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Identification of Coherent Structures of Turbulence at the Atmospheric Surface Layer

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ABSTRACT

A parameter-free method based on orthonormal wavelet transforms is recommended for calculating the principal time scale of coherent structures in atmospheric boundary-layer measurements. First, the atmospheric turbulent signal is decomposed into the small scale vortex that has approximate isotropy and the large scale vortex with the digital filter. Then, the large scale vortex is used to detect coherent structures with this method. The principal time scale and profile of coherent structures for velocity components (u, v, w) above rice fields are obtained. In order to testify the validity of this method, the correlation of coherent structures and non-coherent structures are also calculated.

Key words: turbulence, coherent structures, orthonormal wavelet, principal time scale

1. Introduction

On research of turbulent flows, coherent structures play an important role, especially in the atmospheric boundary layer (ABL) for the exchange of heat, mass, and momentum across the land-atmosphere interface (Gao et al. 1989; Raupach et al. 1989; Wilczak 1984). This is due to the large amount of the total vertical momentum and heat fluxes found to take place in coherent structures (Sullivan et al. 1994). Coherent structures in the atmosphere can be clearly identifiable in measured time series as ' ramps' arising from the sweep-ejection motion in the surface layer (Gao et al. 1989; 1991).

It is generally considered that the coherent structures are distinct large scale fluctuation patterns regularly observed in turbulent flows (Gao et al. 1991). But, it is an ongoing problem how to extract objectively coherent structures in a turbulent signal. Most methods proposed to identify coherent structure properties are subjective (Sullivan et al. 1994). Lately, wavelet analysis, a relatively new mathematical method, which provide both space and time information of analyzed signals, is becoming an important tool for identifying and studying coherent structures (Katul and Vidakovic 1996). In this study, an objective method based on discrete orthonormal basis functions is suggested for detecting coherent structures in atmospheric turbulent flow.

In this paper, the measured time series are decomposed into two parts with digital filter. One is small scale vortex that is nearly isotropic, and the other is large scale vortex that is anisotropic. Coherent structures must be in the large scale vortex signals, but, not all of the

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large scale vortex signal are coherent structures. The above view is also proved and supported by results obtained in this paper. Consequently, a discrete orthonomal wavelet transform is used to extract coherent structures from the large scale vortex signals. The principal time scale for coherent structures is defined to be the scale where the normalized (i.e., the sum of the squared wavelet coefficients at the given scale divided by the sum of the variances of all scales) energy content of the analyzed data is maximum.

Based upon the calculated principal time scales for coherent structures, the profiles of coherent structures are obtained using wavelet inverse transform. We also use directly the original velocity fluctuations at the atmospheric surface layer for wavelet analysis to identify the principal time scales of coherent structures in the flow.

2. Observation data

The data analyzed in this paper came from the Huaihe River Basin Energy and Water Cycle Experiment (HUBEX). HUBEX, a nationaly important basic research program during 1997–2001, was also incorporated into GEWEX / GAME by Japanese Department of Education. Therefore, HUBEX is one of the important climatic research programs in the end of the 20th century.

Atmospheric surface layer measurements were carried out at Shouxian of Anhui Province in China (32.33°N, 116.47°E) during the summer of 1998 (from 5 June to 30 July). At the time of this experiment, the ground was almost completely covered with rice stubble (Chen 1999). The turbulent velocity components were recorded with a sampling frequency of 20 Hz using a SAT–211 / 3K 3–D ultrasonic anemometer located at 4 m above the rice surface.

The analysis is based on a total of 15 twenty–minute data files throughout atmospheric conditions of unstable stratification. Since the principal time scales for the coherent structures are considered to be greater than 1 second (Gao and Li 1993), we averaged the 20 Hz measurements to 1 Hz. As a result, the original 20 min data sets could be reduced to 1024 $(=2^{10})$ points.

3. Algorithms and results

3.1 *Digital filter*

The digital filter is an effective method which can decompose the turbulent velocity measurements u_i into the small scale vortex and the large scale vortex, as

$$u_i = u_{il} + u_{is} \ , \tag{1}$$

where, u_{il} is the large scale vortex, and u_{is} is the small scale vortex. We often use the techniques of FFT and IFFT to carry out this process. In this paper, we decompose a turbulent signal based on the following rules, which are proposed in order to eliminate subjectivity (Wang et al. 1995). Where u, v, and w, are the longitudinal, transverse and vertical velocity fluctuations of the atmospheric boundary layer turbulence respectively, the rules that we comply with are given by

(1) the small vortex should be nearly isotropic; namely

$$u_{is}^2 \approx v_{is}^2 \approx w_{is}^2 \tag{2}$$

(2) the small vortex should be nearly irrelevant to the large scale vortex;

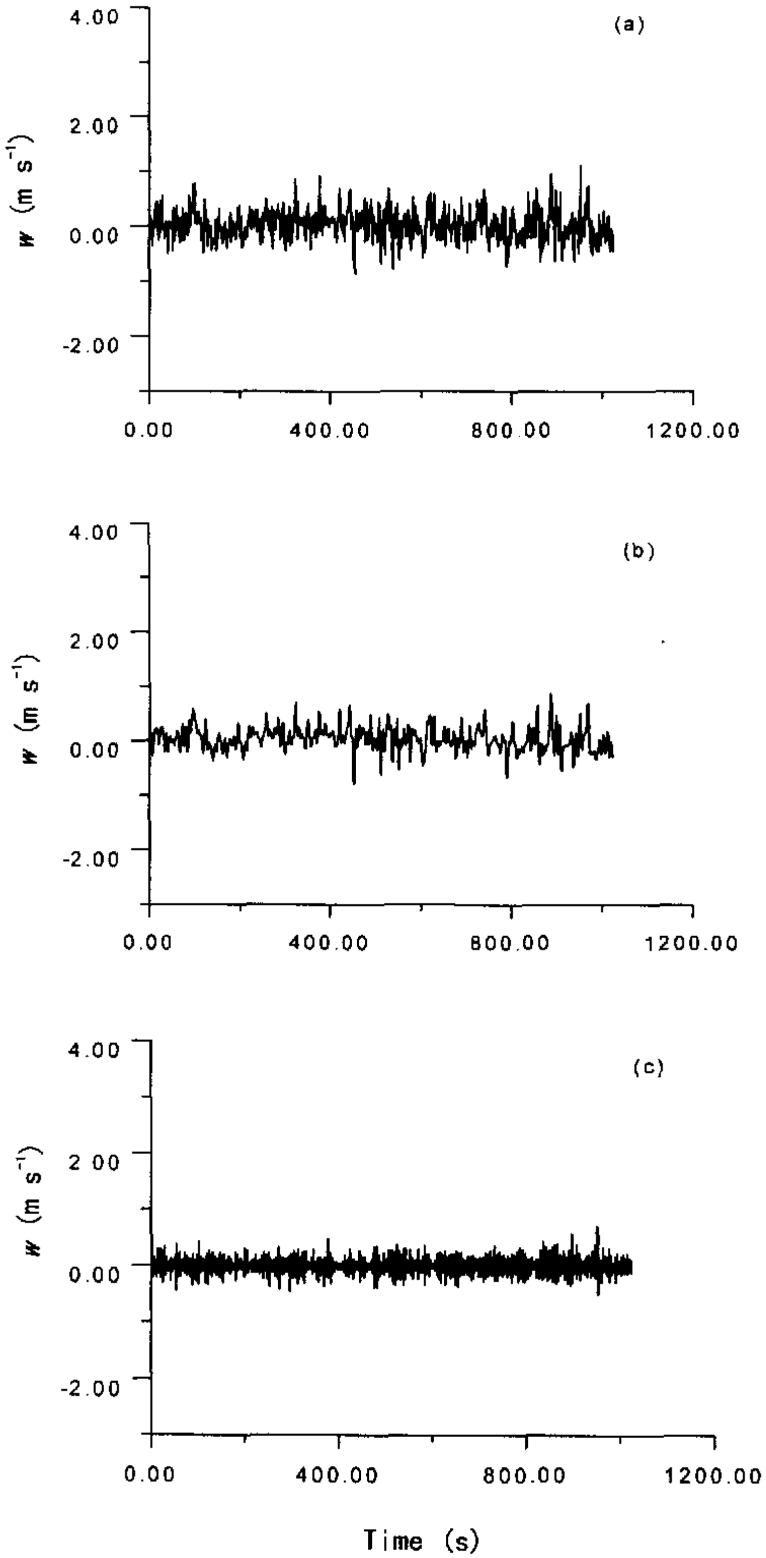

Fig. 1. The vertical component of the original turbulent signal (a), and large scale vortex (b) and small scale vortex (c) signals obtained via the digital filter.

$$u_{is}u_{il} \approx 0 \ , \quad v_{is}u_{il} \approx 0 \ , \quad w_{is}w_{il} \approx 0 \tag{3}$$

(3) the majority of the turbulent kinetic energy should be kept in the large scale vortex;

$$\frac{1}{2}(u_{il}^2 + v_{il}^2 + w_{il}^2) > \frac{1}{2}(u_{is}^2 + v_{is}^2 + w_{is}^2) \tag{4}$$

(4) the coherent structure is the large scale vortex, which contributes to most the Reynolds stress, namely;

$$u_{il}v_{il} > u_{is}v_{is} \cdots \tag{5}$$

In fact, the signal can be decomposed by using the first condition. The other conditions are used for validation. As an example, the digital filter decomposition of a velocity signal measured over the atmospheric surface layer is presented in Fig. 1. It can be seen that the differences are distinctly presented for the original, large scale, and small scale signals of the vertical component of atmospheric flow measured over the rice field. The large scale signal is of the most concern to us.

3.2 *Wavelet transform*

Wavelet transforms can be used to make the decomposition of data into different scale components distributed in space or time (Mahrt and Gibson 1992; Meneveau 1991). In the present study, discrete orthonormal wavelet expansions are applied to identify the principal time scales of the coherent structures in atmospheric surface layer turbulence.

For a discrete one–dimensional signal $f(j)$, the wavelet transform is defined by

$$w^{(m)}(i) = \sum_{j=1}^{N} g^{(m)}(i - 2^m j)f(j) \tag{6}$$

Here, $w^{(m)}(i)$ is the wavelet coefficient at location i and with scale 2^m, N is the total number of data points, and $g^{(m)}(i)$ is the discrete orthonormal basis function. Three anti–symmetric wavelets (Daubechies–4, Daubechies–6, Daubechies–8) are employed in order to study the effect of the choice of basis function on the analysis.

It is possible to estimate the relative contribution of the different coherent structure scales to the total variance of the signal using

$$p_m = \frac{\sum_{i=1}^{2^{M-m}} [2^{m/2} w^{(m)}(i)]^2}{\sum_{j=1}^{M} \sum_{k=1}^{2^{M-j}} [2^{m/2} w^{(j)}(k)]^2} \qquad m = 1, \cdots, M, \quad M = \log_2 N \tag{7}$$

where p_m is the normalized (i.e., sum of the squared wavelet coefficients at the given scale divided by the sum of the variances of all scales) energy content of the analyzed data. For the more distinct a turbulent structure is, the higher will be the value of the squared wavelet coefficient at the corresponding location and scale (Meneveau 1991; Wang et al. 1997). The scale with the largest positive value in the differences p_m corresponds to the principal time scale (2^m s) of the coherent structures in the turbulent flow. These differences are presented in Fig. 2 applying anti–symmetric wavelets for the three components of the large scale signal, which are the decomposition of atmospheric flow measurements over a rice field. The peak in each graph indicates the principal time scale of the coherent structures.

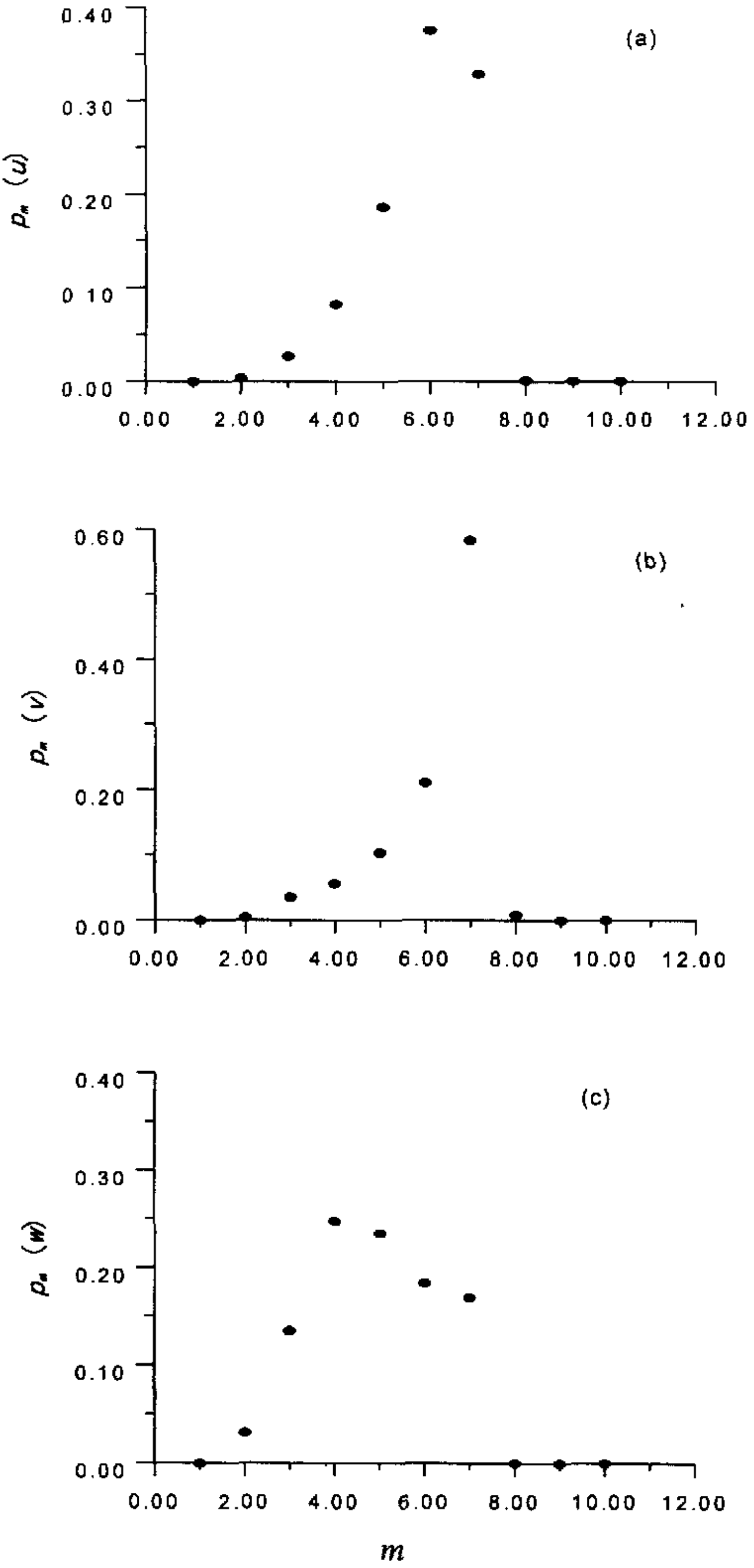

Fig. 2. Normalized variances (p_m) of the wavelet scales by anti–symmetric wavelets (the large scale signal filtered for analysis): (a) longitudinal velocity, (b) transverse velocity, (c) vertical velocity.

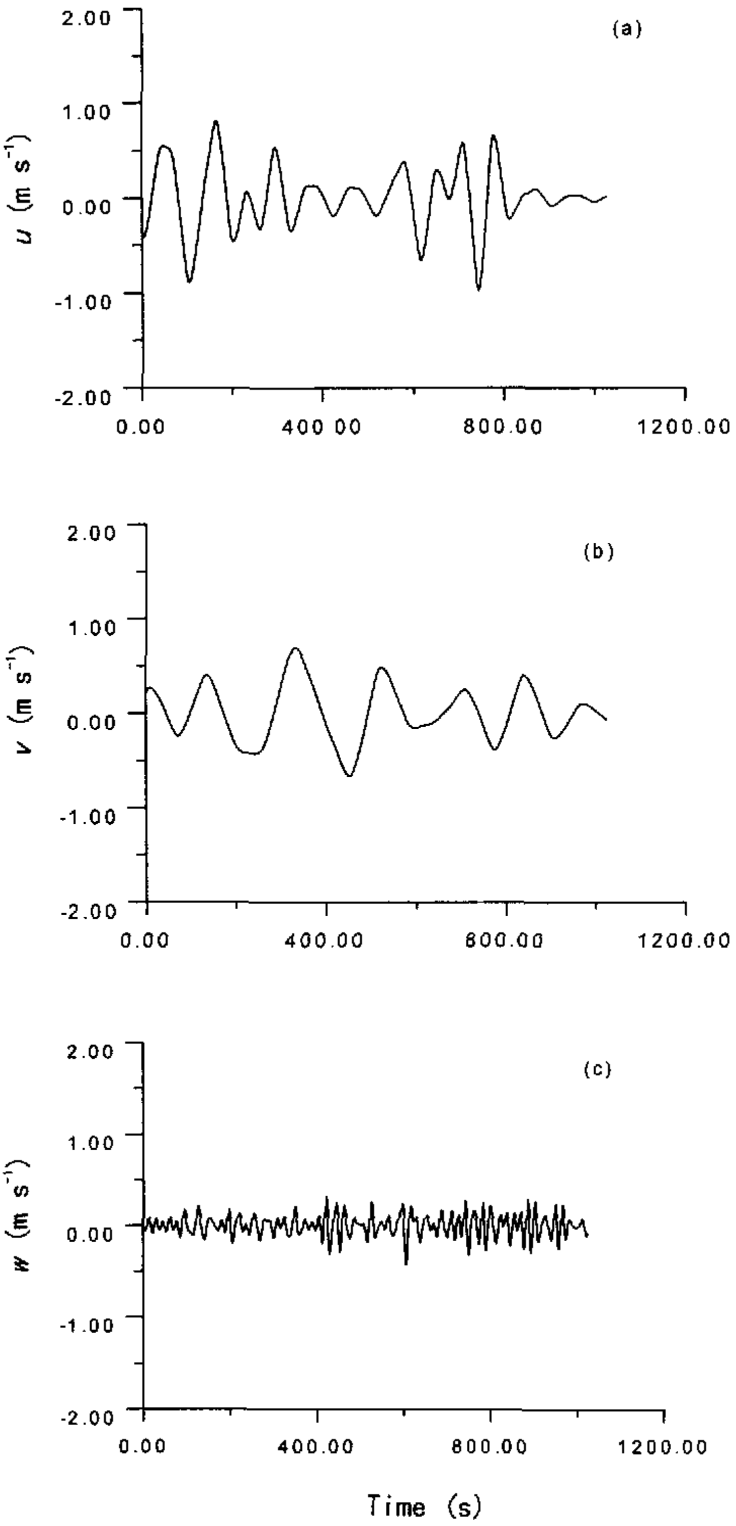

Fig. 3. The coherent structure extracted from the large vortex digital filtered: (a) longitudinal velocity, (b) transverse velocity, (c) vertical velocity.

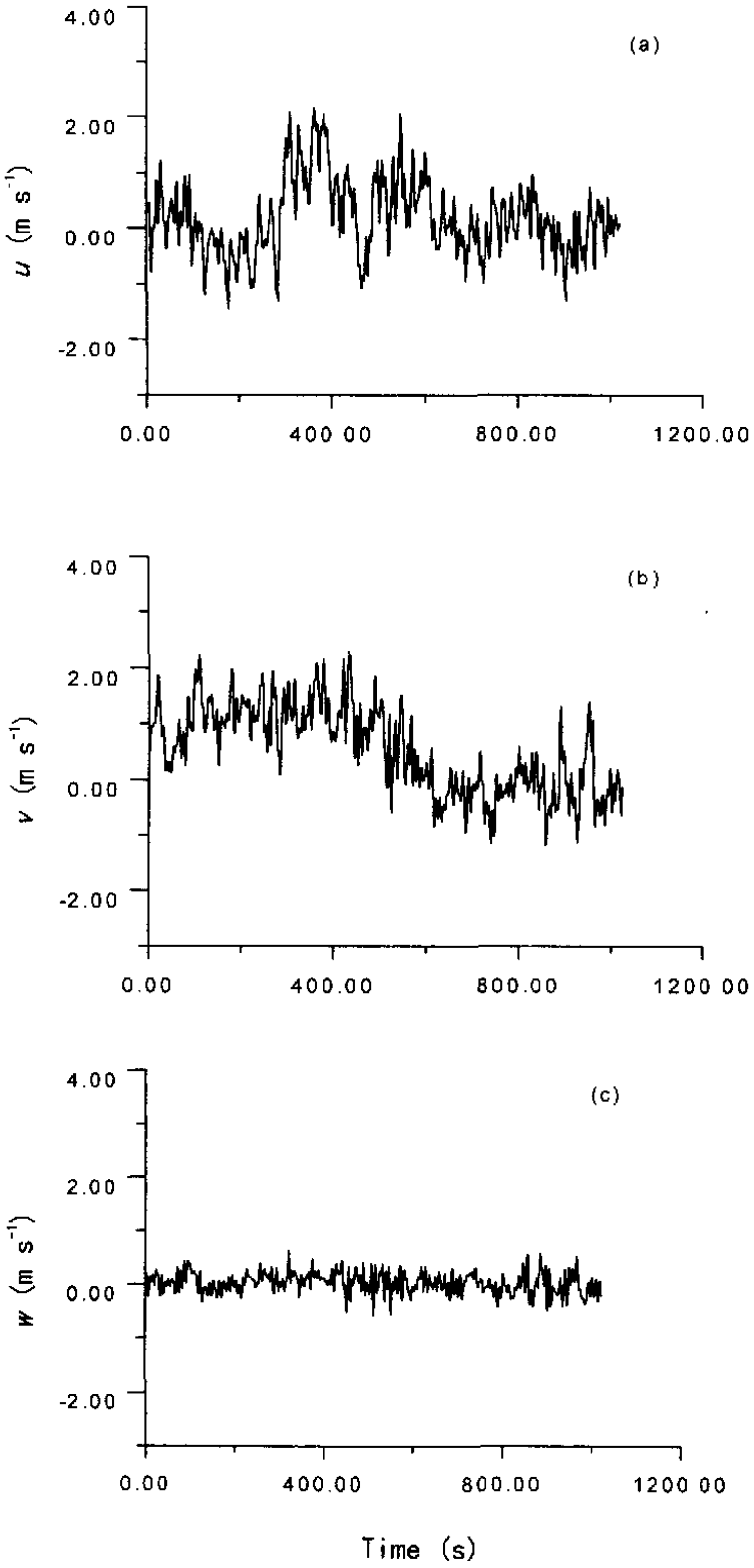

Fig. 4. The non–coherent structure signal: (a) longitudinal velocity, (b) transverse velocity, (c) vertical velocity.

Consequently, the coherent structure signal can be reconstructed from its wavelet coefficients using

$$f(m,j)=\sum_{i=1}^{N} w^{(m)}(i)g^{(m)}(i-2^{m}j) \tag{8}$$

For illustration, Fig. 3 and Fig. 4 show the signal of the coherent structure which was reconstructed with the inverse wavelet transform, and the signal of the non–coherent structure which was residual part after removing the coherent structure from the large scale signal for analysis, respectively.

The principal time scales of the coherent structure for three fluctuating velocity components of atmospheric flow for two different data sets can be seen in Table 1. Furthermore, the correlation between the coherent structure and the non–coherent structure was calculated to show the validity of the method based on orthonormal wavelet analysis, as shown in Table 2. According to the characteristics of coherent structure, its signal is irrelevant to the non–coherent structure signal.

Table 1. The time scales (s) corresponding maximum normalized energy

Local time \ Fluctuating velocity component	u	v	w
14:00, June 9, 1998	32	64	16
10:00, June 14, 1998	64	32	16

Table 2. The correlation between coherent structure and non–coherent structure singnal

Local time \ Fluctuating velocity component	$\overline{u_{co}u_{nco}}$ ($m^2\ s^{-2}$)	$\overline{v_{co}v_{nco}}$ ($m^2\ s^{-2}$)	$\overline{w_{co}w_{nco}}$ ($m^2\ s^{-2}$)
14:00, June 9, 1998	4.795×10^{-3}	1.167×10^{-2}	1.947×10^{-3}
10:00, June 14, 1998	2.031×10^{-2}	6.072×10^{-3}	6.762×10^{-3}

From Table 1, it can be found that the principal time scale of coherent structures for the vertical velocity fluctuation is around 16 s, and for the longitudinal and transverse velocity fluctuations are about 32– 64 s or so, which can also be seen in Fig. 2.

At the same time, 'the maximal value of the correlation between coherent and the non–coherent structure for different data sets is only 0.02 (see Table. 2). It can be proved that the method of using discrete wavelets for the identification of the time scale and profile of coherent structures for atmospheric flow is effective and credible.

4. Discussion and conclusions

4.1 *Discussion*

In the above method of identifying coherent structures, the signal for analysis is the large scale vortex extracted from the original turbulent signal with the use of the digital filter. It is

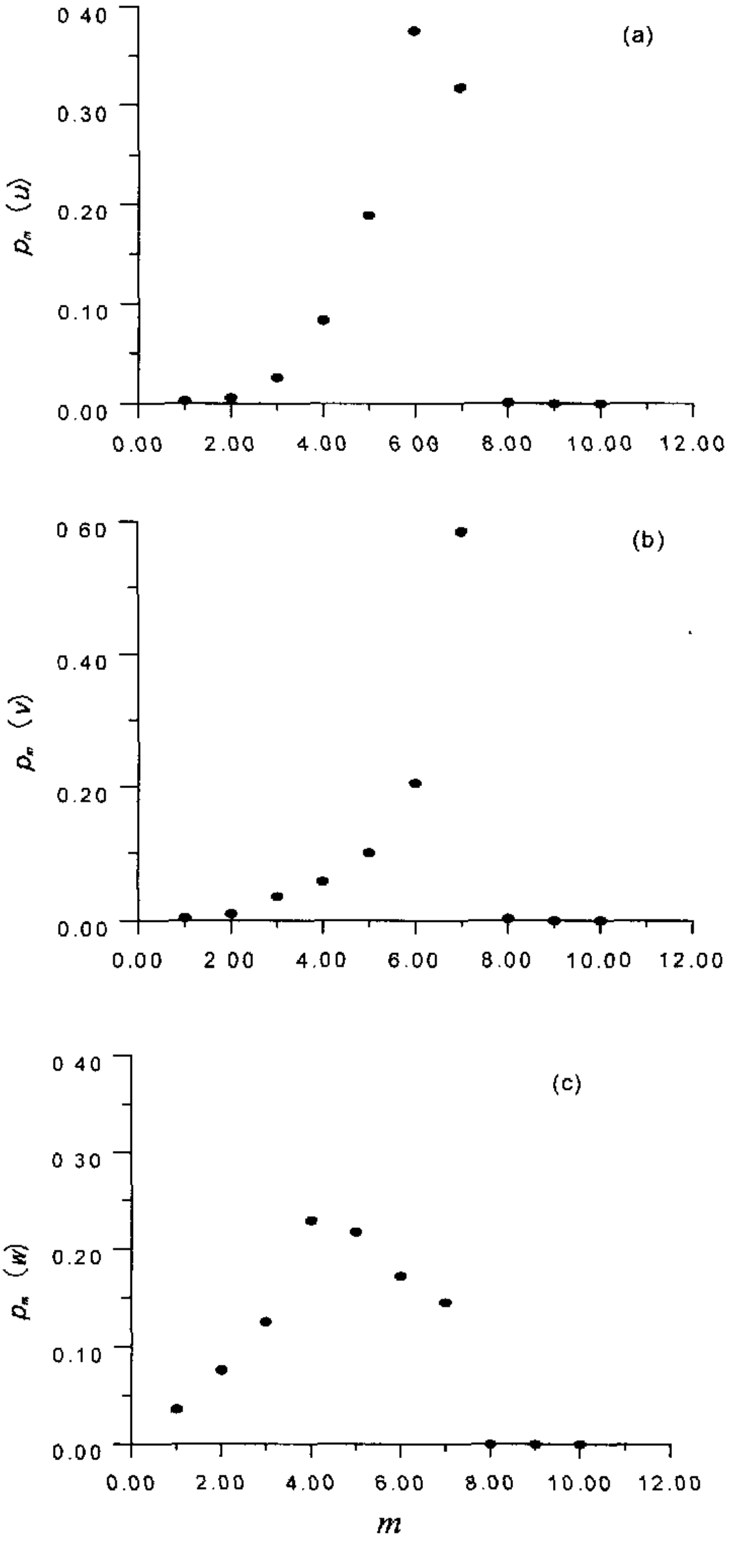

Fig. 5. Normalized variances (p_m) of the wavelet scales by anti-symmetric wavelets (the original turbulent signal): (a) longitudinal velocity, (b) transverse velocity, (c) vertical velocity.

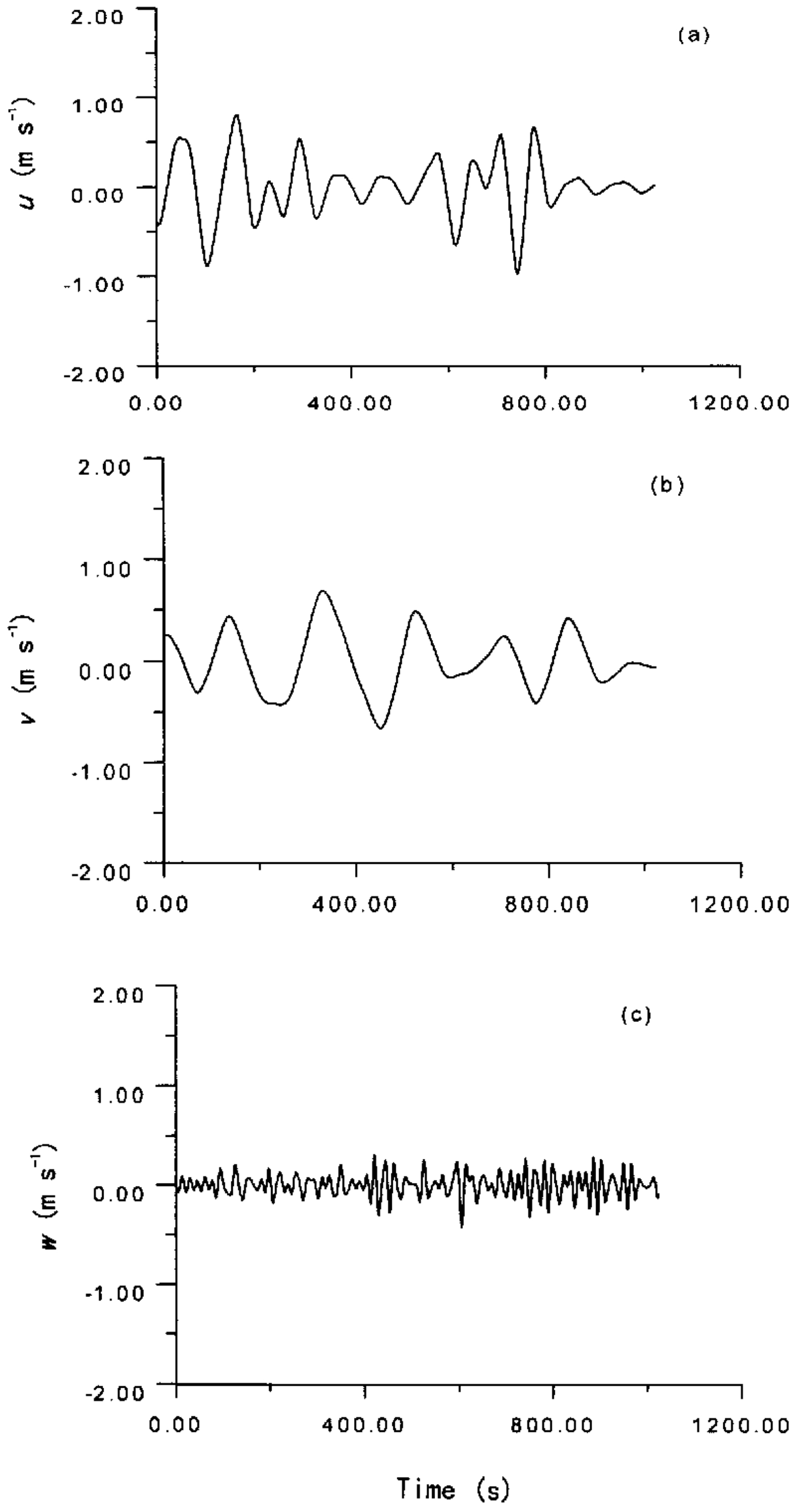

Fig. 6. The coherent structure extracted from the original turbulent signal: (a) longitudinal velocity, (b)transverse velocity, (c) vertical velocity.

natural to ask what results can be obtained if the original turbulent signal is used directly to identify coherent structures with wavelet analysis. Specifically, it is necessary to know whether the principal time scale of coherent structures for atmospheric turbulent flow will be the same as the above results which we obtained. Therefore, the same data sets which are the original turbulent signal, not filtered, were used to detect coherent structures in the turbulent flow. The differences p_m are the same as in Section 3 (see Fig. 5). The reconstructed profile of the coherent structure is shown in Fig. 6.

Comparing the results of the original turbulent signal with the large scale signal filtered for identifying the coherent structure, it was found that the principal time scale of coherent structures for the two kinds of signal was the same (see Fig. 2 and Fig. 5). The profiles of the two coherent structures were also similar (see Fig. 3 and Fig. 6).

4.2 *Conclusions*

The analysis described in the previous sections of the three velocity components of atmospheric flow over a rice field with the method based on discrete orthonormal wavelets reveals the following:

(1) The principal time scale of the coherent structures for the vertical velocity fluctuation was found to be around 16 s over rice fields, which is in agreement with the results of other authors under similar meteorological conditions (Jozef et al. 1999; Qiu et al. 1995).

(2) The principal time scales of the coherent structures for the longitudinal and transverse velocity fluctuations were found to be about 32–64 s.

(3) It was also found that the resulting principal time scales were only slightly dependent on the choice of the basis function within the same type. It was clarified that anti–symmetric wavelets are more sensitive in detecting zones of sharp transitions connected to coherent structures (Hagelberg and Gamage 1994).

(4) The application of wavelet analysis with the use of a large scale vortex signal extracted from the original turbulent signal with the digital filter or the use of the original turbulent signal is recommended for coherent structure principal time scale calculations. In so doing, the profile of the coherent structures for atmospheric flow can be obtained.

In summary, the method for detecting coherent structures of atmospheric turbulent signals as described in this paper is feasible and objective. Yet, further investigations must be done to apply the method to identify coherent structures of atmospheric boundary layer turbulence.

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大气边界层湍流相干结构的识别

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摘要

首先利用数字滤波方法对淮河流域试验的大气边界层湍流观测资料进行三项分解，将大气边界层湍流的风速信号分解为近似各项同性的小尺度涡和各向异性的大尺度涡。然后再将大尺度涡信号进行离散正交小波分解，寻找相干结构的主要特征尺度。对于大气边界层湍流垂直脉动风速来说，其相干结构的主要特征尺度为 16 s；对径向与纬向脉动风速来说，其相干结构的主要特征尺度为 32～64 s。在此基础上，利用小波的反变换提取出相干结构的信号与非相干结构的信号，并计算两者间的相关系数，最大仅有 0.02。此外，对原始大气湍流观测信号不进行数字滤波，直接利用本文中子波分析法提取湍流相干结构所得结果作比较研究；并探讨了采用对称或似对称离散正交小波对此研究的影响。

关键词：大气湍流，离散小波，相干结构，特征尺度