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PLANETARY BOUNDARY LAYER HEIGHT MEASURED BY A WIND PROFILER BASED ON THE WAVELET TRANSFORM

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Abstract: Planetary boundary layer height (PBLH) is an important input parameter for any boundary layer study or model, either climate or atmospheric. The variation of the PBLH is also of great significance to the physical processes of numerical prediction, diagnosis of weather forecasting and monitoring urban pollutants. However, effective ways to monitor the PBLH continuously are lack. Wind profilers are commonly used in monitoring PBLH continuously because of its high temporal and spatial resolution, coupled with capability of continuous detection. In this paper, the covariance wavelet transform (CWT) is used to analyze the range-corrected signal-to-noise ratio (SNR) of the wind profiler to determine the PBLH, which is then compared with the results measured by the gradient method and the radiosonde. The conclusions are as follows: (1) The scaling parameter a and translation parameter b of the wavelet are critical in determination of the PBLH by applying the CWT as different values may get completely different results, which requires to select appropriate values in the calculation carefully. (2) Quality control is crucial in determining the PBLH because good quality control can help remove mutation points, which makes the determined PBLH more consistent with the actual situation. (3) In clear-air, the gradient method is not applicable if the boundary layer turbulence is inhomogeneous and the impact of noise is large for that it is easy to be impacted by the mutation of SNR caused by the atmosphere turbulence instability and other factors, which will cause large errors, while the CWT method as an improvement of the gradient method can determine the PBLH quite well. (4) Through quality control, the PBLHs determined by the CWT are consistent with those of radiosonde, and the correlation coefficient between them is 0.87.

Key words: CWT; wind profiler; PBLH; detection

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1 INTRODUCTION

The earth's lowest atmosphere is marked by a planetary boundary layer (PBL) that is usually 1—2 km from the ground, which makes it directly influenced by the earth's surface. The PBL is also an atmosphere layer in which free atmosphere exchanges material, energy, heat and vapor with the earth's surface (Stull[1]). The time scale at which the PBL responses to the impact of the ground is one hour or less by friction, evaporation and transpiration, heat transfer and pollutants emission, as well as geography that affects the airflow evolution.

There is obvious diurnal variation in the height of the PBL that mainly composed of near surface layer, mixed layer and clip volume layer in the daytime. The surface layer and the mixing layer are the parts from the ground to about 0.8 times of the PBLH, while the entrainment zone is at the top of the PBL and often a temperature inversion layer, which makes it become the transition zone between the PBL and free atmosphere. The PBLH is usually located in the entrainment zone which covers the boundary layer like a lid. Through the entrainment zone, aerosol mass concentration and relative humidity usually have a sharp gradient with the height distribution. Nighttime stable PBLH is very low compared to the daytime's, for the mixed layer height decreases obviously and significant turbulence only exists in the thin layer near the ground, which results from turbulence attenuation in the original mixed layer after sunset. The thin layer near the ground is the nighttime stable boundary layer, and the remaining layer is above it. In this paper, the PBLH we discuss is mainly the height of daytime convective boundary layer and nighttime stable boundary layer.

Physical quantities such as potential temperature, atmospheric aerosol concentration and relative humidity usually change sharply at the top of PBL. The wind profiler SNR is proportional to the atmospheric refractive index structure constant (Ottersten[2]), while is highly dependent on the relative humidity of the

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atmosphere (Cohn and Angevine[3]). Therefore, the sharp gradient of the atmospheric relative humidity on top of the PBL can be reflected in the wind profiler SNR data. The radiosonde can detect meteorological elements at different heights such as temperature and humidity, and has the ability to find the entrainment zone where potential temperature reverses and atmospheric relative humidity gradient changes sharply. As a result, the PBLH can be determined by calculating the vertical changes of relative humidity measured by radiosonde.

Particulate matter and ozone are harmful to people's health (Lippmann[4]; Bell et al.[5]), which makes it more and more significant to forecast air quality accurately. Most of the aerosol particles in the atmosphere are contained in the PBL, the height of which determines the range and concentration of aerosol diffusion. The obstacle of surface pollutant diffusion from the entrainment zone on top of the PBL leads to a higher concentration of pollutants in the PBL (Kane et al. [6]). The PBL also plays an important role in numerical simulation (Cha et al. [7]). Therefore, an accurate judgment of the PBL is very important for both air quality control and weather forecast. Wind profiler range-corrected SNR data was used to calculate the top of PBL by Angevine et al.[8]. In this method, the tops of the maximum SNR in 30 min of five beams are extracted, the middle one of which is taken as the PBLH. This method will be interfered by many factors, such as the existence of a residual layer, the entrainment of the PBL top is very weak or the vertical range is too wide so that the SNR distribution is relatively uniform, which makes it difficult to determine the PBLH. Results obtained from this method are compared to those from an airborne lidar. The PBLHs obtained from them agree to a certain extent but it is not clear in condition of cumulus convection (White et al. [9]). This method was further improved, by adding spectral width profiles to overcome the existence of the remaining zone in the morning and the influence resulting from the wide vertical range of entrainment zone at the top of PBL makes the maximum SNR less obvious, which is also suitable for the existence of clouds over the PBL (Heo et al.[10]). Laura Bianco et al. [11] applied the fuzzy logic method twice in extracting the PBLH from the wind profiler data. For the first time, the fuzzy logic method is applied to the quality control of the wind profiler spectral data to eliminate the influence of the ground clutter in the spectral data and then to calculate the SNR. Then the fuzzy logic method is used to calculate the PBLH by using the range-corrected SNR data, the result of which is quite accurate. In particular, the variance profile of the vertical velocity is added, which is useful to avoid the influence of the remaining zone in the morning. The method was enhanced further by improving the judging rule of the fuzzy logic method and adding the vertical profile of spectral width, which further improved the reliability of the results, especially the accuracy of PBLH in the presence of cloud. However, the fuzzy logic method is relatively complicated, and the judging rules are quite a lot (Laura et al.[12]). Compton et al.[13] explored the application of the CWT to lidars and wind profiler data to examine the possibility of accurate and continuous PBLH measurements on short temporal resolution. They found that accurate determination of the PBLH by applying the CWT to lidars and wind profilers will allow for improved air quality forecasting and understanding of regional pollution dynamics.

Although the PBLH in certain conditions can be gotten by using these methods, the actual atmosphere boundary layer is complicated and changeable, and its change forms of time and space is difficult to fix. In this paper, the method proposed by Jiang et al. [14] of using a wavelet transform to process the NRB signal of the laser radar to determine the PBLH is used for reference. We determine the PBLH by applying this method in the range-corrected SNR data of wind profilers. Suitable wavelet transform parameters can be chosen by this method according to the different PBL forms. More accurate PBLH can be gotten by changing the wavelet transform parameters to eliminate the influence of ground clutter, aerosol particles, remaining layer etc. effectively. Finally, we compare results calculated by this method with the one measured by radiosonde to prove the accuracy of the application of the wavelet transform in continuous detection of the PBLH variation by wind profilers.

The paper is organized as follows. Section 2 presents instruments and physical mechanism. In addition, the wind profiler based PBLH detection method is explained in Section 3. Besides, quality control of the PBLH detection is described in Section 4. In Section 5, the observations (case studies) are discussed. A short summary and concluding remarks are given in Section 6.

2 INSTRUMENTS AND PHYSICAL MECHANISM

In this study, we employ a L-band wind profiler which is located at a reference station in Nanjing (31.94°N, 118.9°E) at an altitude of 41.9 m. The time and range resolutions of the radar that operates at a wavelength of 234 mm are respectively 6 min and 60 m. Data used in this study is in a low mode.

In clear air, the basis of wind profiler detection is the scattering of radar electromagnetic waves by atmospheric refractive index inhomogeneous distribution shown in c, which is caused by atmospheric turbulence. At a given distance, the wind profiler SNR is proportional to the refractive index structure constant (Ottersten[2]; VanZandt[15]), so the SNR is proportional to the range-corrected value, which can reflect the evolution of atmospheric turbulence intensity. The SNR mentioned below is the one range-corrected. Its specific revised formula is given by

$$\mathrm{SNRC}=\mathrm{SNR}+20\lg(\frac{R}{Z_S}) \tag{1}$$

where SNRC is the range-corrected SNR with a unit of dB, Z_S is range normalization factor which is selected appropriately. The atmospheric refractive index is significantly dependent on the atmospheric vapor content for those electromagnetic waves whose wavelengths are over 1 cm. The SNR of a very wet atmosphere can vary by several orders of magnitude compared to the one of an absolute dry atmosphere (He [16]). The top of PBL is covered by an inversion layer in the entrainment zone. The air above PBL is relatively dry, and the turbulence intensity is relatively weak, while the humidity of the air in PBL is larger, and the turbulent activity is stronger. Consequently, atmospheric humidity and atmospheric turbulence intensity will change significantly near the top of PBL, which can then be reflected in the wind profiler SNR data.

3 PBLH RETRIEVAL METHODS

As is analyzed in the previous section, the wind profiler SNR decreases dramatically at the PBL top, so the gradient method can be used to simply determine the PBLH in theory, i.e., derive the derivative of the range-corrected SNR at each height. The height of the maximum negative derivative value $-\frac{\mathrm{d}(f(z))}{\mathrm{d}z}$ can be considered as the PBLH. In practical application, we find that the gradient method can detect the PBLH when the atmospheric turbulence is relatively uniform and the echo signal is less affected by the noise. However, the actual atmospheric structure is usually very complex and the atmospheric turbulence is not uniform, which causes the echo signal to be affected by the influence of noise and the local SNR to change suddenly. The error of the results obtained by the gradient method is quite large, which affects the judgment of PBLH.

The vertical profile of the wind profiler range-corrected SNR data has a significant step property in the transition zone of the PBL top to the free atmosphere, so we can use a Haar wavelet transform to perform on it; at the same time, due to the strong descending property of the SNR data in the transition region, which will perform as a mutation point in the vertical gradient of SNR, Morlet, Meyer, and Mexican Hat wavelet basis functions have good locality both in time domain and frequency domain, therefore, we can use these three kinds of wavelet basis functions to perform a wavelet transform on the SNR data, in order to determine the position of the mutation points. Then the stability of these four methods are compared to find the best wavelet basis function.

3.1 *Wavelet basis functions*

3.1.1 HAAR WAVELET BASIS FUNCTION

The Haar function is defined as (Radomir et al.[17])

$$h(\frac{z-b}{a})=\begin{cases}1: & b\quad \frac{a}{2}\leqslant z<b\\ +1: & b\leqslant z\leqslant b+\frac{a}{2}\\ 0: & \text{elsewhere}\end{cases} \tag{2}$$

where a is the spatial extent, or dilation, of the function, b is the location at which the wavelet function is centered, the translation of the function, and z is the height. The CWT of the Haar function is defined by Gamage and Hagelberg using the equation (Cha et al.[7]).

$$W_f(a,b)=a^{-1}\int_{z_b}^{z_t} f(z)h\left(\frac{z-b}{a}\right)dz \tag{3}$$

where z_t and z_b are the lower and upper limits of the profile respectively, $f(z)$ is the signal of interest, in our case a wind profiler SNR vertical profile.

The principle of the method to determine the PBLH is to compare the similarity between the wind profiler SNR vertical profile and the Haar wavelet basis function (Menut et al.[18]), i.e., the similarity between wind profiler SNR vertical profile and Haar wavelet function at the height of $b\pm a/2$ range. The greater the similarity extent, the smaller $W_f(a,b)$, i.e., the more obvious the signal step performance. Therefore, the height of the b when $W_f(a,b)$ obtains the minimum value is the PBLH.

3.1.2 MORLET WAVELET BASIS FUNCTION

Morlet wavelet basis function is defined as (Huang et al.[19])

$$\varphi_{j0}(x)=e^{ij_0x}(e^{\frac{-x^2}{2}}-\sqrt{2}e^{-\frac{j_0^2}{4}}e^{-x^2}) \tag{4}$$

where j_0 represents the distortion degree of the wavelet. When j_0 is relatively large, the first item of the formula above is much larger than the second one, and we can omit the second item to get

$$\varphi_{j0}(x)=e^{ij_0x}e^{\frac{-x^2}{2}} \tag{5}$$

The wavelet transform is

$$W_f(a,b)=\frac{1}{\sqrt{a}}\int_{z_b}^{z_t} g(z)\varphi(\frac{z-b}{a})\mathrm{d}z \tag{6}$$

where $g(z)$ is the vertical gradient of the wind profiler SNR profile. A wavelet transform using Morlet wavelet basis function to determine the PBLH is to change a to find the best height b to make the wavelet coefficient $W_f(a,b)$ obtain the minimum value, i.e., find the mutation point of the wind profiler SNR vertical gradient profile, and take b at this time as the PBLH.

3.1.3 MEYER WAVELET BASIS FUNCTION

Meyer wavelet basis function φ and scaling function Φ are both defined in frequency domain, which is an orthogonal wavelet with compact support set and has good local characteristics in both time and frequency domains.

$$\hat{\varphi}(\omega)=\begin{cases}(2\pi)^{\frac{-1}{2}}e^{\frac{jw}{2}}\sin\left(\frac{\pi}{2}v\left(\frac{3}{2\pi}|\omega|-1\right)\right), & \frac{2\pi}{3}\leqslant|\omega|\leqslant\frac{4\pi}{3}\\ (2\pi)^{\frac{-1}{2}}e^{\frac{jw}{2}}\cos\left(\frac{\pi}{2}v\left(\frac{3}{2\pi}|\omega|-1\right)\right), & \frac{4\pi}{3}\leqslant|\omega|\leqslant\frac{8\pi}{3}\\ 0, & \text{elsewhere}\end{cases} \tag{7}$$

where v is an auxiliary function which composes Meyer wavelet. It can be a polynomial or other forms. The wavelet transform is

$$W_f\left(a,b\right)=\frac{1}{\sqrt{a}}\int_{z_b}^{z_t} g(z)\varphi(\frac{z-b}{a})\mathrm{d}z \tag{8}$$

where $g(z)$ is the vertical gradient of the wind profiler SNR profile. The best height b is found by changing a to make the wavelet coefficient $W_f\ (a,b)$ obtain the minimum value, i.e., find the mutation point of the wind profiler SNR vertical gradient profile, and take b at this time as the PBLH.

3.1.4 MEXICAN HAT WAVELET BASIS FUNCTION

The Mexican Hat wavelet basis function is defined as (Zhou and Adeli[20]).

$$\varphi(t)=(1-t^2)\exp(-\frac{t^2}{2}) \tag{9}$$

Similarly, for the gradient function $g(z)$, the wavelet transform is

$$W_f\left(a,b\right)=\frac{1}{\sqrt{a}}\int_{z_b}^{z_t} g(z)\varphi(\frac{z-b}{a})\mathrm{d}z \tag{10}$$

The wavelet coefficients give the minimum value at the mutation point of the gradient function by using the wavelet basis function to fit the wind profiler SNR profile gradient function $g(z)$, and b at this time is taken as the PBLH.

3.2 *Case studies*

When using the same wavelet basis function to perform a wavelet transform to determine the PBLH, we can usually find that the results differ a lot in the different resolution scales. In order to study the sensitivity of the PBLH determined by different wavelet basis functions to the scaling parameter, we choose the vertical profile of a typical wind profiler SNR. As shown in Fig.1, the SNR decreases significantly in the transition zone between the PBL and free atmosphere (entrainment layer), and the transform of the SNR is relatively small in the PBL and free atmosphere. The dotted line in the figure indicates that the boundary layer height obtained by radiosonde is about 2,400 m.

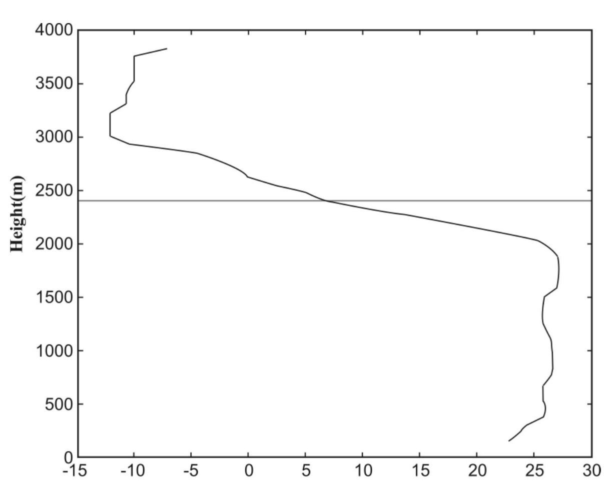

Figure 1. A vertical profile of SNR.

Figure 2 is the PBLH determined by the wavelet transform at different wavelet scales for different wavelet basis functions. Fig.2a is the result obtained from the Haar wavelet basis function. When the value of scaling parameter a is relatively small, the PBLH obtained by the Haar wavelet basis function differs greatly from the actual situation, and it is easy to be disturbed by the change of SNR in small scales. However, when value a is greater than 600 m, the results from the Haar wavelet function are very stable with the increase of a, the maximum deviation of which is less than 100 m and is consistent with the actual situation. Fig.2b is the result obtained from Morlet wavelet basis function. As we can see, with the increase of value a, the determined PBLH has a certain degree of fluctuation, and the maximum height difference is more than 200 m. When value a is larger than 900 m, the results are very stable and accurate. Fig.2c is the result obtained from the Meyer wavelet basis function, which is very volatile and inaccurate. Fig.2d is the result obtained from the Mexican wavelet basis function. As is shown in the figure, with the increase of a, the results have some fluctuation, and are quite accurate. When value a is relatively large, the deviation of the results is relatively large.

From the results analysis, we can find that in addition to the results of the Meyer basis wavelet function, the results of other wavelet basis functions can be used to get the correct PBLH when we take appropriate value a, but they have fluctuations with the transformation of a. When value a is larger than the scale of small scaling SNR interference, the results of Haar wavelet are most stable, the biggest difference of which is not more than 100 m. Besides, the calculation of Haar wavelet basis function is easy because of its simple form. As a result, the Haar wavelet basis function should be selected when the wavelet transform is used to determine the PBLH.

Further analysis, it can be obtained by substituting Eq.(2) into Eq.(3) so that

$$W_f\left(a,b\right)=\begin{cases} -a^{-1}\int_{z_b}^{z_t} f\left(z\right)dz, & b-\frac{a}{2}\le z<b \\ a^{-1}\int_{z_b}^{z_t} f\left(z\right)dz, & b\le z\le b+\frac{a}{2} \\ 0, & \text{elsewhere} \end{cases} \tag{11}$$

The integral function and the integral interval of the first type and the second type in Eq. (11) are the same, and the definition domains of the two terms are continuous, so it can be combined as

$$W_f(a,b)=\begin{cases} a^{-1}\int_b^{b+\frac{a}{2}} f(z)\mathrm{d}z-a^{-1}\int_{b-\frac{a}{2}}^{b} f(z)\mathrm{d}z & b-\frac{a}{2}\le z<b \\ 0 & \text{elsewhere} \end{cases} \tag{12}$$

Finishing the equation above to get

$$W_f(a,b)=a^{-1}\left[\int_b^{b+\frac{a}{2}} f\left(z\right)-f\left(z\right)\mathrm{d}z\int_{b-\frac{a}{2}}^{b} f\left(z\right)\mathrm{d}z\right] \tag{13}$$

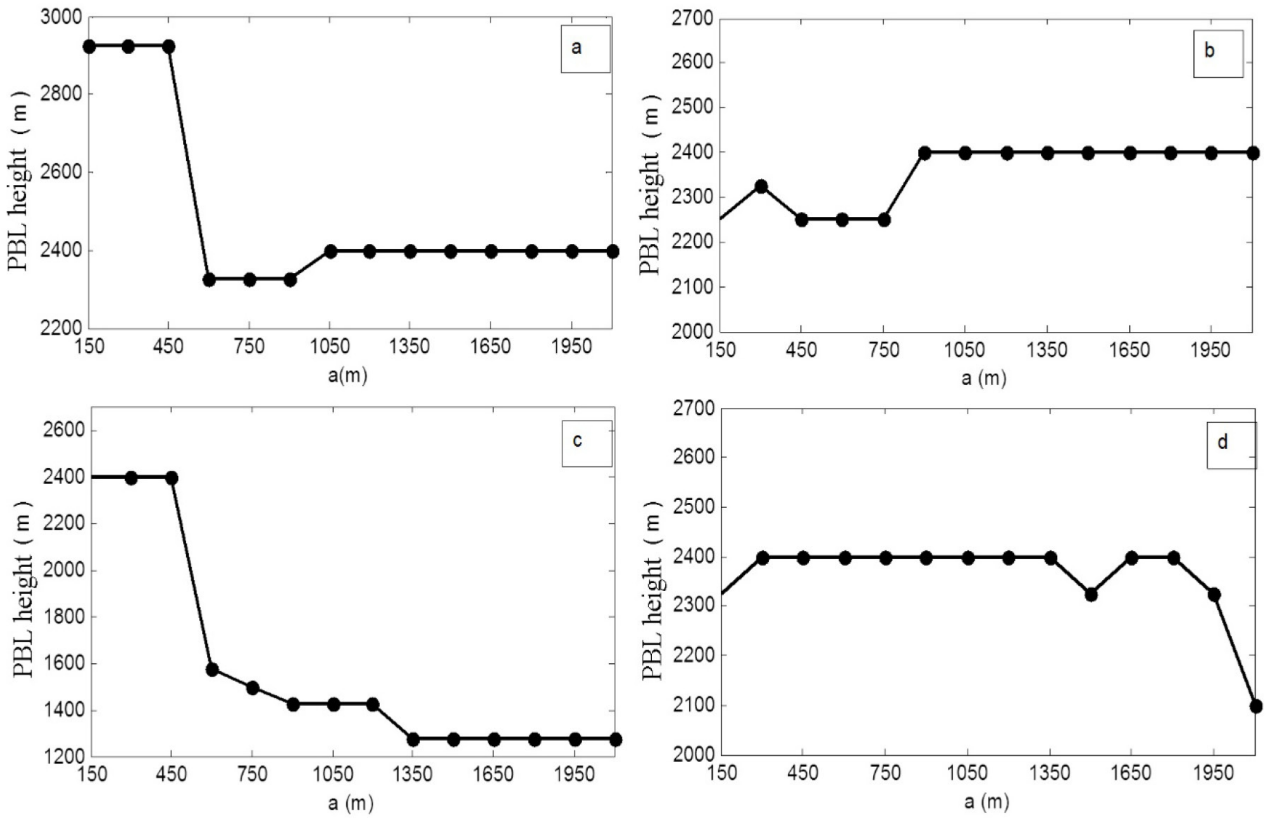

Figure 2. The PBLHs obtained from various wavelet basis functions at various wavelet scales.

From Eq.(13), we can see that covariance wavelet transform (CWT) method is actually an extension of the gradient method, which can be understood as the gradient between the two layers: b to $b+a/2$ and $b-a/2$ to b. As a result, the calculation results can be more accurate by choosing appropriate value a according to the wind profiler SNR gradient.

The most important thing is to determine the two wavelet parameters a and b before applying the CWT. b is the translation parameter, and any wind profiler SNR profiles are limited. According to Eq.(13), the minimum value b is located at the place that is higher than a/2 of the lowest end of the SNR profiler, and the maximum value b is located at the place that is lower than a/2 of the highest end of the radar SNR profiler. a is the window width of the wavelet, so the maximum value a that can be obtained in theory is the length of the SNR profiler. However, the maximum value is meaningless in practical application, because the maximum value a can have only one b and it is at the center of the length of the SNR profile. The minimum a is two times of the radar range resolution, which can ensure that the wavelet window range has the SNR data. From the physical meaning of a that has been discussed above, we can know that small value a can detect slight changes of the SNR profile, but it can also detect little fluctuations of temperature, pressure and humidity due to the turbulence inhomogeneity, and the SNR gradient caused by atmospheric noise, aerosol, thin clouds and other factors. Large value a can smooth out the small gradient caused by noise etc. However, the PBLH may not be detected when the boundary layer is not obvious especially the nighttime stable boundary layer, and the accuracy determined by the PBLH can also be affected. Fig.3 shows wavelet coefficients under different a. The wavelet coefficient is greatly affected by noise etc. when a=120 m. There are a lot of local minimum and maximum values, so it is difficult to determine the PBLH. With the increase of the value a, many gradients of relatively small SNR will be smoothed out, and the minimum value of the wavelet coefficients of relatively large SNR is left. When a=120 m, wavelet coefficients only leave the minimum value at the PBLH.

Figure 4 intuitively shows the transformation of the wavelet coefficients with the increase of a. Fig.4b is a wind profiler SNR profile at a time, in which the red line is the PBLH determined by radiosonde. Fig.4a shows changes of wavelet coefficients with the increase of a at each height, in which the white area is the eliminated data because wavelet functions will have no definitions if it exceeds the data boundary in the area of less than $a/2$ at both ends of the profile. We use the average of a to calculate, which increases the accuracy. As a result, wavelet coefficients obtained in that range cannot reflect the changes of the SNR profile. With value a increases, the range of the value b decreases, and the white area will become larger. When the value a is less than 500 m, the wavelet coefficients does not change significantly in height, which makes it difficult to recognize the local minimum area. When the value a is greater than 500 m, the wavelet coefficients have an obviously small local values area (red area) near the height of 1,000 m, which is in line with the height of the red line b at the right and makes the PBLH clearly distinguished. With the further increase of a, the minimum values area increases gradually, which has certain influence on the accuracy of the PBLH determined.

Figure 5 shows the PBLHs determined by different values of a. As we can see, when value a is less than

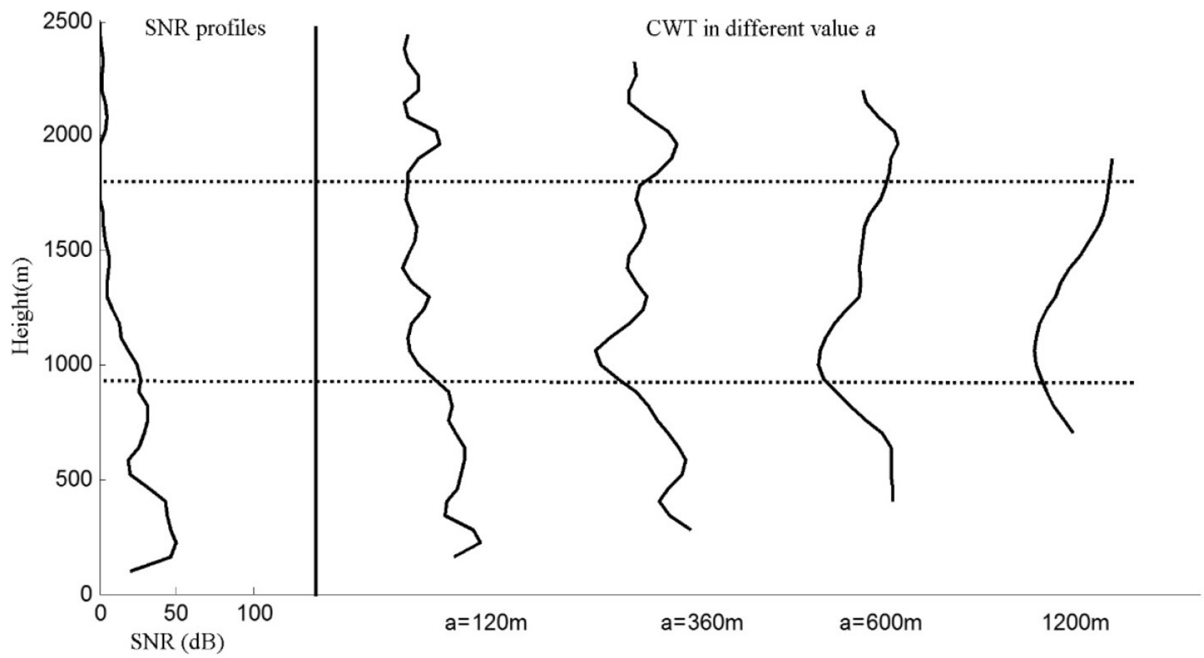

Figure 3. Variation of wavelet coefficients under various values of a.

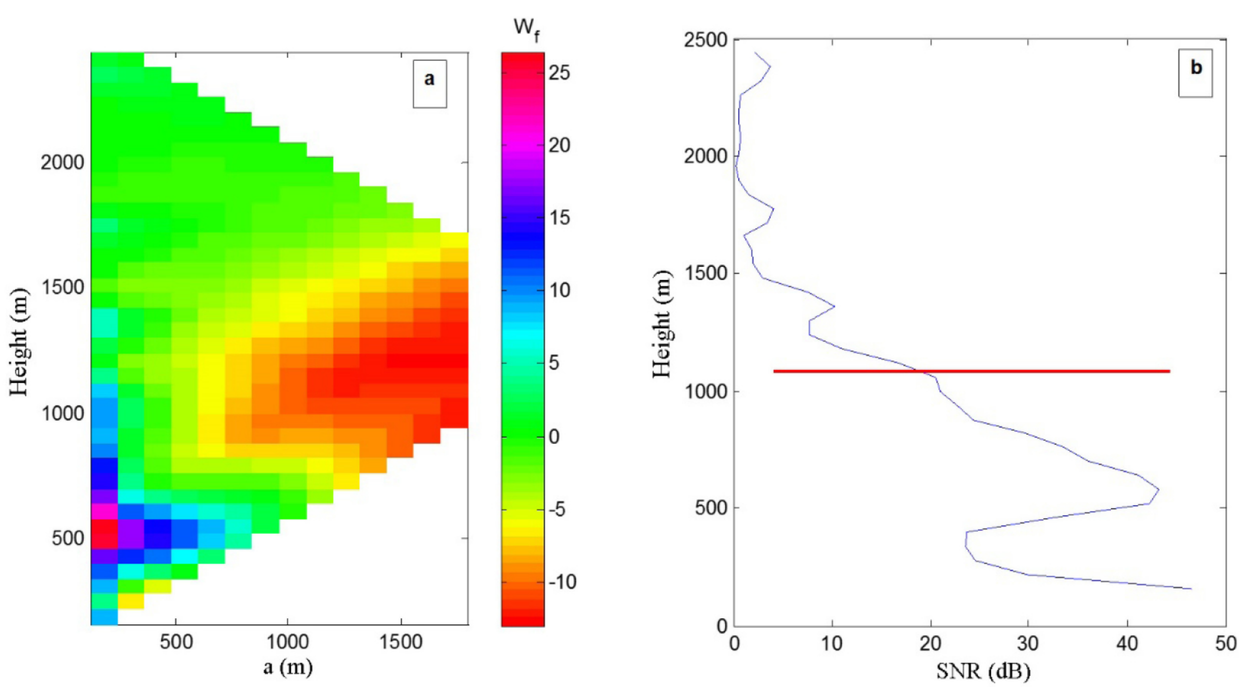

Figure 4. Relationship between a and wavelet coefficients.

600 m, the PBLHs which are determined by the CWT method vary greatly with the changes of a, and they are in the form of jump, which is affected by interference such as noise etc. When value a is greater than 600 m, the determined PBLH is basically stable, and is basically in the range of 900—1,200 m.

In this paper, the scheme we select value a is concretely as follows: a changes in a certain range (generally greater than those greatly affected by the noise). The wavelet coefficients of each value a at each height are obtained in turn, and then the wavelet coefficients are averaged at each height. Finally, the height of local minimum in the wavelet coefficients on average is taken as the PBLH. Taking the great difference of the physical quantities between the day and night in the PBL into account, we separate the day and night for treatment. At night, due to the weak effect of turbulence, the PBL top is not particularly evident. We make maximum value a smaller, but the minimum value a must be greater than the one that can smooth out noise interference etc. Small gradient features below the deep remaining layer can be detected by using small value a; During the day, we choose a larger value a because the daytime turbulence is strong and there are a lot of small fluctuations of temperature, pressure and humidity in the PBL, which results in a lot of small gradients of wind profiler SNR. We make the minimum value a relatively large because using large value a can smooth out the impact of small gradients and determine the PBLH more accurately. In this paper, we also use two different variation ranges of b to calculate the PBLH in the day and night respectively. Due to the heating of the ground during the day, the mixed layer is very high, and the PBLH is respectively high, so the maximum value b should be large; Due to the weak turbulence at night, the PBLH is respectively low. Coupled with the existence of the remaining layer over it, the top of the remaining layer will have a large gradient of water vapor, which makes it easy to mistake the top of the remaining layer as the PBLH. As a result, we limit b on the lower part of the remaining layer top (usually below 1 km) (Compton et al.[13]).

4 QUALITY CONTROL OF THE PBLH

From synoptic principles, we know that the weather evolution can be considered as a continuous process which will not be particularly intense in short time. The time resolution of wind profiler is a few minutes, which makes the difference between the PBLHs obtained at two adjacent moments not especially large. Based on this principle, the quality control is carried out by setting maximum change threshold of the PBLHs of adjacent time. The specific scheme is shown in Fig.6 (Compton et al.[13]).

Figure 7 demonstrates the comparison of PBLH before and after quality control. The time resolution of

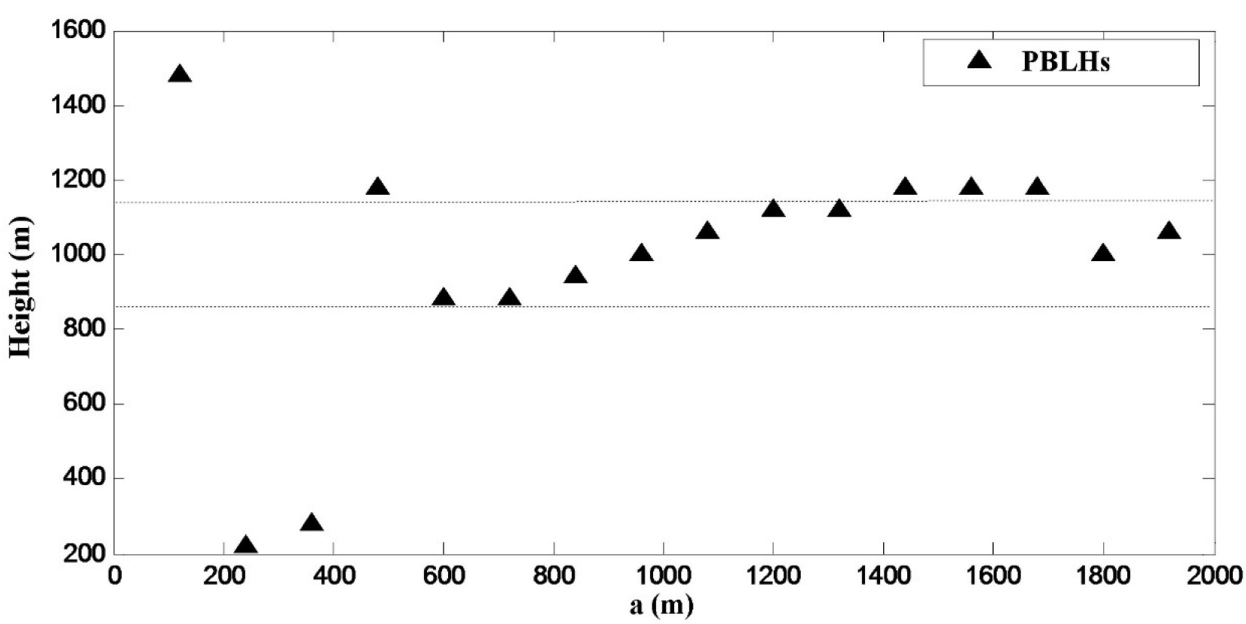

Figure 5. PBLHs determined by various values of a.

the wind profiler is 6 minutes. Fig.7a shows the evolution of PBLH determined by directly applying the CWT over time. As we can see, from 9:00 a.m. to 2:00 p.m ., the overall trend of the boundary layer height increases gradually, which is in accordance with the actual situation. However, there are many heights of mutation, and some even with the height of two adjacent times differing by more than 1,000 m, which is not consistent with the actual weather evolution. The points where SNR increases or decreases suddenly are not the actual PBLH. It may be changes of signal-to-noise ratio that are caused by aerosol layer, humidity layer and other factors resulting from turbulence inequality. Fig.7b shows the evolution of the PBLH over time after quality control. Its height curve is much smoother compared with that of Fig.7a. Those heights of mutation are determined after quality control, and those newly determined heights are more in line with the evolution of the actual atmosphere. Therefore, it is necessary to carry out quality control of the determined height when using this method to determine the evolution of PBLH over time.

5 CASE STUDIES

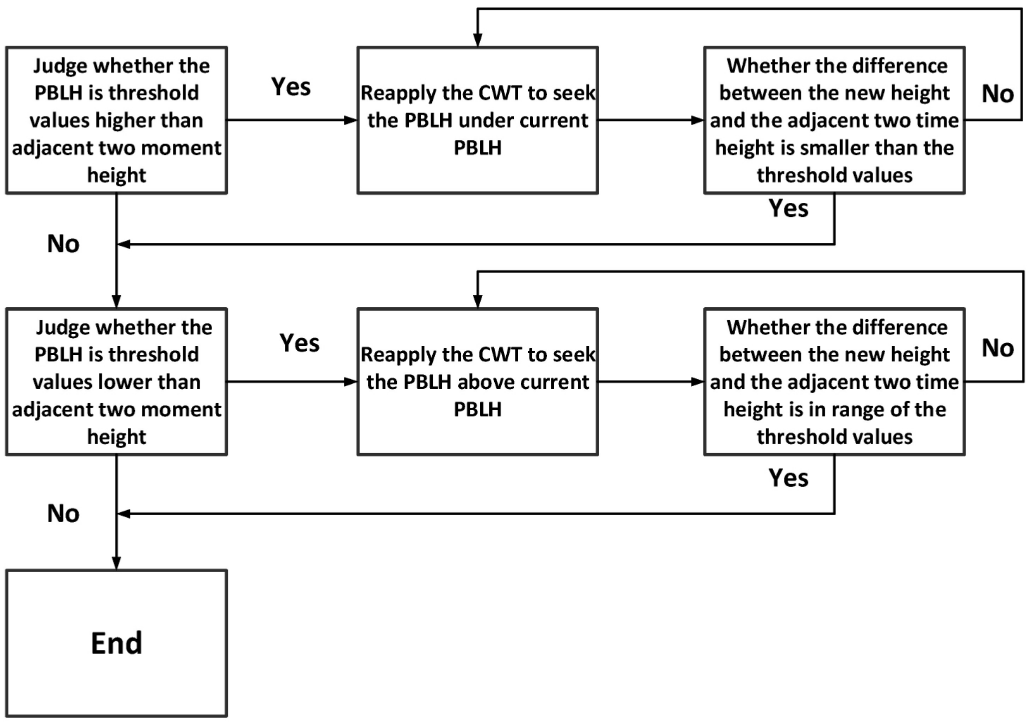

Figure 6. Schematic figure of the PBLH detection algorithm.

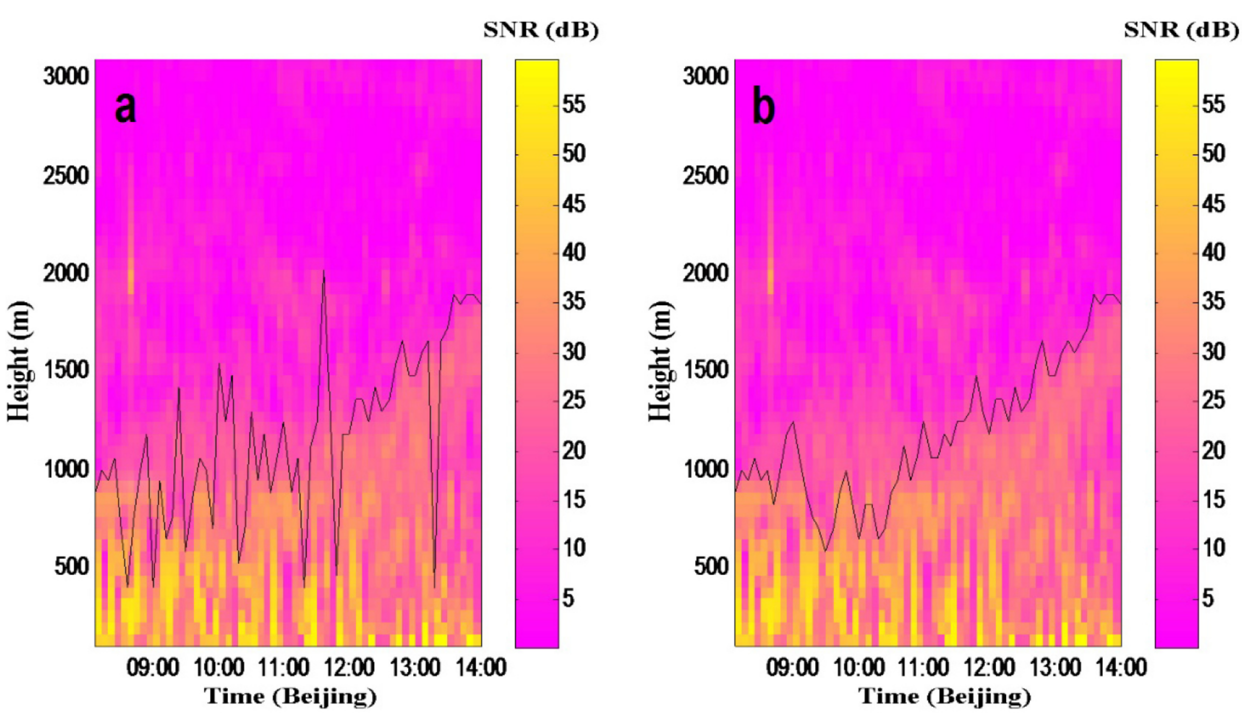

Figure 7. Comparison of the PBLHs before and after quality control.

The wind profiler detection data on 14 August 2013 in Jiangning, Nanjing is selected in the first case. The SNR data in the low mode from 10:00 a.m. to 8:00 p.m. and the radiosonde data measured at the same location within the same time period are selected. There are two sets of data detected in total, respectively at 1:00 p.m. and 7:00 p.m. In this paper, we use the comprehensive evaluation method to determine the PBLH (Davis [21]). Liu discussed the method and compared it with the Roche method used in atmospheric environmental quality assessment [22]. The results obtained by these two methods are quite close and the relative error is less than 15%.

Figure 8 presents the comparison between the PBLH calculated by the wavelet transform method and that determined by radiosonde. The blue line shows the changes of the PBLH determined by the wavelet transform method over time, and the black dots represent the PBLHs determined by radiosonde of two times. The changes of range-corrected SNR over time are showed by background colors. As we can see in the figure, the PBLHs determined by the wavelet transform method and radiosonde are quite consistent. There is an obvious rise of the PBL at 11:00 a.m., and it reaches the highest point of about 1.8 km at 4:00 p.m. because of the effect of ground radiation heating. After that, the PBLH falls due to the weakening of ground radiation.

The wind profiler detection data on 12 August 2013 in Jiangning, Nanjing is selected in the second case, the weather of which was sunny and cloudless. The processing results of the data from 8:00 a.m. to 10:00 p.m. on that day are demonstrated in Fig.9. Fig.9a shows the changes of wind profiler SNR profile over time, in which atmospheric layered structure in the vertical direction can be seen. Fig.9b shows the PBLH determined by applying the CWT to process the range-corrected SNR data. The solid black line in it is the curve of changes of the determined PBLH over time, which coincides with the evolution of the boundary layer atmosphere. The PBLH begins to rise at about 12:00, which is mainly due to the enhancement of the solar radiation resulting in the enhancement of the ground to atmosphere heating and the boundary layer turbulence. Each physical flux begins to accelerate upward, so the PBLH rises. It reaches the highest level of about 2 km at 2:00 p.m., maintains at a high altitude from 2:00 p.m. to 5:00 p.m. and decreases since then, as the weakening of solar radiation leads to the weakening of the turbulence in the PBL. To 8:00 p.m. at night, the PBL falls to the lowest, and the stable PBLH does not change a lot into the night. Fig.9c shows the PBLH at the same time of the day determined by the gradient method. The PBLH determined by the gradient method have a great difference with the atmospheric evolution and does not reflect the real changes of the PBLH, the reason of which is that the gradient method is easy to be affected by the small fluctuation of SNR and it can only calculate the gradient of SNR of adjacent distance. The comparison of Fig.9b with Fig.9c demonstrates that by changing a, the wavelet transform can calculate the SNR gradient of two layers of arbitrary thickness flexibly and smooth out the influence of individual mutations, which helps calculate the clear-air PBLH accurately.

Figure 10 gives a linear relationship between the PBLH determined by radiosonde and those obtained by

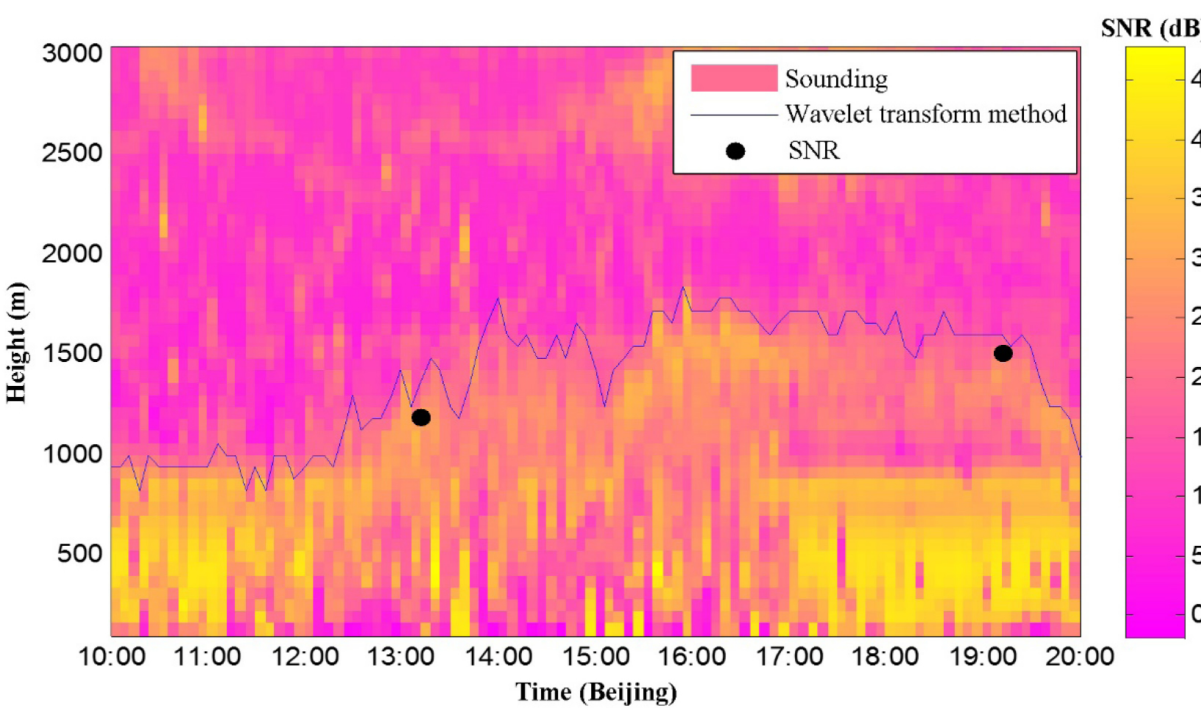

Figure 8. Variation of PBLHs determined by the wavelet transform method and radiosonde.

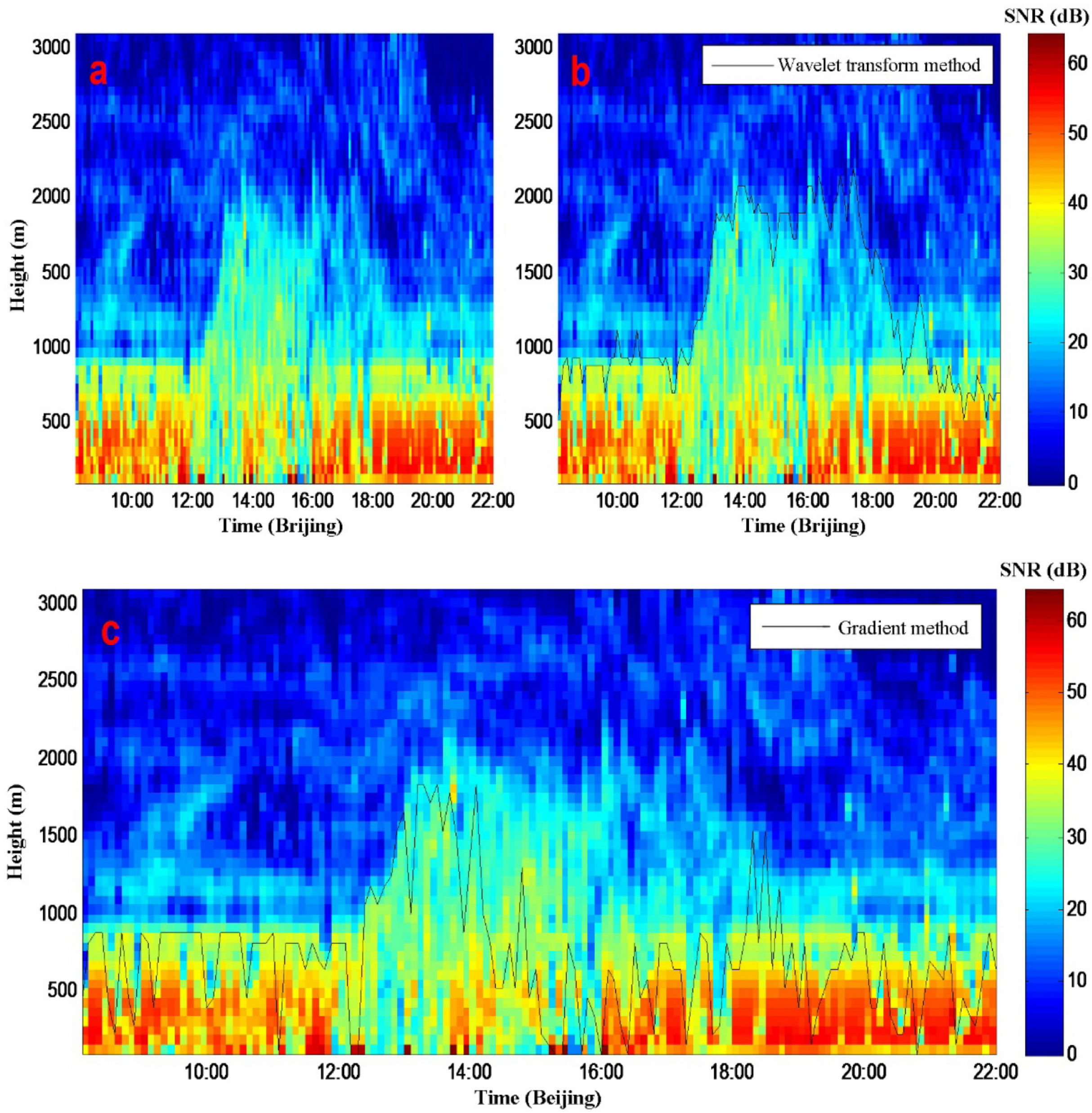

Figure 9. Variation of PBLHs determined by different methods.

applying the CWT to the wind profiler range-corrected SNR data. The data is selected from the days of sunny and less cloudiness weather in August 2013. It can be found that the PBLHs obtained by the two different methods have good consistency, and the correlation coefficient R can reach 0.87, which indicates the reliability of applying the CWT method to determine the PBLH.

6 SUMMARY AND CONCLUSIONS

In this paper, the CWT is applied to the wind profiler SNR data to determine the PBLH, the results of which are then compared to those obtained by the gradient method and radiosonde. This method is based on the sharp gradient of atmospheric turbulence intensity, potential temperature, relative humidity and other meteorological elements of the PBL top. Case analysis shows that the method is feasible.

The selection of scaling parameter a and translation parameter b is of great significance when the CWT is applied to the determination of the PBLH. Generally, larger ranges of value a and value b are selected after sunrise, while smaller ranges of value a and value b are selected after sunset. However, the minimum value a must be large enough to smooth out the interference of noise, small temperature, pressure, and humidity fluctuations, and the range of nighttime value b should be under the remaining layer. It is easy to mistake the top of the remaining layer for the nighttime stable PBLH otherwise.

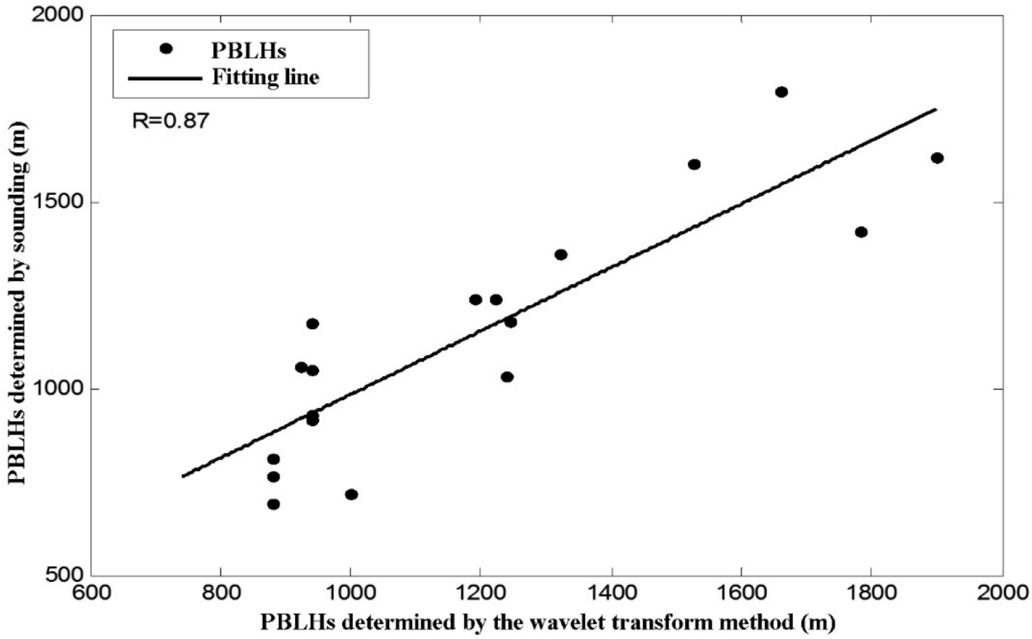

Figure 10. Linear regressions comparing PBLH's from the wavelet transform method to radiosondes.

Quality control is critical to determine the PBLH correctly. Through it, the accuracy of the method that applies the wavelet transform to determine the PBLH by using wind profiler SNR data is relatively high. The correlation coefficient between the PBLH determined by this method after quality control and the height obtained from radiosonde is 0.87.

The PBLH can be determined by combining wind profiler data with the wavelet transform. Due to the high time resolution of wind profiles, the advantages of this method are that the PBLH can be given in real time and the evolution of PBLH in one day can be reflected, so it has great development prospects. However, it has its own limitation. The wind profiler echo is mixed with the echo of precipitation with rainfall weather and a lot of clouds, which makes it impossible to determine the PBLH by using the SNR data, so this method is not applicable to precipitation weather.

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