

Comparative analysis of temperature and CO₂ fluxes for winter wheat in Tibetan Plain and North China Plain using the EMD method*

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Abstract Comparative study of spectral properties of temperature and CO₂ fluxes measured by eddy covariance method at Yucheng (36°57'N, 116°36'E, 28 m a. s. l., in the North China Plain) and at Lhasa (29°41'N, 91°20'E, 3688 m a. s. l., on the Tibetan Plateau) is described using the empirical mode decomposition (EMD) method. The main results are: (1) The intrinsic oscillation modes or intrinsic mode functions (IMFs) were extracted from data of temperature (T) and CO₂ fluxes (F) measured at Yucheng (T_1 and F_1) and Lhasa (T_2 and F_2). (2) Hilbert transform was applied to these IMF components, then the Hilbert-Huang spectra and the marginal spectra of these data were obtained. (3) Comparison of temperature and CO₂ fluxes in North China Plain and on Tibetan Plain illustrated that the characteristic frequencies corresponding to T_1 , F_1 , T_2 and F_2 are 0.05 Hz, 0.03 Hz, 0.014 Hz and 0.005 Hz, respectively.

Keywords: empirical mode decomposition (EMD), intrinsic mode function (IMF), flux, Hilbert transform, wheat, Tibet.

Microclimatic variables like temperature and CO₂ flux are non-linear and non-stationary stochastic variables^[1,2]. A series of continuous records of these variables often contain components with time scales from seconds to months^[3,4]. Changes in temperature and flux density are the results of variations of microclimatic factors and characteristics of plants, caused by interactions between atmospheric movements and physiological processes of vegetation^[5,6]. The analysis of spectral properties of variations with time series of microclimatic variables may help to reveal the causes of the changes in density and frequency of the variables^[7-9]. Many models developed to describe the interactions between the biosphere and atmosphere have become essential parts of simulations of regional or global climatic processes^[10-12]. This multi-scale nature of microclimatic variables is now being simulated by some models using data of long-term (over one or more years) measurement^[13], but periods shorter than a day do not appear in the results of such simulations^[14].

Spectral and auto-correlation or cross-correlation

analyse are often used in meteorology^[15,16] with some success. The traditional method used in spectral analysis is Fourier transform, which has been used successfully in the analysis of time series of land surface fluxes.^[17] However, as has been pointed out by some authors^[18,19], Fourier transform finds only limited use in the analysis of non-stationary signals, which has many components of different frequencies. To extract information from such signals, it is desirable to use windows with different temporal characteristics so that both high-frequency information with high precision and wholesome low-frequency information can be obtained^[20]. Signal decomposition can be implemented in many ways, for instance, by some set of appropriate eigenfunctions^[21,22]. Recently, the wavelet eigenfunctions set has been of much use because it decomposes a signal into a convenient set of levels of resolution^[23-25]. Unfortunately, in the case of non-stationary or non-linear signals, a large number of terms are needed for convergence which results in undesired spread of the signal energy among the various expansion modes^[25]. To avoid this shortcoming, empirical mode decomposition (EMD) method has been devel-

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oped to analyze the non-stationary or non-linear signals^[22,26]. The EMD method is included in the so-called Hilbert-Huang technique based on the direct extraction of the energy associated with the intrinsic time scales in the signal^[22,26]. This process generates a set of components, called the intrinsic mode functions (IMF).

Tibetan Plateau is the highest plateau on the earth, which covers 1.2 million km² of area with an average height of more than 4000 m above sea level^[27]. Because of its high altitude, it has the highest solar radiation (total radiation between 6704—7500 MJ·m⁻²·a⁻¹) and lowest CO₂ partial pressure of all crop-growing regions on the Earth. It has been observed that global solar radiation even exceeded the solar constant on the plateau if the sky is clear and accompanied by some low clouds^[28]. As solar radiation is the energy and CO₂ is one of the chief materials for photosynthesis, these influences on photosynthesis result in the fact that the productivity of vegetation is very different from that on low plains.

The aim of this study was to compare the spectral properties of temperature and CO₂ fluxes measured on Tibetan Plateau and in North China Plain using EMD method and Hilbert-Huang transform. Comparative analysis was adopted to reveal the changes in temperature and CO₂ fluxes measured in different areas on time scales from seconds to minutes, which may serve as the basis of building up models for microclimate of a particular locality and be more accurate and closer to reality.

1 Site description and experiment

Eddy covariance and meteorological measurements for winter wheat were carried out in 1994 at Lhasa Agricultural Experiment Station, Chinese Academy of Sciences (29°41'N, 91°20'E, 3688 m a. s. l.), on the Tibetan Plateau from June 10 to 30 under the extreme conditions of the highest solar radiation and lowest CO₂ partial pressure on the Earth. Similar measurements were also carried out in a low plain at Yucheng Agricultural Experiment Station, Chinese Academy of Sciences (36°57'N, 116°36'E, 28 m a. s. l.) in the North China Plain in 2002 from November 10 to 30. Yucheng belongs to the semi-arid temperate plateau climate zone. The fields in which measurements were performed occupied an area of 800 m × 1000 m and the fetch was more than 500 m for winds from all directions. During the period of mea-

surements, the leaf area index (LAI) and the height of wheat canopy were 3.0 and 0.1 m, respectively.

The contents of observation include (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 a CO₂/H₂O infrared gas analyzer (Li-7500, LI-COR, USA, the sampling frequency is 20 Hz), and a triaxial sonic anemometer (DA600, KAIJO, Japan) set at a height of 2 m above the ground surface. A data taker sampled the data of all these variables every 20 Hz (Lhasa) and 10 Hz (Yucheng). These original data were then averaged every 1 s using the procedures described by Katul et al.^[29–31].

2 Results and discussion

When examining the spectral properties of meteorological variables, it is helpful to consider three basic time scales: seconds to minutes (turbulent time scales), hours to days (meteorological time scales), and months to years (seasonal time scales)^[9]. On the seconds to minutes time scales, the interactions between the physiological and biophysical processes of the canopy and its microclimate were driven mainly by atmospheric turbulence. The analysis is therefore focused on turbulent time scales, to compare the spectral properties of temperature and CO₂ fluxes measured in the North China Plain and Tibetan Plateau.

2.1 Data description

Eddy covariance measurements were carried out in the fields of winter wheat in 1994 at Lhasa on the Tibetan Plateau, and in 2002 at Yucheng in the North China Plain. Time series of the 1s-averaged temperature and CO₂ flux measured from 11:00 to 12:00 on June 15, 1994 at Lhasa and on November 17, 2002 at Yucheng (a total of 3600 sets of data of each measurement) are shown in Fig. 1. The temperature (T_1) and CO₂ flux (F_1) measured at Yucheng are shown in Figs. 1(a) and (b), and the corresponding T_2 and F_2 measured at Lhasa are shown in Figs. 1(c) and (d). The time series of the four measurements are non-linear and non-stationary stochastic variables. There are rich pulsations superimposed on

these measurements.

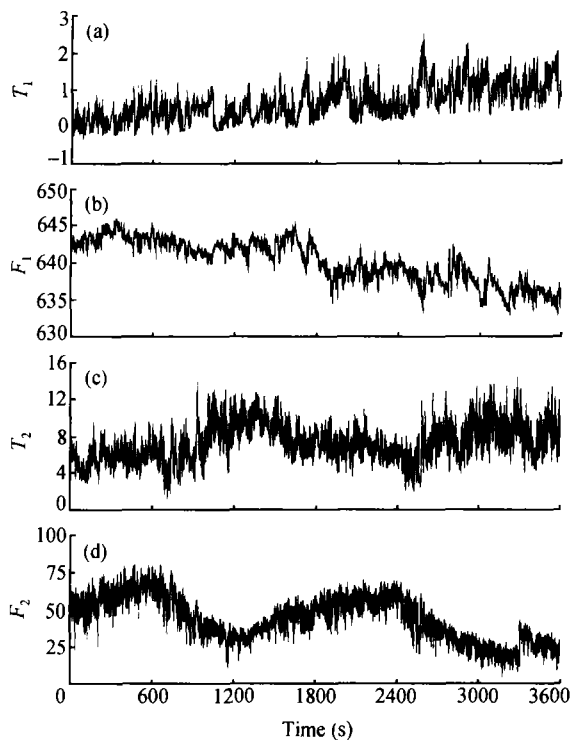


Fig. 1. Time series of temperature and CO₂ fluxes measured by eddy-covariance at 2 m above the ground surface at Yucheng and Lhasa (sampling frequency, $f_e = 1$ Hz). (a) Temperature measured at Yucheng (T_1); (b) CO₂ flux measured at Yucheng (F_1); (c) temperature measured at Lhasa (T_2); (d) CO₂ flux measured at Lhasa (F_2).

2.2 Application of empirical mode decomposition (EMD) to the extraction of the intrinsic mode functions (IMFs)

The intrinsic mode function (IMF) $c_i(t)$ represents the oscillation mode embedded in the data of temperature and CO₂ fluxes measured at Yucheng and Lhasa. Therefore, the decomposition of these time series expressed as IMFs will have two advantages. The first one is that it will allow us to examine the physical meaning of each IMF component. The second one is that the residual will contain the data trend, and in this way we can perform the analysis even if the data are not stationary.

The EMD method was applied to the analyses of the temperature and CO₂ fluxes shown in Fig. 1. There were a total of eleven IMFs components decomposed from the time series of T_1 , F_1 and F_2 , but the decomposition of the time series of T_2 gave a total of twelve IMFs components. The first four IMFs components c_1 to c_4 are probably associated with

noise. c_5 to c_8 , or c_9 components represent the main oscillation mode of the four measurements. The other components or low frequency components are related chiefly to the trend of the data.

2.3 Hilbert-Huang spectrum

Since the Hilbert-Huang transform defines the instantaneous frequency of each IMF, the transform was applied to the IMF matrix of the four measurements of T_1 , F_1 , T_2 and F_2 . Then, the instantaneous frequency (IF), the average instantaneous frequency (AIF) and marginal Hilbert spectra could be calculated.

2.3.1 The Hilbert-Huang spectra of the data measured at Yucheng and Lhasa Fig. 2 shows the low-frequency domains (lower than 0.2 Hz) of the Hilbert-Huang spectra of T_1 (a), F_1 (b), T_2 (c) and F_2 (d). In all these figures displaying Hilbert-Huang spectra, the basic units are 1 s for time (X-axis) and 1 Hz for frequency (Y-axis), and the lighter the gray scales, the larger the values of the Hilbert-Huang transform coefficient. In the Hilbert-Huang spectra of the four measurements, most of the signal energy along the time axis accumulates from 0.03 Hz to 0.01 Hz and from 0.015 Hz to 0.005 Hz for T_1 (a), from 0.02 Hz to 0.01 Hz and from 0.015 Hz to 0.004 Hz for F_1 (b), from 0.015 to 0.01 Hz and from 0.008 to 0.003 Hz for T_2 (c) and from 0.025 to 0.015 Hz and lower than 0.005 Hz for F_2 (d), respectively. There are almost no energy concentrations in the domains lower than 0.005 Hz of the Hilbert-Huang spectra of the data measured at Yucheng, but the domains concentrate most of the energy of the Hilbert-Huang spectra of the data measured at Lhasa on the Tibetan Plateau.

From the Hilbert-Huang transform, the average instantaneous frequency (AIF) of each IMF component of the four measurements was calculated. The AIFs of each IMF component of T_1 , F_1 , T_2 and F_2 are shown in Fig. 3. Almost each AIF of the IMF components T_2 and F_2 is slightly larger than these of T_1 and F_1 .

2.3.2 The marginal frequency spectra of the data measured at Yucheng and Lhasa With the help of the sifting algorithm explained in Ref. [22], the marginal frequency spectra $h(\omega)$ can be deduced from the Hilbert-Huang spectra of the four measurements. Fig. 4 displays the marginal frequency spectra

of T_1 (a), F_1 (b), T_2 (c) and F_2 (d). These marginal frequency spectra display very similar spectral properties to the Fourier spectra of these mea-

surements, and the slopes of the spectra of T_1 , F_1 and T_2 are nearly $-4/3$, but the slope of the spectrum of F_2 is nearly -1 .

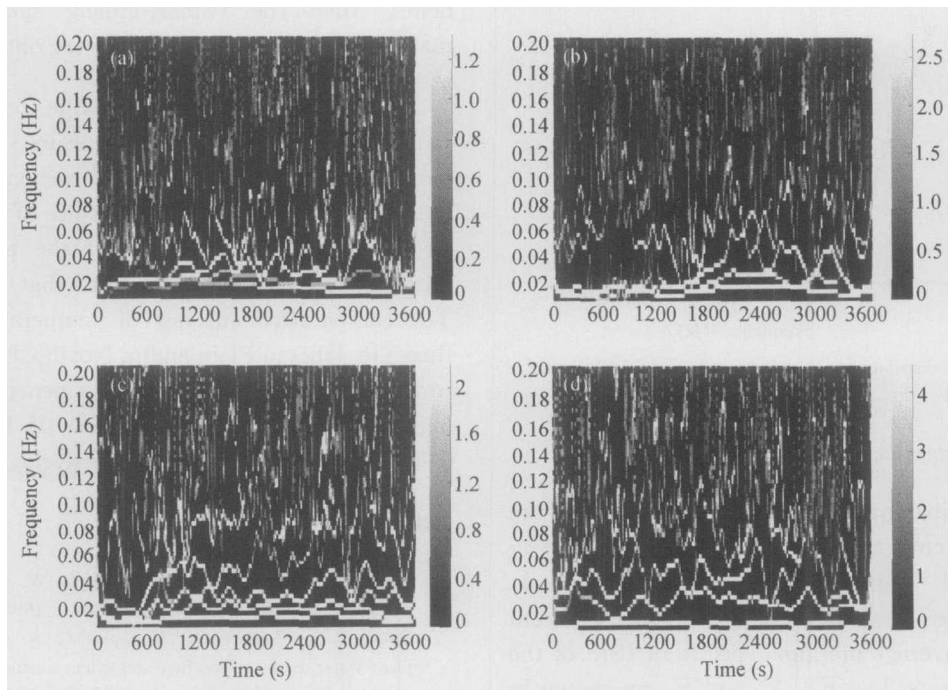


Fig. 2. Lower frequency domain (lower than 0.2 Hz) of Hilbert-Huang spectra $H(\omega, t)$ of T_1 (a), F_1 (b), T_2 (c) and F_2 (d).

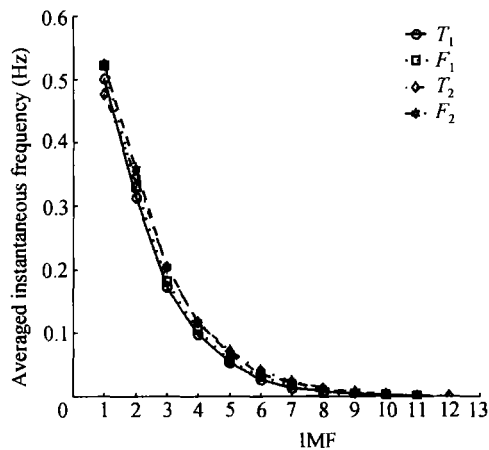


Fig. 3. The averaged instantaneous frequency (AIF) for IMFs of T_1 , F_1 , T_2 and F_2 .

The percentages of relative energy accumulated at different frequency levels of resolution of the four measurements are presented in Fig. 5, which shows the energy distribution corresponding to the Hilbert-

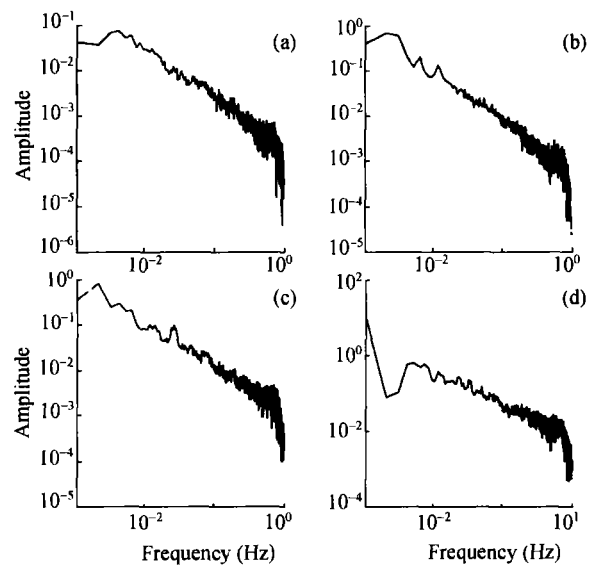


Fig. 4. The marginal spectra $h(\omega)$ of T_1 (a), F_1 (b), T_2 (c) and F_2 (d).

Huang spectra in Fig. 2. In Fig. 5, more than 60% of the energy (or amplitude) of the spectra of the four measurements are concentrated in the lowest frequency domain.

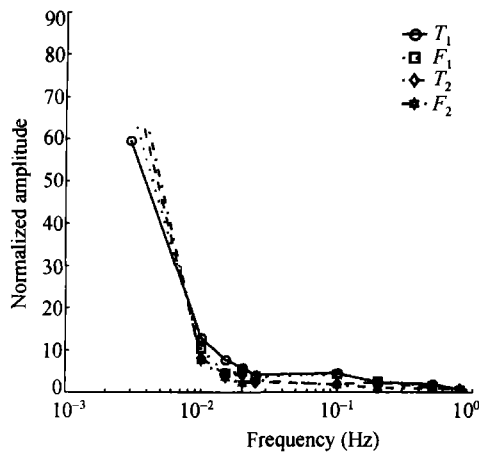


Fig. 5. Energy distribution plot corresponding to the marginal spectra $h(\omega)$ of T_1 , F_1 , T_2 and F_2 .

2.4 The average local marginal spectra analysis

After the instantaneous frequencies of IMFs are computed, the characteristic frequencies located at c_i can be obtained. The local marginal spectra $h'(\omega)_i$ can be obtained from the Hilbert-Huang spectrum analysis. The average marginal spectra of IMF of the four measurements T_1 , F_1 , T_2 and F_2 are shown in Fig. 6. The average marginal spectra illustrate clearly the characteristic frequencies corresponding to c_8 (0.05 Hz) for T_1 , c_9 for F_1 (0.03 Hz), c_{11} for T_2 (0.014 Hz), and c_{11} for F_2 (0.005 Hz).

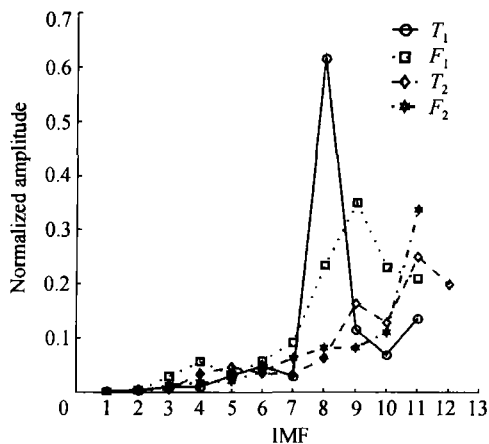


Fig. 6. Average marginal spectra of T_1 , F_1 , T_2 and F_2 .

3 Conclusions

The EMD method has been shown to be a useful tool to analyze changes in micrometeorological variables in this study. The intrinsic oscillation modes or intrinsic mode functions (IMFs) were extracted from the data of temperature and CO_2 fluxes measured at Yucheng and Lhasa. The IMFs corresponding to low

frequency (lower than 0.02 Hz) components were shown to be the main components for those variables. Hilbert transform was applied to these IMF components, then the Hilbert-Huang spectra and the marginal spectra of these data were obtained.

The climate in Tibet is unique for its high solar radiation and low CO_2 partial pressure. As solar radiation and CO_2 supply energy and carbon for photosynthesis, respectively, the importance of their influence on photosynthesis and thereby the productivity of vegetation is very different from that in low plains. The comparative analysis of temperature and CO_2 fluxes in Tibetan Plain and in North China Plain illustrated that the characteristic frequencies corresponding to T_1 , F_1 , T_2 and F_2 are 0.05 Hz, 0.03 Hz, 0.014 Hz and 0.005 Hz, respectively.

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