A study of turbulent signals measured above Amazon Forest and pasture using wavelet transform

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ABSTRACT

Wavelet Transform (WT) is a new and powerful tool for the analysis of nonhomogeneous or non stationary signals. It permits an evolutionary spectral decomposition of the signal, which was almost impossible to be got with the traditional Fourier signal decomposition. In this study a WT is applied to analyze wind speed signals measured at a frequency of 21 Hz above the Amazon Forest and Pasture. Surface boundary layer measurements are analyzed. The results show the essentially nonhomogeneous behavior of the turbulent fields above those vegetation covers, which appear to be organized in extremely localized structures.

Keywords: turbulence, wavelet transform, Amazon Forest.

2. INTRODUCTION

This study will investigate the characteristics of the turbulent field variability above the Amazon Forest (AMF) and deforested zones. This kind of research is important for several reasons. The AMF has a very important role on: a) the distribution of the solar energy, incident on the earth surface, in water vapor and sensible heat fluxes, which diffuse in the atmosphere and are transported to the regions of high latitude, influence the planet climate. b) on the absorption of momentum of the air flux by the forest canopy roughness. c) on both, absorption and emission, of trace gases (methane, ozone, CO_2, etc) by the forest that affect the radiation budget of the terrestrial atmosphere.

Also, replacing forest by pasture changes the interaction between soil, vegetation and atmosphere. If large areas are deforested it can be expected changes in surface energy budget.

It is known that the process of interaction between the land surface and the atmosphere has a turbulent nature. Therefore, it is necessary to understand better the structure of this kind of process, to improve the estimation of momentum and energy fluxes interchanged between vegetation and atmosphere.

Historically, the first studies of atmospheric turbulent exchanges tried to estimate temporal averages of the physical quantities involved[1], such as vertical fluxes on the surface boundary layer. These investigations assume the turbulent field is horizontally homogeneous and stationary in time. Turbulent spectra is estimated as if it was uniform[2].

However, advances in the studies of turbulence with new experimental techniques have shown that it is heterogeneous in the horizontal direction and it is not stationary in time[3,4,5,6]. To this contribute the coherent structures frequently found in turbulent flows that seem to have a crucial role in turbulent exchange near the surface boundaries. Hussain[7] in his extensive review about coherent structures comments "there is yet no consensus in what is meant by coherent structures". However, the need to measure coherent structures and assess their dynamical significance motivated him to construct a definition of coherent structures. According to him, a coherent structure is a connected turbulent fluid with instantaneously phase-correlated vorticity over its spatial extent. As a result of this definition, the turbulent shears flow could be decomposed into coherent structures and incoherent turbulence. The interaction between coherent structures and incoherent turbulence is the most critical and least understood aspect of turbulent shear flows. This coupling appears to be different from the classical notion of cascade, even considering the large and fine scales. They are not decoupled as widely presumed. Monin[8] investigated this problem from thermodynamic point of view. For him, the presence of coherent structures is an indication of thermodynamic non-equilibrium. This could imply that the spectra of the system is a non-uniform function of space.

The appearance of organized structures in the atmospheric boundary layer turbulence[9] and in the canopy region[10,11] has been well documented. In the canopy region such structures seem to result from the large shear created by the presence of the forest dossel in the flow.

The confirmation of the intermittent character in turbulent fields led the researchers to look for other analysis instruments not globally statistical. The classical example of the latter is the Fourier Analysis. Some important alternative of analysis are[12]: a) **Conditional Sampling Methods**: Shaw and Businger[5] for the Near-Neutral Marine Atmospheric Surface Layer; Bergström and Högström[11] for forest flow; b) **Quadrant Analysis Method**: Bergström and Högström[11] for the air flow over different vegetation canopies; c) **VITA (Variable-Interval Time-Averaging method)** used by Schols[4] in the atmospheric surface layer; d) **Eigenvector Decomposition Method** used by Sirovich[13] and Mahrt and Frank[14].

To overcome the problem in the failure of the Fourier Analysis to show the characteristics of transient signals a local transform was recently developed. This new transform is able to detect isolated events and preserve information about their occurrence in time, and features. It is called Wavelet Transform (WT)[15,16,17]. It is a time-frequency representation of signals using specific wavelet functions.

Beginning in this decade the WT had been used with success to decompose and study the turbulent atmospheric signal. This can be used in isolation[18,19,12,20] or in conjunction with other techniques for signal analysis[21,22,23]. Most of these studies tried to characterize the nature of structures of the flow with the help of the WT. However, it is not of our knowledge any use of the **Complex Morlet Wavelet** to characterize the outflow above the forest in general, or above the Amazon Forest in particular. This technique will be used in the present paper.

3. EXPERIMENT

The data used in the present work were collected during the RBLE3 experiment (Rondonia Boundary Layer Experiment), in the Brazilian state of Rondonia, Western Amazonia, in august 1994. (dry season). The main goal of this experiment was to obtain meteorological data of the boundary layer above the Amazon Forest and Pasture (grassland). The experiment was carried out in the east of Rondonia, near of the small town named Ji-Parana. The data, above the forest, were measured inside the Rio Jaru biological reserve, a huge intact forest site (268,000 ha) at 10° 05' S , 61° 55' W and 120 m above the sea level. The data above grassland were obtained at "Nossa Senhora de Aparecida" farm, a deforested area 10 km far from the town of Ouro Preto do Oeste.

On the forest, the meteorological data were measured in a tower at a place of 15 m above the canopy. On the grassland, the data were collected in a mast at 3.5 above the ground. The wind velocity data were measured with a "three-dimensional ultrasonic anemometer-thermometer Gill" (Gill Instruments, Solen House), with sampling frequency at 21 Hz.

4. METHODOLOGY

4.1. The Wavelet Transform (WT):

In pure and applied Mathematical Analysis, one of the most important topic is the Fourier Analysis. The Fourier Series and Fourier Integral are used in many branches of science and technology, and they suggest practical and physical interpretation. Also they have computing aspects very interesting.

As in the Fourier Analysis, there are two important entities in the Wavelet Analysis: the continuous WT and the WT series. The continuous WT consist of a convolution operator with basic functions:

$$g_{ab}(x) = a^{-1/2}\, g\left(\frac{x-b}{a}\right) \qquad (1)$$

obtained with translation and dilatations of a unique function **g(x)**, a wavelet-mother[15]. In the wavelet series this function appears only for discrete set of parameter of translation and dilatation[24].

With appropriated choice of mother-wavelet, the WT allows an analysis of local multi-resolution in both, space (or time) and frequency domains. In each basic function $\mathbf{g_{ab}(x)}$ the space localization is determined by the translation parameter **b**, and the frequency localization is determined by the scale parameter **a**. For example, if one takes a function which is time dependent and shows a variation of frequency in a short period of time. The property of double localization implies that the information is not distributed all over the over coefficients, for the wavelet series of this function. The information is concentrated in those coefficients of the basic functions whose parameters **a** e **b** are important for that variations of time and frequency.

The property of double localization does not happen in the Fourier analysis, which permits only the frequency localization. However, the property of double localization, combined with efficient algorithms of decomposition (calculation of the coefficients of a wavelet series) and synthesis (reconstruction of the function starting with these coefficients), allows a large list of applications of the wavelet analysis technique.

The WT analyzes a signal "**s(x)**" in each position "**x**" over a interval of scale "**a**". The WT of a known signal defined in a one-dimension interval is a function of double variables, assumed independent. Therefore, the WT study a given scale by the convolution of "**s(x)**" with the wavelet "**g(x)**", which is dilated in function of scale in question. The WT is defined by[17]:

$$T_g(a,x) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} g_{ax}\left(\frac{x-y}{a}\right)\, s(y)\, dy \qquad \textbf{(2)}$$

The wavelet "$\mathbf{g_{ax}}$" is defined starting from a given base, "**g**", called "wavelet-mother". The values of "$\mathbf{T_g(a,x)}$" shows the decomposition of signal "**s(x)**" in the position "**x**" and scale "**a**". Thus, the set of the values of "$\mathbf{T_g(a,x)}$" furnishes the two-dimensional representation of the signal in the space (or time) and wavenumber (or frequency).

In this work the Complex Morlet Wavelet which has been used and is given by:

$$g(x) = e^{i\,\omega_o x}\, e^{-x^2/2}, \qquad \omega_o = 5.4 \qquad \textbf{(3)}$$

4.2. Calculation of the dissipation rate of turbulent kinetic energy:

To investigate the eventual dissipative character of the structures, revealed by the analysis of time and scale given by the WT, it was calculated the values of the dissipation rate to the turbulent kinetic energy (TKE), called "ε".

To estimate "ε" the Kolmogorov hypothesis[25] was assumed to be valid over the fully developed turbulence. According to, for large Reynolds numbers there is a region of the power spectra, named inertial sub-interval, where the statistical features of the small-scale components of turbulence are completely determined by ε, and the energy flux per mass unit which flows towards ever greater wave-numbers. Hence, using simple dimensional analysis, it can be shown that the values of ε may be obtained from the power spectra of the longitudinal component of the wind speed, according to the following expressions:

$$S(n) = \alpha \left(\frac{2\pi}{U}\right)^{-2/3} \epsilon^{2/3} n^{-5/3} \qquad (4)$$

where "**S**" is the spectral energy, "α" is the constant of Kolmogorov, "**U**" is the wind speed relative to the instrumentation and "**n**" is the frequency. The estimation of ε with this technique is robust despite the intermittent character of the turbulence flow[23].

5. ANALYSIS OF RESULTS

To study the variability of the wind speed above the Amazon Forest and the deforested zone, time-frequency analysis of typical data of these quantities was performed for the diurnal (unstable conditions) and nocturnal (stable conditions) periods.

The Complex Morlet Wavelet was used since it provides useful information about both, the amplitude and the phase of a signal. Therefore, it is better suited to capture sudden and localized variations in the turbulence measurements. Further, the scale can be varied up to the resolution limit. This makes it convenient to study real turbulence fluctuation, where the time scales are continuous. This wavelet has already been applied successfully to investigate the development of cloud clusters structures above the Tropical Pacific Ocean[26] and to analyze the flow structure above the ocean [27].

Figure 1 shows the graphs of a typical situation found above the forest at night (day n° 232, 18:40 h, LT). In Figure 2, the same is shown for the flow above the pasture during night (day n° 228, 12:40 h, LT). Figure 3 refers to the pasture during the night (day n° 228, 19:40 h, LT). For each one of these figures, the following are shown: a) Signal of the longitudinal component of the wind speed, u; b) Its time-frequency decomposition and; c) Turbulent kinetic energy (TKE) dissipation rate for u.

In the signal's time-frequency analysis it was used a three-dimensional representation, with time on the horizontal axis, and frequency on the vertical axis and the real part of the wavelet coefficient on the third axis, each of its values appearing in different colors, as indicated in Figures 1(b), 2(b) and 3(b), which depict both the amplitude and phase of the signal's variation at particular scales and locations in the wavelet domain.

To understand physically these time-frequency diagrams, the graphs (c) of figures 1, 2 and 3 show the time-variation of the TKE's dissipation rate, ε. This parameter was estimated from the u-power spectra, assuming the Kolmogorov's Hypothesis for about fully developed turbulence[25]. To obtain these spectra the Fourier Transform was performed over short moving samples (246 points) for every 32 new samples in order to have a graph of the ε-variability in time.

Comparing the diurnal and nocturnal data in Figures 1(b), 2(b) and 3(b), one can observe that the former are much more energetic than the latter due to the unstable (convective) character of the diurnal atmosphere, in contrast to the nocturnal stability. Since the diurnal surface boundary layer has no natural oscillation value, Figure 2(b) has a more irregular distribution of energy in time-frequency. At night, on the contrary, there is a natural oscillation of the atmosphere, with the Brunt-Väissällä Frequency, $N = [(g/T)\,(\partial T/\partial z)]^{1/2}$. For typical values of the nocturnal atmosphere above the forest a $N \approx 1/8$ Hz value is obtained. This can be seen when one examines Figure 1(b). In examining figures 3 (b), for pasture, one finds this natural oscillation band at higher frequencies, which is explained by the fact that the radiative loss via long-wave emission is much more intense above the pasture (very dry) than above the forest (more humid). One observes, for the nocturnal period, time-intervals in which there are turbulent fluctuations at frequencies much higher than those mentioned, which are intermittent and have energetic spots much localized and in the higher frequencies. This leads to a more detailed discussion of the localized energetic patterns.

Effectively, when observing the time-frequency analysis diagrams resulting from the Complex Morlet Wavelet Transformation of the u-signals, one realizes that they present patterns similar to those already mentioned by other authors in the investigation of the turbulent signal[28,27] and in the research on climatologic and chaotic signals[26]. The patterns are extremely time-localized energetic patterns (ETLEP), which have large frequency bands and bifurcate as frequency increases. These ETLEPs are probably created by a process in which typically a structure divides (while decreasing in scale) asymmetrically (in intensity) into smaller ones[28]; this subdivision process repeats itself several times before reaching the smaller scales as the resolution allows. As other authors have stressed, these successive forkings produce a branching structure which looks very much like the kind of structures obtained when they applied the WT to non-uniform Cantor sets. They show how turbulence activity becomes more and more intermittent at smaller and smaller scales as quantified by appropriate statistical measures, such as flatness factors[29].

When comparing Figures 1(b) with 1(c), 2(b) with 2(c) and 3(b) with 3(c), one notes a strong coincidence of the regions where ε is more intense with those where the ETLEPs are found. Our conjecture is that it is in these regions that the flux of energy to the inferior scales is more intense, which implies in an increase of the local ε. It is worthy remembering the physical meaning of ε, based on the hypothesis of Kolmogorov concerning the fully developed turbulence. The quantity ε plays multiple roles[30]. It is the rate at which energy is fed into turbulent fluctuations; it is the rate at which energy is transferred from large to small scales; and it is also the rate at which energy is dissipated at the smallest scales. According to these interpretations, the results shown in Figures 1-3 seem to effectively indicate a relationship between the occurrence of the ETLEPs and the increase of ε in such regions, which suggests a physically dissipative character to such structures.

However, these conclusions, resulting from the study of a few experimental data, can only be seemed preliminary, and more systematic studies are necessary until one arrives to definitive conclusions. It is necessary to study longer samples and at frequencies higher than the present ones. Investigations concerning the self-similar character of the coherent structures of the flow with the aid of the WT should also be performed.

6. CONCLUSIONS

For the first time the WT has been used to study data from the turbulent field of the horizontal component of the wind speed, u, measured in Amazonia, both in the forest and in a deforested zone. The results from analyzing the real part of the wavelet coefficient in time-frequency show patterns characteristic of fluctuations distribution already found by other authors who studied the atmospheric turbulence under different boundary conditions. They suggest that these patterns are universal ones and confirm the non homogeneous and intermittent character of atmospheric turbulence. They also show how turbulent activity becomes more and more time-localized at smaller and smaller scales and these spots of large turbulence fluctuation seem to be related with large kinetic energy dissipation rate zones.

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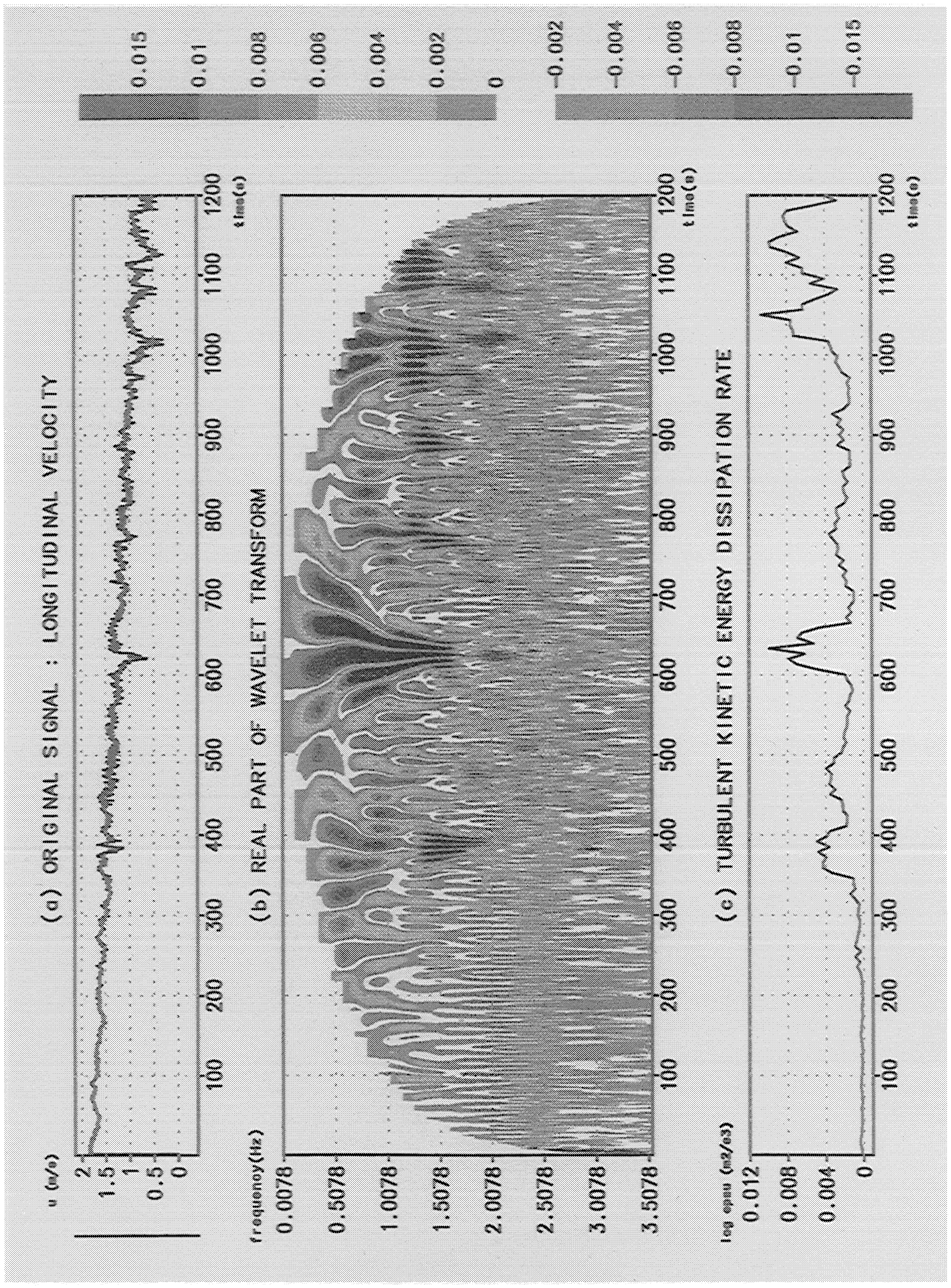

Fig. 1 — DATA OBTAINED ABOVE FOREST (NIGHT)

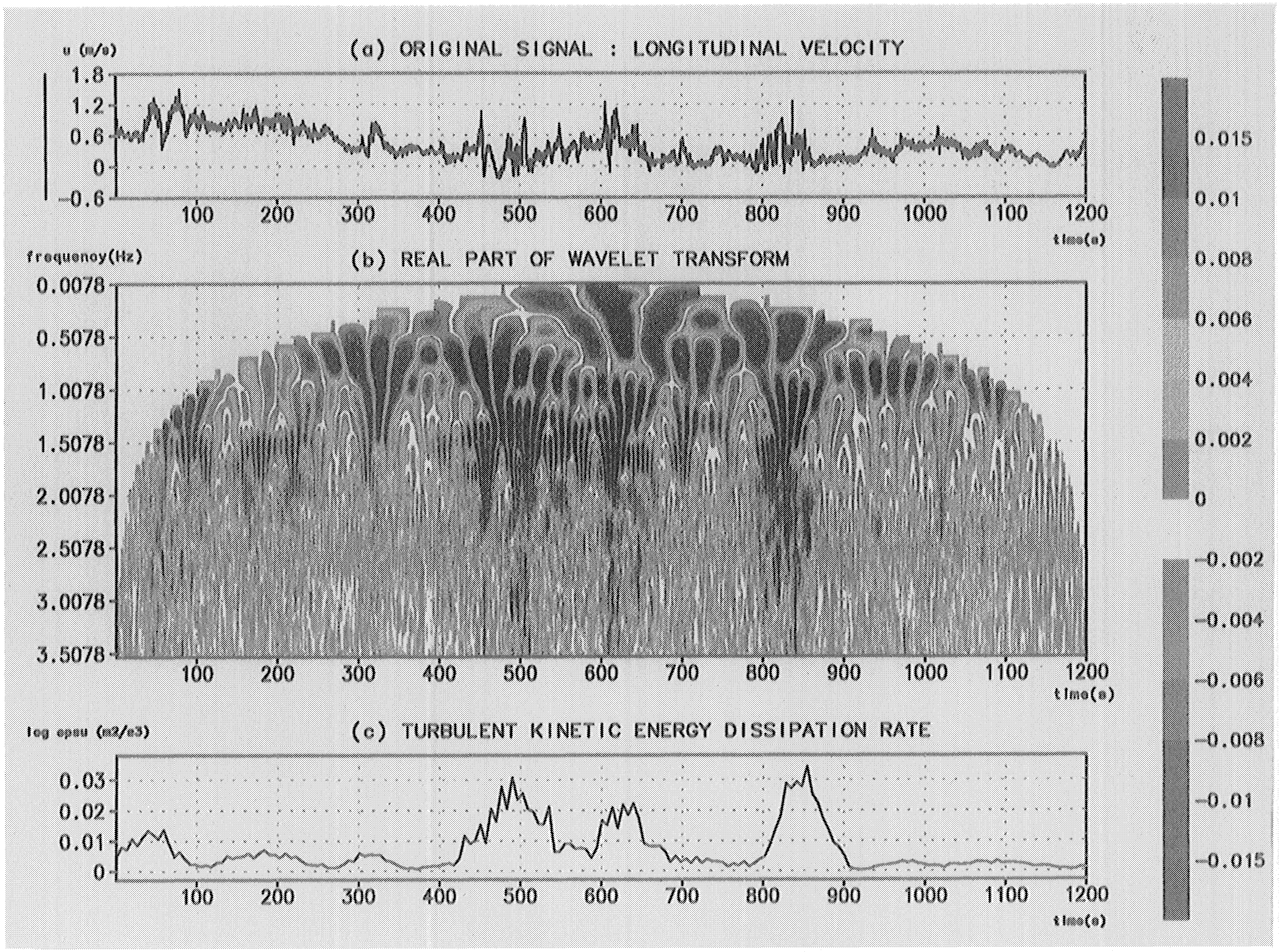

Fig. 2 — DATA OBTAINED ABOVE GRASSLAND (DAY)

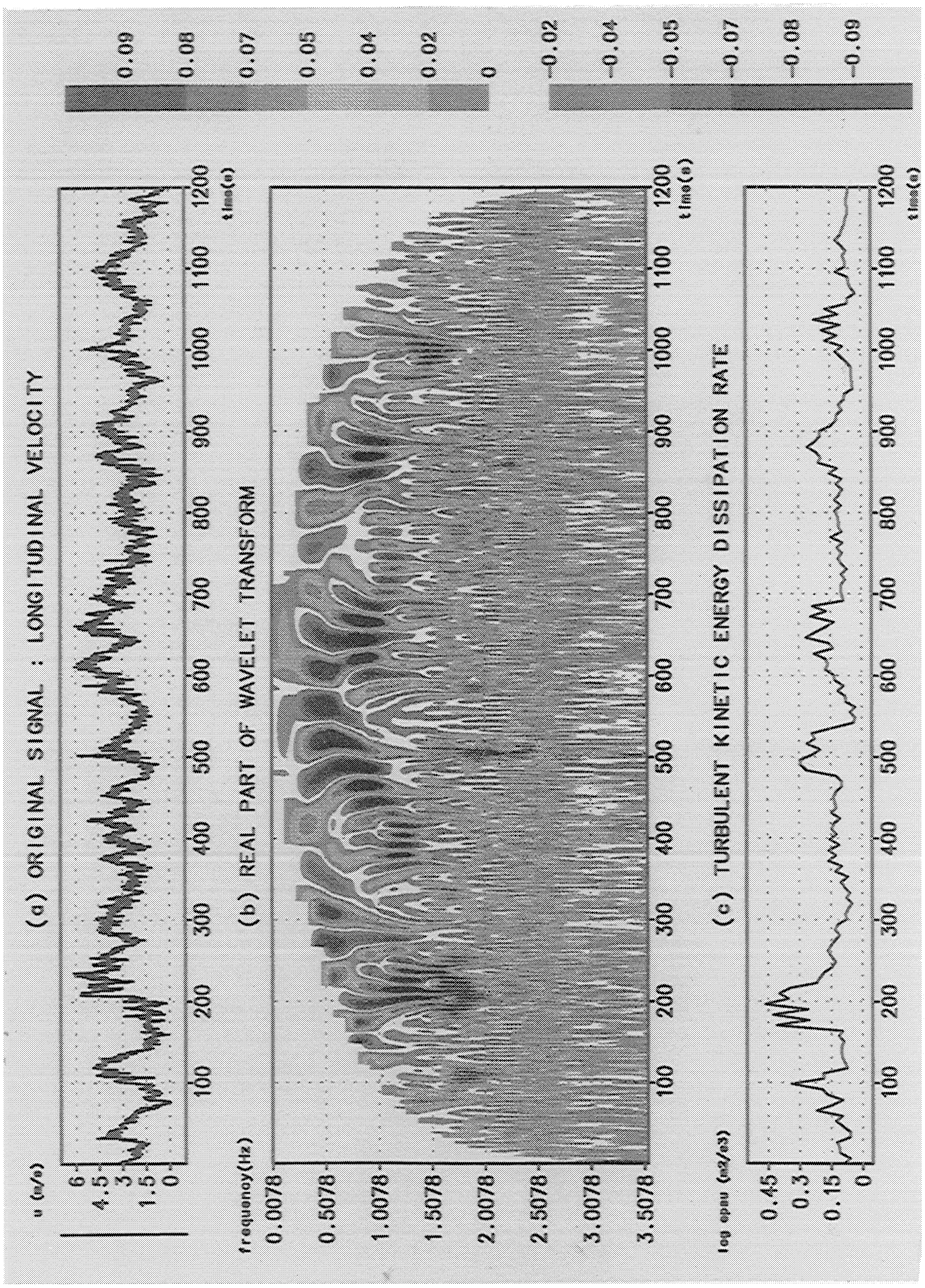

Fig. 3 — DATA OBTAINED ABOVE GRASSLAND (NIGHT)