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Proposal of a new autocorrelation function in low wind speed conditions

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HIGHLIGHTS

- We propose a new mathematical expression to describe the meandering phenomenon.
- We employ wind data measured in a nocturnal PBL to obtain experimental ACF.
- The new ACF satisfactorily represents the negative lobes of the meandering phenomenon.

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ABSTRACT

In this study a new mathematical expression to describe the observed meandering autocorrelation functions in low-wind speed is proposed. The analysis utilizes a large number of best fit curves to show that the proposed theoretical function well reproduces the general form and the negative lobes characterizing the experimental meandering autocorrelation function. Further, the good agreement of the measured autocorrelation curves with the proposed algebraic autocorrelation function allows to calculate the magnitudes of the meandering period and of the loop parameter. The results agree with the values presented and discussed in the literature. Therefore, the new formulation describing experimental meandering autocorrelation functions can be used to simulate the dispersion of contaminant during low wind episodes and to determine relevant meandering parameters.

1. Introduction

The autocorrelation function (ACF) is a statistical quantity relevant both for dispersion studies and to obtain fundamental equations associated to the turbulence phenomenon. In this aspect, the employment of autocorrelation functions obtained from experimental data for different movement patterns in the planetary boundary layer (PBL) allows to estimate important

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parameters employed to understand complex phenomena in geophysical flows. Simulating turbulent transport and, as a consequence, atmospheric passive scalar diffusion in low wind speed conditions is a difficult physical problem. For very low wind speed conditions, below a certain critical value of the mean wind velocity (about 1–2 m s^{-1}), it is no longer possible to determine a precise mean wind direction since low-frequency horizontal wind oscillations prevail and the dispersion of contaminant in the planetary boundary layer is dominated by these degrees of freedom that disperse the contaminant plume over a rather wide angular sector [1,2]. In the literature, these large horizontal wind oscillations are called meandering and are responsible for the fact that the observed autocorrelation functions of the horizontal wind velocity components show a looping behavior, characterized by the presence of negative lobes [1–4]. Normally, classical functions such as the exponential function [5], which adequately describes fully developed turbulence, fail completely to describe the observed meandering autocorrelation functions [1]. Anfossi et al. [1] proposed to utilize the well known Frenkiel's form [6] to fit the meandering ACF determined in low wind-speed.

The aim of this study is to present a new autocorrelation function, alternative to the Frenkiel's form to describe the observed negative lobes in the meandering of the horizontal mean wind vector. The new function (Eq. (3)) is a hybrid expression constituted by both turbulent and meandering characteristic parameters describing pure and connected states of turbulent and meandering movements. In Section 2, the new proposed ACF is presented. In Section 3 it is tested on meandering observations measured at a pasture site in the Brazilian Amazon region [7]. An additional purpose is to employ this new autocorrelation function, with the dataset measured in Brazilian Amazon region to evaluate the meandering time scale and the loop parameter magnitudes in nocturnal and stable low wind speed cases. The mean values of the meandering period and of the loop parameter are then used to determine the magnitudes of the turbulent integral time scale. Additionally, values of the meandering period are related to the mean wind speed. All these topics are presented and discussed in Section 4.

2. Obtaining the meandering autocorrelation function

For a fully developed turbulence, the autocorrelation function for the horizontal wind velocity components u, v may be written as [8]

$$R_{u,v}(\tau) = \left(1 + \frac{\tau}{T_{u,v}}\right)^{-2} \tag{1}$$

where τ is the time lag and $T_{u,v}$ is the turbulent integral time scale, defined by the following relationship

$$T_{u,v} = \int_0^\infty R_{u,v}(\tau)\, d\tau. \tag{2}$$

This integral time scale describes the memory effect associated to the organized eddies patterns that compose a turbulent flow. Eq. (1) well describes the scalars lateral turbulent dispersion in the situation of high wind speeds in the PBL. On the other hand, for very low wind conditions, when the observed autocorrelation function presents negative lobes [1,4], Eq. (1) fails to describe the scalars dispersion in the PBL. Therefore, considering these manifold manifestations, characterized by cases in which turbulence coexists with low-frequency motion associated to the meandering phenomenon, the following new formulation is suggested:

$$R_{u,v}(\tau) = \cos\left(\frac{m_{u,v}\tau}{(m_{u,v}^2 + 1)T_{u,v}}\right) \Big/ \left(1 + \frac{\tau}{(m_{u,v}^2 + 1)T_{u,v}}\right)^2. \tag{3}$$

Eq. (3) is a hybrid expression containing $T_{u,v}$ and the loop parameter $m_{u,v}$, that controls the meandering oscillation frequency associated to the horizontal wind. High values of $m_{u,v}$ characterize a strong manifestation of the meandering (accentuated negative lobes) [9]. Differently, very low magnitudes of $m_{u,v}$ are associated to fully developed turbulence. Such behavior can be seen in Fig. 1, where Eq. (3) is plotted for different values of the loop parameter. This figure shows the presence of negatives lobes associated to the meandering movement, whose relevance is enhanced as $m_{u,v}$ increases.

It is worth noticing that for $m_{u,v}$ approaching zero Eq. (3) tends to Eq. (1). Eq. (3) can also be written in a different manner, namely

$$R_{u,v}(\tau) = \frac{\cos(q_{u,v}\tau)}{(1 + p_{u,v}\tau)^2} \tag{4}$$

with

$$p_{u,v} = \frac{1}{(m_{u,v}^2 + 1)T_{u,v}} \tag{5}$$

and

$$q_{u,v} = \frac{m_{u,v}}{(m_{u,v}^2 + 1)T_{u,v}} \tag{6}$$

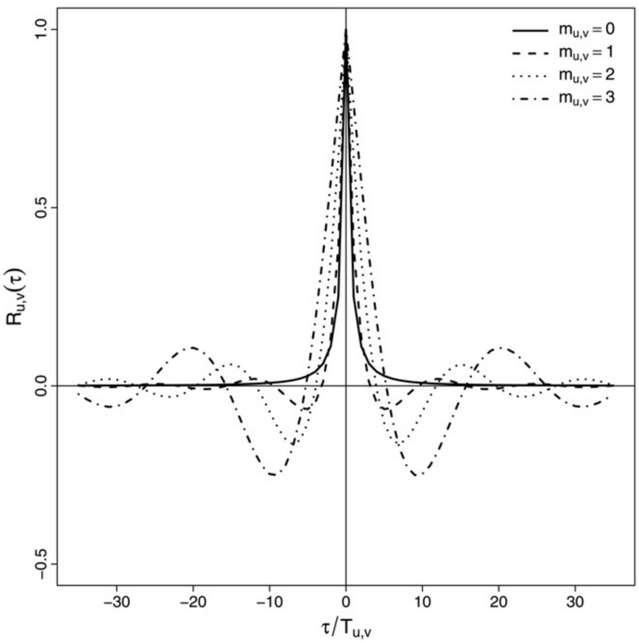

Fig. 1. Autocorrelation functions obtained from Eq. (3) using different values of the loop parameter.

$p_{u,v}$ and $q_{u,v}$ are hybrid quantities described in terms of $T_{u,v}$ and $m_{u,v}$. It is important to note that from Eqs. (5) and (6) a meandering time scale (meandering period) can be defined as $T_{*u,v} = 2\pi/q_{u,v}$ and will be expressed by [1]

$$T_{*u,v} = \frac{2\pi T_{u,v}(m_{u,v}^2 + 1)}{m_{u,v}}. \tag{7}$$

Such meandering period is a fundamental parameter to provide air quality precise forecasting [4,10]. Analyzing Eq. (7) for large values of $m_{u,v}$, the following equation yields:

$$m_{u,v} \approx \frac{1}{2\pi}\frac{T_{*u,v}}{T_{u,v}}. \tag{8}$$

Defining $m_{u,v}$ as the ratio of meandering period to the turbulent integral time scale.

3. Fitting observed meandering ACF with Eq. (3)

In this section, we employ meandering data measured in a nocturnal stable low wind speed PBL to obtain experimental autocorrelation functions. These experimental functions are fitted with the new meandering autocorrelation function (Eq. (3)). Thus, Eq. (3) is validated as a mathematical formulation to describe the observed negative lobes in the meandering autocorrelation functions and employed to provide the loop parameter ($m_{u,v}$) and the meandering period ($T_{*u,v}$). The meandering data were collected in a Brazilian Amazon Large Scale Biosphere–Atmosphere project (LBA dataset; [7]). The wind velocities components were sampled at a frequency of 10 Hz by a sonic anemometer (SATI/3K Applied Technologies, Inc., Longmont, CO, USA) located at one level of 8.75 m in a flat pasture region (3.0121° latitude S; 54.5371° longitude W). The dataset employed in this study were continuously measured between January and September 2003.

Figs. 2–5 show characteristic results of the comparison among the ACFs calculated on the LBA low wind speed dataset (gray line) and the associated best fit (black line) evaluated from the new ACF (Eq. (3)). All figures were obtained from one hour nocturnal time series having the mean horizontal speed less than 1.5 m s^{-1}. This limit wind speed value is in agreement with the magnitudes of the low wind speed suggested by Anfossi et al. [1] and Mortarini et al. [11] for the existence of the meandering phenomenon. It can be seen that for these graphs the ACF minimum values, associated to the negative lobes, characterizing the horizontal wind meandering range from −0.61 to −0.53.

From the analysis of 1474 best fit curves of low wind meandering ACF, we can conclude that Eq. (3) provides a good or fairly good fit in about 80% of the observed meandering events. Thus, the present analysis shows that the proposed function, given by Eq. (3), adequately represents the observed form of the meandering ACF. Particularly, its oscillatory behavior and the large negative lobes characterizing the wind meandering phenomenon.

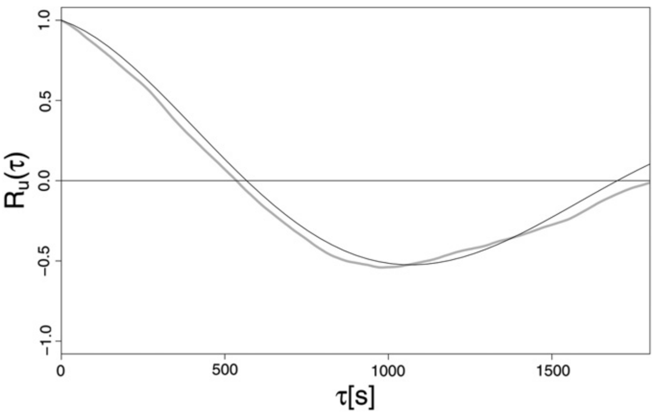

Fig. 2. Comparison between the ACF calculated on the LBA low wind speed dataset (gray line) and the associated best fit (black line) evaluated from Eq. (3). For January 08, 0100 local time, $\overline{U} = 0.47$ m s^{-1}.

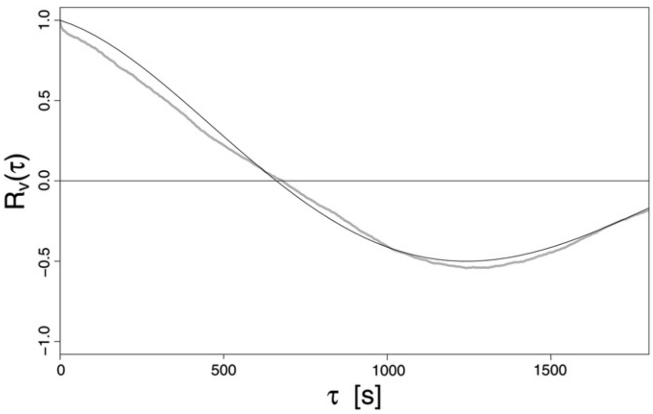

Fig. 3. As in Fig. 2, for January 08, 2100 local time, $\overline{U} = 0.11$ m s^{-1}.

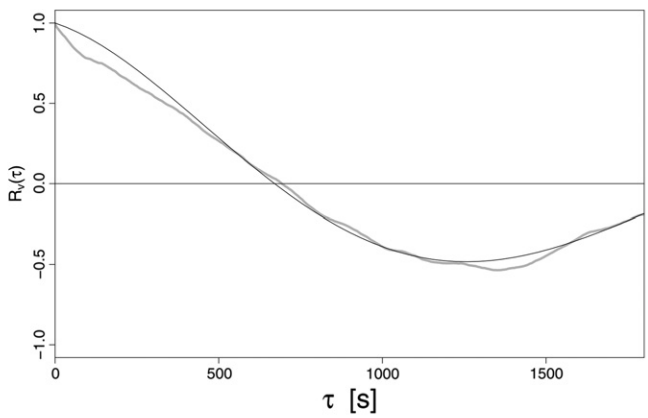

Fig. 4. As in Fig. 2, for January 09, 2200 local time, $\overline{U} = 0.12$ m s^{-1}.

4. Analyzing wind meandering parameters

Employing the best fit generated from the ACF (Eq. (3)), it is possible to evaluate the diverse meandering parameters that compose Eq. (7) (a detailed discussion about this procedure it can be seen in Mortarini et al. [11]). The meandering period, $T_{*u,v}$, consists in an essential characteristic time scale to evaluate air pollution dispersion. On the other hand, the loop parameter $m_{u,v}$ also represents a fundamental physical quantity in the equations that describe the enhanced diffusion occurring in wind meandering conditions [12]. As a consequence, mean values of $T_{*_{u,v}}$ and $m_{u,v}$ need to be evaluated.

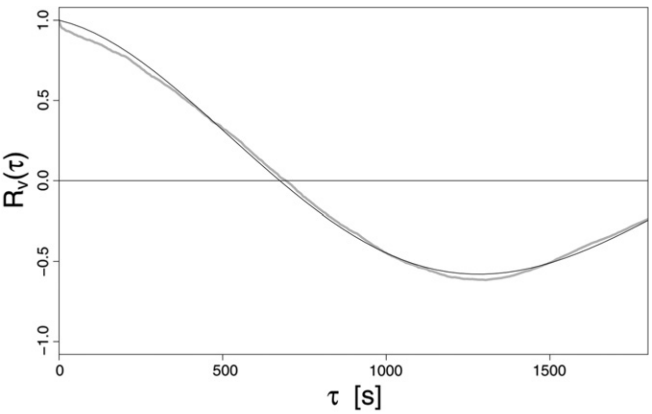

Fig. 5. As in Fig. 2, for January 13, 0300 local time, $\overline{U} = 0.94$ m s^{-1}.

Table 1
Meandering period and loop parameter average values for the u and v components.

	T_{*_u} (s)	T_{*_v} (s)	m_u	m_v
Amazon dataset	2202	2204	4.8	5.1

Table 1 shows these mean values for the wind u and v velocity components averaged over 1474 (mean wind speed less than 1.5 m s^{-1}) observed meandering events. It can be seen that the m_u and m_v values as well as the T_{*_u} and T_{*_v} values are very similar to each other. These magnitudes for T_{*_u} and T_{*_v} agree very well with the mean value found by Anfossi et al. [1] employing the best fit for the meandering ACF determined from the Frenkiel's form [6]. The magnitudes of m_u and m_v in Table 1 are sufficiently large confirming the approximation described by Eq. (8). Therefore, the substitution of the values of $T_{*_{u,v}}$ and $m_{u,v}$ into Eq. (8) provides the following mean values for the integral time scales, $T_u \approx 73$ s and $T_v \approx 69$ s.

Degrazia et al. [13] derived the following formulation to calculate the integral time scales $T_{u,v}$ for a nocturnal stable boundary layer (NBL)

$$T_{u,v} = \frac{z}{\sqrt{c_{u,v}}} \left\{ \frac{0.50}{u_* \phi_\varepsilon^{1/3} \left(1 + 3.7 \frac{z}{L(1-z/h)^{5/4}}\right)^{2/3}} \right\} \tag{9}$$

with the non-dimensional turbulence dissipation rate ϕ_ε given by [14]

$$\phi_\varepsilon = 1.1 \left(1 + 3.7 \frac{z}{L(1-z/h)^{5/4}}\right) \tag{10}$$

where $z = 8.75$ m is the anemometer height above the surface, $c_{u,v}$ are, respectively, 0.27 and 0.36 (turbulence isotropy condition), u_* is the friction velocity, L is the Obukhov length and h is the NBL depth. Considering the 1474 meandering cases analyzed in this study, we determine the following mean values for the friction velocity ($u_* = 0.095$ m s^{-1}) and Obukhov length ($L = 141$ m). Acevedo et al. [15] modeling the NBL in the Amazon pasture region suggested for the NBL depth (h) a value of the order of 100 m. The substitution of these values into Eqs. (9) and (10) yields $T_u = 70$ s and $T_v = 60$ s. These results are close to the values of $T_u \approx 73$ s and $T_v \approx 69$ s previously found using Eq. (8).

Fig. 6 exhibits the dependence of the meandering period on the mean wind speed for the whole LBA dataset (2222 h). The points represent average on wind speed classes. These best fit curves represent the whole set of the observed mean wind speeds. From this figure, it can be seen that, as expected, the magnitude of the meandering characteristic time scale decreases with velocity. The analysis also shows that the largest values of the meandering period occur when the mean wind speed is less than 1.5 m s^{-1}.

Fig. 7, obtained from the 2222 best fit curves, presents the joint dependence of the analyzed wind data distribution on the mean wind speed and on the meandering period for u component. This figure confirms the information provided by Fig. 6. Furthermore, it shows in a visible way that an elevated number of cases for mean wind speed less than 1 m s^{-1} is associated to high values of the meandering period. It can be seen also from this figure that for low wind cases the meandering period varies between 1500 s and 3000 s. These values for the meandering period are in agreement with studies accomplished by Anfossi et al. [1] and Mortarini et al. [11].

The good results and agreements discussed and obtained in this study ensure that the mathematical formulation given by Eq. (3) can be used to investigate the distinct properties of the meandering phenomenon in the PBL.

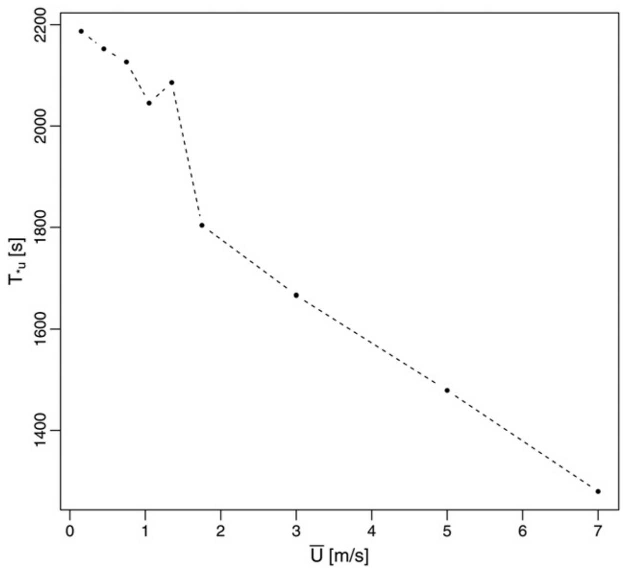

Fig. 6. Relation between the mean wind speed magnitude and the period of meandering (*u* component).

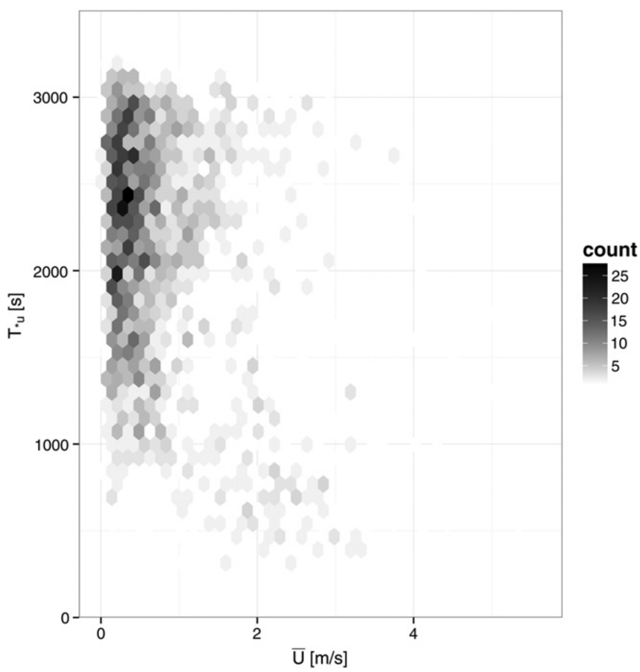

Fig. 7. Wind data distribution with the wind mean speed and the meandering period (*u* component).

5. Conclusion

Horizontal wind meandering is a frequent physical phenomenon associated with a complex flow occurring in a very low wind speed PBL. The wind meandering patterns are characterized by low frequency horizontal oscillations that reinforce the horizontal transport of contaminant and hence need to be incorporated in air pollution models. The principal characteristic of the wind meandering is the presence of accentuated negative lobes in the observed autocorrelation functions. In this study, a new mathematical formulation representing the best fit for the observed autocorrelation functions is proposed. It is composed by the product of a well-known autocorrelation function, describing a fully developed turbulence, and by a cosine function describing the observed oscillation (negative lobes) associated to the experimental meandering autocorrelation function. The present analysis, employing 1474 best fit curves originated from observed meandering cases in a nocturnal stable low wind speed PBL, shows that the new proposed mathematical expression satisfactorily represents the general behavior and the negative lobes associated to the observed meandering autocorrelation function. Based on these good representations, given by the fitting curves originated from the new meandering formulation (Eq. (3)), values of the characteristic meandering time scales are calculated. Values on the meandering period on the order of $T_{*_u} \approx T_{*_v} = 2200$ s were found. Concerning the loop parameter, that in meandering-dominated situations can be interpreted as the ratio of characteristic meandering time scale to the turbulent integral time scale (Eq. (8)), investigation using the new formulation for the meandering autocorrelation function provides values of $m_{u,v}$ on the order of $m_u = 4.8$ and $m_v = 5.1$. With these results for $T_{u,v}$ and $m_{u,v}$ the approximated asymptotic form (Eq. (8)) provides magnitudes for $T_{u,v}$ on the order of $T_u \approx 73$ s and $T_v \approx 69$ s. Finally, to test and evaluate the proposed new autocorrelation function the turbulent time scale has been calculated from Eqs. (9) and (10) employing the micrometeorological parameters mean values measured in the Amazon nocturnal PBL. Thus, from this equations the determined values for $T_{u,v}$ are on order of $T_u = 70$ s and $T_v = 60$ s. Such magnitudes agree with the results obtained from Eq. (8) therefore confirming Eq. (3) ability to reproduce the observed meandering autocorrelation functions. Considering the statistical development and the arguments discussed above, the new mathematical parameterization (Eq. (3)), describing the observed meandering phenomenon, is found to be suitable to simulate the meandering enhanced dispersion of contaminants as well as to estimate the various parameters that quantify the meandering movement.

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