at 850 hPa from 1980 to 2008. However, MADIS QC and B01 QC only identify a few of those errors (15 and 14, respectively), with ratios of 9.2% and 8.6%, respectively. Among the 163 errors, only two are incorrectly marked, while 137 errors occur in 1 m s^{-1} and 2 m s^{-1} wind speeds, with a high percentage: 84% of total errors. These errors are not identified by MADIS QC and B01 QC at all. In NewQC, they are established by comparing with the paper-based daily re-

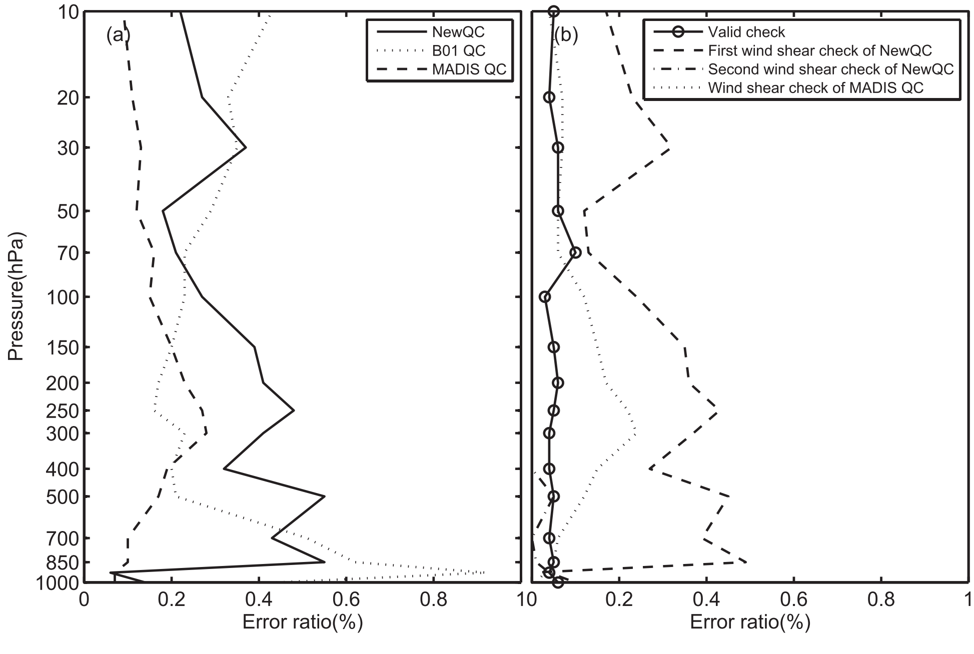

Fig. 10. Vertical distribution of the percentages of errors identified by (a) NewQC (solid line), B01 QC (dotted line), and MADIS QC (dashed line), and (b) the validity check (solid line with circles), the first vertical-wind-shear check (dashed line), second vertical-wind-shear check (dash-dotted line) of NewQC, and the vertical wind shear check of MADIS (dotted).

Table 2. Percentages of wrong-rejection, lost-rejection and good-judgment data of NewQC, MADIS QC and B01 QC.

		Wind vector	Wind speed	Wind direction
NewQC	Wrong rejection	0.048%	0.034%	0.026%
	Lost rejection	0.071%	0.313%	0.329%
	Good judgment	99.881%	99.653%	99.645%
B01 QC	Wrong rejection	0.128%	0.092%	0.079%
	Lost rejection	0.669%	0.347%	0.422%
	Good judgment	99.203%	99.561%	99.499%
MADIS QC	Wrong rejection	0.106%	0.072%	0.044%
	Lost rejection	0.651%	0.342%	0.403%
	Good judgment	99.243%	99.585%	99.554%

Table 3. Numbers rejected by NewQC, B01 QC and MADIS QC for station 54776, Shan Tung, China, at (37.40°N, 122.68°E).

	Rejected by NewQC					
			Wind speed			
	Rejected correctly	Rejected incorrectly	1 m s^{-1}	2 m s^{-1}	Rejected by MADIS QC	Rejected by B01 QC
Number	161	2	100	37	15	14
Percentage of the total number of errors rejected by NewQC	98.8%	1.2%	61.3%	22.7%	9.2%	8.6%

port. Regarding the two incorrect rejections, one is caused by incorrect reference data in the first wind shear check, and the other is caused by the strict threshold value in the second wind shear check. In November 1992, six errors in 1 m s^{-1} and 2 m s^{-1} cause the extreme lower monthly value of station 54776 (Fig. 1). It is difficult to establish these errors without the first vertical-wind-shear check.

4. Summary

In this paper we have proposed a new method for the QC of Chinese rawinsonde observation winds. The new method, named NewQC, was applied to the QC of MPL winds of upper-air reports from 1980–2008. With two vertical-wind-shear checks, NewQC identifies a large number of errors that fail to be identified in both B01 QC and MADIS QC, and thus reduces incorrect data by the B01 dataset, particularly when the checked data are in the high troposphere and stratosphere. Considering the regional and vertical differences of upper-air winds, different threshold values are used in the vertical-wind-shear checks with respect to different stations and vertical levels. With respect to the incorrect QCs, including the incorrectly rejected observations and retained incorrect observations, which are associated with the selection of threshold values, comparisons among NewQC, B01 QC and MADIS QC were conducted, using the same threshold values in the validity checks for all QC methods at all stations and layers. NewQC was found to perform better than the other two methods. Moreover, because the CHL data are used as reference data in NewQC, successive observation errors are easily identified. NewQC is efficient in real-time data processing, and can be easily applied in operational systems.

In this study, the target of the QC was MPL winds coming from the GTS when describing and evaluating the QC methods. NewQC is applicable to the paper-based daily reports of Chinese upper-air winds, which include more complete MPL winds and the digitization of which has been recently completed by the CMA. In fact, NewQC has already been applied in the QA of digitized CHL winds coming from the paper-based monthly reports of Chinese upper-air winds. Most suspect and incorrect data marked by NewQC have been manually audited and corrected. Certainly, when it is applied to the QC of global historical rawinsonde observed winds, more experiments and evaluation regarding the second vertical-wind-shear check should be carried out, given the lack of CHL winds in other countries.

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APPENDIX I

Algorithm of Wind-shear Check in Real-time Updates of the B01 Dataset

Wind data at MPLs are checked level-by-level from the lowest to the top MPL. When checking level i, wind shear "DS" is defined as

$$\mathrm{DS}=\sqrt{(U_i-U_{i-1})^2+(V_i-V_{i-1})^2}\ ,$$

where U_i and U_{i-1} are zonal components on level i and level $i-1$, and V_i and V_{i-1} are the meridional components. If DS is greater than 30 m s^{-1}, the wind shear would be considered questionable. If the wind on level i–1 is marked as "suspect" or "error", the wind on level i would be marked "suspect". If the wind on level i–1 is marked as "correct", the wind on level i would be mark "error".

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