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Measured and modelled wind variation over irregularly undulating terrain

John D. Wilson

Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada

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ABSTRACT

The steady-state, Reynolds-averaged momentum equations, with a simple eddy viscosity closure, are solved numerically to compute the spatial variation in surface-layer mean windspeed over irregular, gently rolling terrain. Simulations, with both this non-linear model "ASL3D" and (for comparison) with the pre-existing linear "Mixed Spectral Finite-Difference" or MSFD model, are compared with observed winds from anemometers aligned on a 140 m transect in a rolling field near Lacombe, Alberta. Recorded wind speeds, normalized and aggregated by wind direction sector, characterize local wind variation over terrain whose elevation varied by roughly ± 10 m over a radius of about half a kilometer from the instrumented transect.

For northeast and southwest winds particularly, both models agree well with the observations. In southeast winds, observed spatial variation of the wind was weak, except that an anemometer close to fences and gates recorded distinctly lower speeds: provided those obstructions are represented by adding a localized sink in the momentum equations, the ASL3D model transect is (again) in quite good agreement with the observations. For northwest winds, however, agreement of modelled and measured transects is poor, presumably because a steep, wooded slope lay upwind from the anemometer array. Overall the linear correlation coefficient between modelled and observed *fractional deviations* of wind speed from the reference value is 0.72.

Other than as regards the flexibility to represent such complications as fences, plant canopies (etc.), computed wind fields over for the present terrain do not suggest any compelling advantage of the more laborious non-linear model (ASL3D) over the semi-analytical MSFD treatment. It is concluded that, when applied over gentle terrain, the skill intrinsic to even such a simple paradigm as ASL3D (and MSFD) represents a meaningful and potentially useful alternative to the neglect of lateral inhomogeneity.

1. Introduction

The supposition that velocity (and other) statistics are invariant on horizontal planes underlies many or even most practical applications of surface layer meteorological theory, but most experimentalists will have faced the conundrum of an imperfect field site at which one is obliged – or in the interests of simplicity, one chooses – to overlook lateral inhomogeneity, and take wind and turbulence measurements at a single point as being sufficient, courtesy of Monin–Obukhov similarity theory (MOST), to characterise overall site conditions. An example relevant to this paper is the trace gas experiment of Hu et al. (2016), performed on hilly land: though it was known (and acknowledged) to be untrue, their Lagrangian stochastic inverse dispersion calculations treated wind statistics as if they had been laterally uniform, when "seen" in a terrain-following coordinate.

The approximation invoked by Hu et al. proved adequate and their "bLS" (backward Lagrangian stochastic) inversion method robust, but there are liable to be circumstances where accounting for the impact on wind statistics of varying topography and/or cover is worthwhile — even if doing so mandates that one resort to an onerous wind calculation. Taking inverse dispersion as case in point, wherever concentration measurements are made very close to a source a Lagrangian (i.e. trajectory simulation) treatment to determine emission rate is preferred, because the Eulerian description misrepresents the non-diffusive near field of a source (e.g. Raupach, 1989). In this context the role, potentially, of a wind model, would be to provide three-dimensional fields of mean velocity, Reynolds stress and turbulent kinetic energy (TKE) dissipation rate to a suitable LS trajectory model (e.g. Thomson, 1987; Wilson et al., 2010).

It is broadly in the above context then — the micrometeorology of mildly non-uniform sites — that this paper will explore the utility of numerical fluid mechanics in almost its simplest form: the steady-state, Reynolds-averaged momentum equations, with eddy viscosity closure, are solved for the situation where irregular terrain undulations cause wind variations that could be said to occur on the surface layer scale. The approach taken (Fig. 1) is to adopt a laterally periodic computational flow domain. This obviates the need to provide a known upwind profile of flow statistics; and if those lateral boundaries are placed

E-mail address: jaydee.uu@ualberta.ca.

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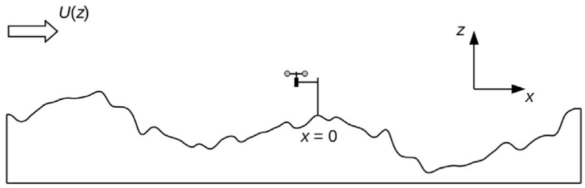

Fig. 1. A complicated field site where wind statistics are horizontally (as well as vertically) inhomogeneous, such that it is nowhere plausible that Monin–Obukhov similarity theory correctly describes wind statistics in the atmospheric surface layer (ASL). The approach used here to describe the wind field is to compute its structure within a laterally periodic domain centered over the region of interest, and rescale modelled wind statistics to match the measurements made at a single point. It is assumed that the wind is practically uniform, at the top of the atmospheric surface layer ("ASL").

sufficiently far from the area over which it is of interest to evaluate the wind statistics, the influence of the distant terrain ought to be weak. The calculation is driven by an imposed shear stress (or an imposed horizontal velocity) far overhead, and computed velocity statistics are re-scaled so that they match experimental input *at a single point in the flow*.

A brief overview on boundary layer wind models is in order (for detailed reviews see, e.g., Hunt, 1980; Taylor et al., 1987; Finnigan, 1988; Carruthers and Hunt, 1990; Wood, 2000). By carrying out a perturbation analysis (linearising the governing equations by an expansion in powers of small parameters) Jackson and Hunt (1975 showed that variation of the wind blowing over a smooth ridge could be regarded as being "driven" by a streamwise pressure gradient that could be obtained by solving for the velocity field in an irrotational (non-turbulent) "outer layer", the Fourier transform of the perturbation pressure field being determined by the Fourier transform of the hill profile. Below the outer layer a turbulent inner layer is perturbed by this imposed pressure field, and its response is modulated by a shear stress field that, for the geometry considered, is adequately treated in terms of a Prandtl eddy viscosity with an undisturbed turbulence length scale (, where k_v is the von Karman constant and η the distance from ground). Furthermore although the validity of the JH75 analysis hinged on stringent restriction of the geometry (i.e. hill slope and other dimensionless factors) the solution, generalised to three dimensional terrain by Mason and Sykes (1979, has been found useful to predict the changes in mean windspeed above topography that in fact violates those restrictions. Wind models — including the JH75/MS79 model, a family of less restrictive linear models (notably the "Mixed Spectral Finite-Difference" model MSFD originated by Beljaars et al., 1987a, and briefly described in Appendix A), and numeric, non-linear simulations (e.g. Taylor, 1977a, Taylor, 1977b; Zeman and Jensen, 1987; Raithby et al., 1987) — have been tested against wind tunnel (e.g. Britter et al., 1981) or field measurements of winds over a number of more or less isolated hills, the early studies including Kettles Hill (Taylor et al., 1983b), Ailsa Craig (Jenkins et al., 1981), Askervein (Castro et al., 2003; Golaz et al., 2009) and Brent Knoll (Mason and Sykes, 1979). Experience suggests that eddy viscosity closure is adequate for prediction of the mean wind field over gently sloping terrain (e.g. Ayotte et al., 1994; Ying et al., 1994), but that a more sophisticated turbulence closure is demanded to realistically model spatial variation of turbulence statistics.

Returning to the goal (here) of modelling wind over terrain whose elevation changes are relatively insignificant — at least compared to the above named test sites, and the sort of topography of interest in regard to wind energy resources — there is no reason to suppose that an approach well proven for terrain the amplitude of whose elevation is of order 100–1000 m should not be equally (or even more) satisfactory for much lower terrain. However the above studies generally focused on one relatively isolated and dominant terrain feature (hill or ridge), whereas this study addresses the case where there is no dominant topographic feature. As a consequence it is less clear what should constitute an adequate domain size, and whether available topographic data will offer adequate resolution.

Section 2 outlines the numerical wind model whose performance is tested here (for convenience of reference, "ASL3D"), while Appendix A briefly describes the linearized MSFD model to which (apart from the linearization) it is closely matched. Section 3 tests the performance of ASL3D in idealized, previously studied flows; and Section 4 compares simulations (ASL3D & MSFD) with near-ground wind measurements over irregular, rolling pasture.

2. Numerical model: ASL3D

The objective here is to model variation of the surface layer wind over horizontal distances spanning of the order of a few hundred metres, in response to disturbance by smooth and gentle terrain whose height $h = h(x, y)$ varies by an amount of the order of 10 m. Tacitly excluding application to any case of very light winds — such cases anyway having been excluded from the data used here to test the model — it seemed not unreasonable to treat the (model) atmosphere as being unstratified (i.e. uniform in its mean potential temperature), and to consider the topographic disturbance to the wind as taking place within a "host" (i.e. background) flow that could be approximated as being a constant stress layer.[1] Support for the latter simplification can be found in Taylor (1977a, Table II), where his comparison of "surface layer" versus "PBL" model results for the pressure and shear stress deviations over a Gaussian hill indicates them to be consistent, to within about 10%.

The mean momentum equations and the turbulent kinetic energy (TKE) equation were transformed into a terrain following coordinate

$$\eta = H\,\frac{z-h}{H-h} \tag{1}$$

where H is the computational domain depth: on ground the absolute elevation is $z = h(x, y)$, whereas $\eta = 0$. The resulting equations were closed using an eddy viscosity $K = \lambda\sqrt{c_e E}$, where E is the turbulent kinetic energy and λ a prescribed turbulence length scale, and after elimination of terms considered unimportant they were solved numerically using periodic lateral boundary conditions. The widely used control volume method "SIMPLEC" (van Doormaal and Raithby, 1984; Patankar, 1980) was adopted, along the lines explored earlier (Wilson, 1985, 2004b) for windbreak flows. Details follow.

2.1. Governing equations

Let (u, v, w) be the local, instantaneous, Cartesian velocity components, U (etc.) the mean velocities and u' (etc.) the velocity fluctuations defined by the Reynolds decomposition $u = U + u'$. Upon transformation of the Navier–Stokes equations into the non-orthogonal (x, y, η)-coordinate system it is convenient to introduce an effective vertical velocity

$$w^* \equiv u\eta_x + v\eta_y + w\eta_z \tag{2}$$

such that (u, v, w^*) is non-divergent in $x - y - \eta$ space, i.e.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w^*}{\partial \eta} = 0\ , \tag{3}$$

and with the result that vertical advection terms take the form $w^*\partial/\partial\eta$ (e.g. Richards and Taylor, 1981; Doyle et al., 2013). After Reynolds averaging, adoption of an eddy viscosity closure, and the simplification or neglect of certain minor terms, the following approximate mean momentum equations result:

[1] The generalization to provide a full boundary layer (with Coriolis forces) as host flow is straightforward.