Continuous wavelet transform and discrete multi-resolution analysis of surface fluxes and atmospheric stability

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Received June 22, 2005

Abstract Variations of land surface fluxes of sensible heat $H$, latent heat $LE$ and CO$_2$-F-CO$_2$ obtained from the eddy-co-variance measurements above a winter wheat field from March 30 to April 24, 2001 have been studied at scales ranging from 10 minutes to days. Wavelet transform is used in the analysis of land surface fluxes and atmospheric stability $\xi$ calculated from the measurements to reveal the changes in land surface fluxes in hours to days scales. The main results are: (1) Concise and compact information about the fluxes of net radiation $R_n$, temperature $T$ and $\xi$ in the scale-time domain are extracted from the data by continuous wavelet analysis and 1 day [0.5 day and short-period] shorter than 0.5 day components are revealed. Continuous wavelet coefficients can be used to characterize periodic components of changes in fluxes and $\xi$ [2 day] Discrete-time multi-resolution analysis can be used to concentrate total energy variance of time series of the measurements to a small number of coefficients $\xi$ plotting the relative energy distribution to get several meaningful characteristics of the data. (2) Under neutral atmospheric conditions the relative energy distributions of the Haar multi-resolution analysis of the three non-dimensional coefficients $T^*$, $T^*$, $q^*$ and $c^*$ display clear similarities.

Keywords atmospheric stability flux, continuous wavelet transform, multi-resolution wavelet analysis.

Land surface fluxes are non-linear and non-stationary stochastic variables. A series of continuous records of fluxes often contain components with time scales from seconds to months. The analysis of the spectral properties of variations with time of $H$, $LE$ and $F$-CO$_2$ may help to reveal the causes of the changes in density and frequency of the fluxes. Many models developed to describe the interactions between the biosphere and atmosphere have become an essential part of simulations of regional or global climatic processes. This multi-scale nature of land surface fluxes is now simulated by some models using data of long-term over one or more years but periods shorter than a day do not appear in the results of such simulations.

Monin-Obukhov Similarity Theory is often taken as the basis of the analysis of meteorological data; the essence of which is to use dimensionless parameters to characterize micrometeorological processes. The scale parameters of various climatic factors are closely connected between themselves through the friction velocity $u^*$ and the atmospheric stability reflects the relative strengths of thermal convection and mechanical mixing. The sources of the changes leading to high-frequency information of fluxes of $H$, $LE$ and $F$-CO$_2$ can be traced to changes in values of the scale parameters and can be sought from the analysis of atmospheric stability.

Spectral and auto-correlation or cross-correlation analyses are often used in meteorological studies with some success. The traditional method used in spectral analysis in land surface fluxes is Fourier transform but it is only limited to the analysis of non-stationary signals. Wavelet analysis developed in the 1980s works in both a multi-resolution and a multi-scale way and windows with adjustable time and frequency are available which automatically becomes narrower in the high-frequency parts to provide high time resolution and becomes wider at lower-frequency parts to provide high frequency resolution. Wavelet analysis is more powerful than Fourier analysis in analyzing non-stationary signals and is therefore widely used in many research fields. Two types of wavelet transform have been developed: continuous wavelet analysis i.e. CWT and discrete wavelet analysis DWT. For details of the mathematical procedures of wavelet analysis see Refs. 6, 25.

* Supported by the State Major Basic Research and Development Program of China Grant No. G1999-11708
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The aim of this study was to use wavelet transform in the analysis of land surface fluxes H, LE and F-CO₂ and atmospheric stability to reveal the changes in land surface fluxes at scales from hours to days which may serve as the basis of building up models for microclimate of a particular locality which are more accurate and closer to reality.

1 Site description and experiment

Meteorological measurements were taken in the unirrigated winter wheat field No. 5 at Zhaquanying Shunyi County Beijing from March 30 to April 24 2001 when wheat was turning green. The site was located in a farming area 39°56'N 116°17'E 54 m above sea level of the North China Plain which is a large flat plain with moderate monsoon climate. The field in which measurements were performed was an area of 800 m × 1000 m and the fetch was more than 500 m for winds from all directions. During the period of measurement the leaf area index LA and the height of wheat canopy were 3.0 and 0.1 m respectively.

The items of the observation were 1 microclimatic variables solar radiation net radiation at a reference height of 1 m air temperature relative humidity and wind speed at three heights 0.9 1.77 and 3.37 m 2 mass fluxes of CO₂ and water vapor between winter wheat field and the atmosphere measured by eddy covariance method.

The eddy-covariance measuring system comprised of a CO₂ H₂O infrared gas analyzer Li-7500 LI-COR USA sampling frequency = 20 Hz a triaxial sonic anemometer DA600 KAIJO Japan set at a height of 2 m above the ground surface. The data of all these variables were sampled every 15 s by a Data Taker and the average values were calculated and recorded every 10 min using the procedures described in Refs. 23—26.

2 Results and discussion

When examining the spectral properties of fluxes it is helpful to consider three basic time scales fractions of seconds to minutes turbulent time scales hours to days meteorological time scales and months to years seasonal time scales. At the hour-to-days time scales the interaction between the physiological and biophysical processes of the canopy and its microclimate were the main sources of fluxes variability. The analysis was therefore focused on these time scales to find the relationship between fluxes and atmospheric stability.

2.1 Data description

Time series of the variables measured from 6 April 16 to 8 April 24 a total of 1024 sets of data of each measurement are shown in Fig. 1. From Fig. 1 it can be seen that temperature and the three fluxes have diurnal changes closely related with that of solar irradiation. The time curves of temperature has the components with periods longer than 24 h. The time courses of the fluxes of the three physical entities have a strong pulsation superimposed on the diurnal changes. H and LE changed violently near noon Fig. 1 b and Fig. 1 e and F-CO₂ curves show violent random fluctuations Fig. 1 f.

Atmospheric stability Fig. 1 g was calculated from eddy-covariance measurements where ζ is calculated as -L z is height and L is the Monin-Obukhov length. Three non-dimensional coefficients T × T × q and c × have also been calculated from the measurements where T × q and c are temperature water vapor pressure and CO₂ concentration.
respectively. And \( T^* = \frac{H}{\rho C_p u_\ast} \) \( R^* \), \( q^* = -\frac{L E}{u_\ast} \) \( R^* \), and \( c^* = -\frac{F}{u_\ast} \) \( R^* \) are temperature scale, water vapor pressure scale and \( \text{CO}_2 \) concentration scale respectively, where \( u_\ast \) is the friction velocity, \( \rho \) is air density, and \( C_p \) is the specific heat capacity of air under constant pressure.

2.2 Application of continuous wavelet transform to the data

The continuous wavelet analysis method was applied to the analysis of the fluxes of three physical entities and atmospheric stability. In all figures which depict continuous wavelet spectra the basic units are 10 min for time X-axis and day for period Y-axis and the lighter the gray scales the larger the value of the wavelet coefficient.

2.2.1 Morlet wavelet analysis

Morlet wavelet analysis was applied to the fluxes of sensible heat \( H \), latent heat \( LE \) and \( \text{CO}_2 \) net radiation \( R_n \), temperature \( T \) and atmospheric stability \( \xi \) in the period from April 16 to 23, 2001.

Fig. 2 shows the continuous wavelet transforms of the fluxes of the three physical entities \( R_n \), \( T \) and \( \xi \). The wavelet transforms of these fluxes have bands of energy concentration with 1 day and 0.5 day periods. Fig. 2(a) \( H \) and \( LE \) showed bands of energy concentration with periods of 1.5—2 days. Fig. 2(b) \( F \) and \( \text{CO}_2 \) showed no energy concentration in these ranges of periods. There were also longer periods. Thus \( H \) and \( \text{CO}_2 \) had each a period near 5 days. Fig. 2(c) \( R_n \) and \( \xi \) had a period of about 4 days. Fig. 2(d) \( R_n \) and \( \xi \) show the wavelet transforms of \( R_n \) \( T \) and \( \xi \). There are bright bands of 1 day and 0.5 day of \( R_n \) and \( \xi \) and also bright band of 1 day of \( T \) but the 0.5 day band is quite weak and the strongest ones are those with 5 day period Fig. 2(d) \( \xi \). When scrutinizing the parts with periods shorter than 1 day, one can see an uneven distribution of periods from 0.5 h to 6 h with quite low energy levels. And all these periods appeared in time intervals with violent fluctuations of fluxes.

2.2.2 Averaging wavelet spectra

The wavelet spectrum of a time series can be defined as the modulus of its wavelet coefficient. The wavelet transforms of the six variables were statistically analyzed and the global wavelet spectra and averages across scales of wavelet spectra are shown in Fig. 3.

The periodic characteristics of the wavelet transforms are seen more clearly in the global wavelet spectra Fig. 3(a) \( H \) and \( LE \) but the high-frequency details with a lower energy content were evened out and could no longer be seen. The diagrams of scalar...
transform show the components of periods of different lengths and the general trends of variations of them with time and each of them had fluctuations with periods of 2.5–3 days. This might be the characteristic of the atmospheric movements in the season when the measurements were carried out.

2.3 Application of multi-resolution to the data

Multi-resolution analysis using Haar wavelets was performed on data measured in the same period 1024 = 2^10 data to visualize the energy amplitude distribution across the scales and to compare it with energy distribution of Fourier spectrum.

2.3.1 Time-scale distribution of Haar multi-resolution wavelet spectra

The temporal distribution of the Haar multi-resolution wavelet energy was analyzed in terms of time scales for the fluxes of sensible heat \( H \), latent heat \( LE \), and \( F-CO_2 \) and atmospheric stability \( \theta \) see Figs. 4 and 5.

It is clear that the energy is not regularly distributed across the scales. At the top levels of the decomposition larger fluctuations in the signal yield high Haar coefficients as that occurred at the first four levels from the 6th to 9th in Figs. 4 and 5. It can also be seen that the time distribution of energy is

![Graphs showing multi-resolution wavelet analysis](image)

Fig. 4. Haar multi-resolution scale-energy repartition showing the persistence of fluctuations at different scale levels.
2.3.2 Haar wavelet spectrum analysis The percentages of relative energy accumulated at different levels of resolution of the data and the energy distribution plot are presented in Fig. 6 which shows the energy distribution corresponding to the signals in Figs. 4 and 5.

The differences between the energy distributions of the fluxes and atmospheric stability can be seen clearly in Fig. 6. For sensible heat, latent heat and CO₂ fluxes, the energy is concentrated in the range of $j = 5\text{–}6$ and $7\text{–}8$ but the energy for atmospheric stability is concentrated at $j = 1\text{–}2$ and 3.

2.4 Energy distribution of Haar multi-resolution wavelet spectra under different atmospheric conditions

To analyze the relationship between atmospheric stability and fluxes, the continuous Haar multi-resolution wavelet analysis was applied to the data under different atmospheric conditions. The values of the time series of $\zeta$ can be decomposed into neutral, unstable and stable components according to their magnitudes. Correspondingly, the three fluxes $H$, $LE$ and $F$-CO₂ and three non-dimensional coefficients $T^*$, $q^*$ and $c^*$ were also decomposed into different components.
Haar multi-resolution analysis was applied to decompose these measurements and non-dimensional coefficients under different conditions. Then the energy distributions of the Haar multi-resolution of these measurements and non-dimensional coefficients showed very similar spectral properties of the three non-dimensional coefficients under neutral conditions but under the other conditions the spectral properties of these non-dimensional coefficients showed a remarkable difference.

3 Conclusions

Wavelet transform was shown to be a useful tool in analyzing changes in land surface fluxes and micrometeorological variables in this study of wheat field. Components with periods 1 day and 5 day were shown to be the main ones for those of fluxes of sensible heat latent heat and CO₂ net radiation and atmospheric stability while those of 1 day and 0.5 day were those main ones for temperature. There were many short periods from 0.5 to 6 h in the fluxes and atmospheric stability but not in net radiation and temperature. There were some differences in components longer than 1 day between different fluxes Fig. 2 a, b, c and d. Such information was seen in the wavelet coefficients averaged over time and scale Fig. 3. Haar discrete multi-resolution analysis concentrated total energy variances of the signals to a few coefficients Figs. 4 and 5. The plot of the relative energy distribution displays different characteristics of the data Fig. 6. Under different atmospheric conditions, it is remarkable that relative energy variances of the three non-dimensional parameters $T, T^*, q^*$ and $c^*$ under neutral conditions had similar distributions while the similarities between them under other atmospheric conditions were less pronounced.

Radiation saturation deficit and the CO₂ concentration differences between intercellular space and the atmosphere are the driving forces of the fluxes of sensible and latent heat and CO₂ but atmospheric conditions and physiological status of the plants also affect the fluxes. Thermal factors and turbulence are affecting exchanges of mass and energy and atmospheric stability is an index of the interactions between these factors. There were rich high-frequency components in fluxes and atmospheric stability Fig. 4 c, d and e. It can be seen that there were some short-period fluctuations near noon Figs. 4 and 5 which reflects the importance of thermal factors in causing such fluctuations. On the other hand the correlation between the changes in fluxes and atmospheric stability of longer periods $>1$ day is not high.

References