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An experimental relationship between airflow and carbon dioxide concentrations at a rural site

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HIGHLIGHTS

- Airflow was described by typical wave parameters.
- Roundness calculation revealed major directional uniformity for high concentrations.
- Composite hodographs for anticyclonic turnings were parameterised using two models.

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ABSTRACT

The influence of airflow on CO_2 concentrations is considered. Two years of measurements recorded with a Picarro G1301 analyser during the night at a rural site were used. Three concentration groups were formed and were related to wind speed. Yearly, directional, and hourly evolution indicated that the isolated contribution of factors affecting CO_2 concentrations proves hard to evaluate. Two approaches to airflow based on average wind and a rotating residual were considered. Around two thirds of observations corresponded to anticyclonic rotations. Firstly, circular hodographs of rotating residuals indicated that wavelengths were in the mesoscale range. The greatest concentrations were linked to the lowest wind speeds and no prevailing directions were revealed by the roundness calculation in a spatial analysis using hexagonal cells. Secondly, composite hodographs for anticyclonic turnings were calculated, the greatest concentrations being associated to hodographs with a pronounced curvature. Moreover, these were successfully parameterised using two models. A harmonic function was first used, which satisfactorily fitted hodographs linked to low and intermediate concentrations. The second model initially described the wind direction of residuals with the error function since its change was slow in early and late night-time. Residuals were later parameterised with a second order logarithmic spiral. This procedure successfully fitted the most curved hodographs of low and high concentrations.

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1. Introduction

In unpolluted environments CO_2 is a trace gas whose concentrations are the result of a balance of interactions between biosphere and atmosphere. The factors involved in its evolution include natural and anthropogenic sources, sinks, transport, and the daily evolution of the lower troposphere (King et al., 2012). The resulting daily cycle shows an increasing trend with one maximum during the night and one decreasing trend up to one minimum during the day (García et al., 2012; Haszpra and Barcza, 2010; Yi et al., 2000; Wang et al., 2010). This has occasionally been ideally modelled by considering its similarity to the rectified electrical alternating current or to asymmetric circular functions (Larson and Volkmer, 2008; Pérez et al., 2012a).

Taking into account that plant respiration is a major CO_2 source, the key role of vegetation in CO_2 concentrations has been the focus of several studies (Davis et al., 2003; Higuchi et al., 2003). However, the influence of meteorological variables is not usually a research goal. Relationships between CO_2 and wind speed or the vertical structure of the lower atmosphere have been quantified (García et al., 2012; Pérez et al., 2012b). Yet, the contribution of other meteorological variables remains unexplored. The current paper focuses on airflow and considers measurements recorded at a rural site where vegetation is sparse and atmospheric evolution plays a major role. Nocturnal periods were selected since the absence of turbulence and stable stratification ensure horizontal air movement and the highest CO_2 concentrations. Pérez et al. (2013) fitted CO_2 to some skewed functions and this analysis revealed that concentration groups should be established to isolate the highest values, which are directly related to their source. The current study emphasises airflow through two main aspects: the first related

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to the flow itself, since horizontal waves are assumed, the second comprising procedures not commonly used to gain insights into this flow.

One initial objective is to determine the type of airflow, with the flow-concentration relationship being considered later. Different processes have been proposed to explain diurnal wind behaviour, such as the influence of sloping terrain (Holton, 1967), with a nocturnal jet being formed as a result of these processes (Davies, 2000). However, observing this evolution near to soil surface may prove difficult, since it may be obscured by other effects such as friction with the ground, passage of fronts, breezes, or orographic influences.

Horizontal waves may be analysed theoretically using different procedures. The present study considers two approaches, both of which begin by decomposing wind velocity into an average vector and a rotating residual (Kusuda and Alpert, 1983) and continue with the hodograph of residuals. A circular hodograph is first considered involving typical wave parameters, which are suitably described using statistical analysis of spatially distributed observations. The composite hodograph is then introduced, the objective in this case being to construct a model which satisfactorily fits observations. The major advantage of these models is that they represent a simplification of the airflow. However, both models are deterministic, with any random processes being excluded.

A second original contribution made by the current paper is the use of graphical and numerical procedures which have been developed and which to date have only been considered in trajectory analysis. Their field of application is thereby expanded. In this sense, wavelength is related to the spatial scale of waves affecting the measuring site, isopleths are useful to analyse the simultaneous distribution of two variables, roundness quantifies the directional distribution of these waves, and composite hodographs enable a more precise description of wind evolution.

2. Materials and methods

2.1. Experimental description

CO_2 dry observations were obtained with a Picarro G1301 analyser (Rella, 2010), which was located on flat terrain at CIBA (Low Atmosphere Research Centre) 41° 48′ 50″ N, 4° 55′ 59″ W, at 850 m above mean sea level. Horizontal homogeneity is guaranteed since no relief elements are present within 10 km around the site, except to the NW, where the plain extends for 5 km. Vegetation is formed by grass surrounded by non-irrigated crops. The soil type is calcaric cambisol, following the FAO classification (from the Agricultural Technological Institute of Castile and Leon, http://suelos.itacyl.es/, accessed in May 2015).

Metzger et al. (2005) considered 13 environmental zones in Europe. This classification described the site climate as Mediterranean North, with a dry summer, maximum precipitation in winter and a growing season lasting 335 days (http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Projects/EBONE-2/Products/European-Environmental-Stratification.htm, accessed in May 2015). However, the climate is temperate without a dry season, and with a temperate summer, Cfb, following the detailed Köppen–Geiger classification from the agro-climatic atlas of Castile and Leon (http://atlas.itacyl.es, accessed in May 2015).

Although measurements were obtained at three levels, only the highest, 8.3 m from soil surface, was used in this paper since wind speed and direction measurements were taken at 10 m. The experimental period lasted two years, and commenced on 15th October 2010. The CO_2 analyser was calibrated each two weeks using three NOAA standards, and slight corrections were made to the concentrations based on the result of these calibrations (Pérez et al., 2013). Finally, semi-hourly averages were calculated. Values from 20 to 5 GMT were selected since atmospheric flow was constrained to a horizontal plane due to stable stratification. This led to CO_2 increasing over the period and reaching the highest concentrations.

2.2. Airflow model

According to Fig. 1(a), wind velocity, **V**, may be considered as an addition of mean wind velocity, $\mathbf{V_M}$, and one residual, $\mathbf{V_i}$. Fig. 1(b) is shown so as to provide a clearer idea of wind evolution. Lines correspond to easterly airflow, taken as an example. Wind velocity is tangent to the flow lines and is greater the closer the lines are to one another. Numbers follow the instants at which wind speed was considered. In this case, the wave presented is observed through anticyclonic wind rotation. However, cyclonic wind rotation would be seen through an airflow obtained by reflecting Fig. 1(b) on a horizontal mirror. Moreover, the waves presented in this figure respond to an idealized shape, since they may be disturbed or their phase may not be the same.

Two simple approaches are suggested to analyse this flow. The first considers the rotation of the residual wind vector presented in Fig. 1(c) where its value is constant and its direction changes as a function of time, and describes a circumference. The second approach is based on the composite hodograph proposed by Baas et al. (2012) to evaluate wind behaviour in the nocturnal boundary layer. This hodograph was calculated using the residual wind speed normalised with the average wind speed. In addition, directions of residual wind were rotated taking the North as the initial direction.

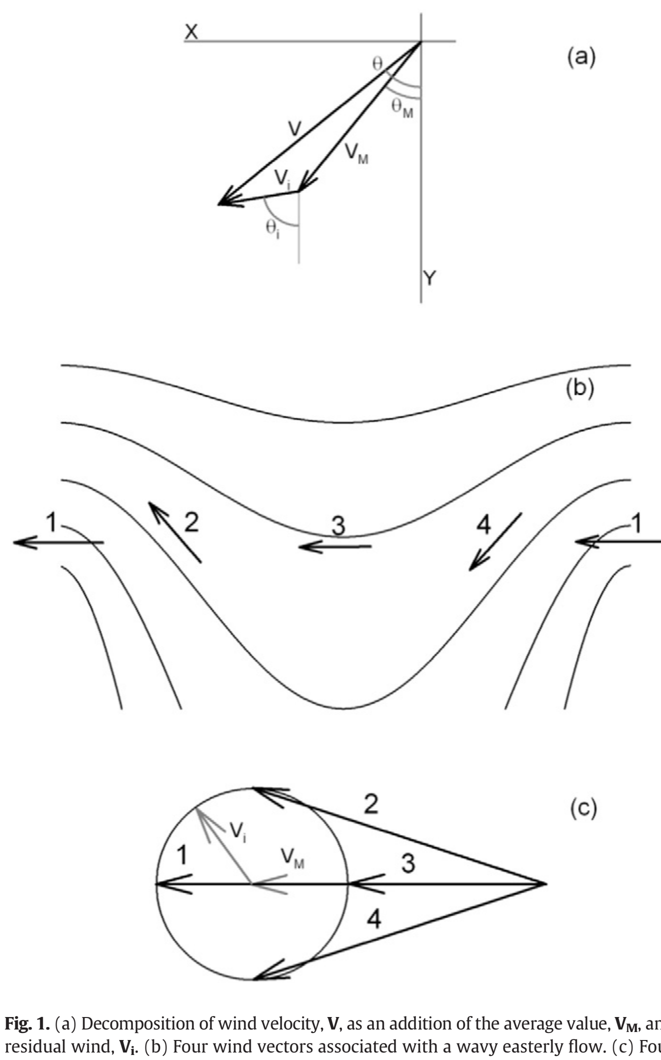

Fig. 1. (a) Decomposition of wind velocity, **V**, as an addition of the average value, $\mathbf{V_M}$, and residual wind, $\mathbf{V_i}$. (b) Four wind vectors associated with a wavy easterly flow. (c) Four wind vectors associated with the easterly flow with a residual wind describing an anticyclonic circumference.

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