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A new hypothesis on meandering atmospheric flows in low wind speed conditions

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Abstract

Low wind speeds are often associated with high pollutant concentrations in the atmosphere. Dispersion modelling in such conditions is still an important challenge for scientists due to phenomena associated with low wind speeds, which are not well understood. One such phenomenon is the large horizontal oscillation of the atmosphere, which is called meandering. This study aims at providing a new hypothesis for the cause of meandering. Meandering is explained as an inherent property of atmospheric flows in low wind speed conditions, and generally no particular trigger mechanism is necessary to initiate meandering as discussed previously by several scientists (e.g. gravity waves). The hypothesis is verified by numerically and analytically solving the two-dimensional Reynolds averaged Navier–Stokes equations under the assumption of negligible Reynolds stress terms, Coriolis forces, and pressure gradients in low wind speed conditions. Meandering is shown to arise when the 2-D flow studied here is approaching or near approximate geostrophic balance, and is damped out and vanishes when the Reynolds stresses are larger. Further, the analytical solution provides an autocorrelation function for the horizontal velocity components, which was recently proposed by Anfossi et al. (Boundary Layer Meteorol. (2005), 114, 179–203) for use in low wind speed conditions. In addition, a new set of Langevin equations is proposed for simulating dispersion in low wind speed conditions.

Keywords: Low wind speeds; Meandering; Navier–Stokes equations; Dispersion; Langevin equations; Coriolis; Geostrophic balance; Reynolds stress

1. Introduction

Simulating airborne dispersion in low wind speed (hereafter LWS) conditions is a difficult task because when the wind speed decreases below a certain threshold value, it is no longer possible to define a precise mean wind direction and the wind direction oscillates with periods of the order of half an hour or more. These large horizontal low frequency oscillations (meandering) seem to be more or less independent of atmospheric stability, specific topographical features, or season (Anfossi et al., 2005).

Currently, no conclusive theory is available, which helps to explain the phenomenon of meandering found under differing stability, meteorological conditions and locations. In this direction, the present paper aims at

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offering a physically based theory of flow meandering in LWS conditions. The main motivation comes from a previous paper (Anfossi et al., 2005), where it was found that meandering induces an important modification of the Eulerian autocorrelation function (EAF) of the horizontal wind components that exhibits an oscillatory behaviour and large negative lobes. It was also found (Anfossi et al., 2005) that an analytical form, proposed by Frenkiel (1953) that accounts for this oscillatory aspect, fitted fairly well the experimental EAFs, namely

$$R(\tau) = e^{-(\tau/(m^2+1)T)} \cos\frac{m\tau}{(m^2+1)T}. \quad (1)$$

This may be written in a different way (Murgatroyd, 1969) as

$$R(\tau) = e^{-p\tau} \cos(q\tau) \quad (2)$$

with

$$p = \frac{1}{(m^2+1)T} \text{ and } q = \frac{m}{(m^2+1)T}. \quad (3)$$

Eq. (1) contains two parameters: one, T, that can be associated with the classical integral time scale due to a fully developed turbulence and the second, m, which is a non-dimensional quantity that controls the meandering oscillation frequency. In fact, the latter controls the absolute value of the negative lobe in the EAF. It was also found that relationship (1) correctly fits the experimental $R(\tau)$ in LWS, while the classical exponential form completely fails. In particular, Frenkiel's form recovers the classical results, valid for non-LWS, when the meandering effects are not considered (i.e. by setting $m = 0$).

We recall that the presence of significant negative lobes in the EAF has a strong effect in dispersion modelling, especially in the immediate vicinity of a source (Oettl et al., 2001).

Based on these previously found results, the aim of the present paper is to investigate the physical processes responsible for the meandering phenomenon and to derive the expression of the above given EAF from basic momentum conservation equations. To meet both these aims, our analysis is based on the Reynolds averaged Navier–Stokes (RANS) equations in two dimensions:

$$\frac{\partial\bar{u}}{\partial t} + \bar{u}\frac{\partial\bar{u}}{\partial x} + \bar{v}\frac{\partial\bar{u}}{\partial y} = f_c\bar{v} - \frac{1}{\bar{\rho}}\frac{\partial\bar{p}}{\partial x} - \frac{\partial\overline{(u'u')}}{\partial x} - \frac{\partial\overline{(u'v')}}{\partial y}, \quad (4)$$

$$\frac{\partial\bar{v}}{\partial t} + \bar{u}\frac{\partial\bar{v}}{\partial x} + \bar{v}\frac{\partial\bar{v}}{\partial y} = -f_c\bar{u} - \frac{1}{\bar{\rho}}\frac{\partial\bar{p}}{\partial y} - \frac{\partial\overline{(v'u')}}{\partial x} - \frac{\partial\overline{(v'v')}}{\partial y}, \quad (5)$$

where $\bar{u}$ and $\bar{v}$ denote the mean wind components in x- and y-direction averaged over a certain time interval ($m\,s^{-1}$), $\bar{\rho}$ is the mean density ($kg\,m^{-3}$), u' and v' are the velocity fluctuations ($m\,s^{-1}$), $\bar{p}$ is the mean pressure (Pa), and f_c is the Coriolis parameter (s^{-1}).

The first topic was studied by means of two complementary methods: a numerical integration and an analytical solution of Eqs. (4) and (5), whereas from the latter, the form of the EAF found in our previous paper is recovered (second topic).

While in the analytical solution, provided it exists, one has an explicit view of all the parameters, kept, in general, constant, controlling the physical process, the numerical integration yields a more general view of the process when the various parameters are allowed to vary. The analytical solution allows the understanding of the role played by any parameter, when kept constant, on the studied process in a concise way. On the other hand, the numerical integration is able to show the role played by the parameters, letting them vary both in time and space, but for a complete understanding of the phenomenon a great number of runs should be performed. The numerical simulations may also be helpful for a discussion about mechanisms necessary to initiate meandering.

2. Numerical simulations

In the following, we try to find out whether meandering could be an inherent property of atmospheric flows under certain conditions similar to e.g. flow behaviour above and below the critical Reynolds number, which describes well whether a flow becomes laminar or turbulent. Here, we try to examine under which conditions meandering will appear in atmospheric flows. As a starting point we use the RANS equations in two dimensions. This implies that the mean vertical velocity and its spatial derivatives are close to zero, and that all spatial derivatives of the cross-correlations including w' can be neglected. These assumptions are generally fulfilled in LWS and flat terrain. Further, it is well known that the Reynolds stress terms (considering a fully developed turbulence only) and the pressure gradient terms on the right-hand side take very low values during LWS, as mechanically induced turbulence due to shear forces is weak then. This is even more so for the stable boundary layer. As the Coriolis forces are also weak in such conditions, we may conveniently start our investigations with the assumption, that the terms on the right-hand sides in Eqs. (4) and (5) can as a first approximation be neglected. Further, taking the time derivative of Eq. (5) and substituting Eq. (4) into (5) gives

$$\frac{\partial^2\bar{v}}{\partial t^2} = \frac{\partial\bar{v}}{\partial x}\frac{\partial\bar{u}}{\partial x}\overline{U} + \frac{\partial\bar{v}}{\partial x}\frac{\partial\bar{u}}{\partial y}\bar{v} - \frac{\partial^2\bar{v}}{\partial t\partial x}\bar{u} - \frac{\partial\bar{v}}{\partial t}\frac{\partial\bar{v}}{\partial y} - \frac{\partial^2\bar{v}}{\partial t\partial y}\bar{v}. \quad (6)$$

Eq. (6) can be considered a hyperbolic differential equation of second order (see Section 2 for a detailed