MODELLING LOW WIND-SPEED STABLE CONDITIONS IN A PROGNOSTIC METEOROLOGICAL MODEL AND COMPARISON WITH FIELD DATA

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INTRODUCTION

Low wind-speed (< 2 m/s) conditions are particularly important for the science of air pollution because it is under these conditions that the highest ground-level concentrations are often experienced. However, it is difficult to define and predict the state of the lower atmosphere that governs the transport and diffusion of contaminant plumes under such conditions (*Smith*, 1992). In this paper, we assess the performance of CSIRO's meteorological and air pollution model TAPM (*Hurley et al.*, 2005) for low wind-speed predictions near the ground using the Cardington (UK) and CASES-99 (USA) field datasets. The model, which is based on an *E*-*e* turbulence closure with the Monin-Obukhov similarity theory (MOST) used for fluxes at the surface, generally does well at simulating low wind speeds under all stabilities except when conditions are strongly stable, such as may be observed on clear nights. Various modifications to the model (e.g. improvements in the land-surface scheme and alternative flux-profile relationships), together with changes in various model options (e.g. finer terrain data and an improved model resolution), are tried in order to investigate whether the model's performance for low wind-speed stable conditions is improved. The data are analysed to study the behaviour of the lower atmosphere under stable conditions.

DATASETS

The following two datasets were selected to study low wind meteorology and to assess TAPM (V3.5). The criteria used for the dataset selection included: relatively flat terrain with a shallow canopy, multi-level measurements of a full set of meteorological parameters, and a relatively high frequency of low-wind periods.

Cardington dataset

Data from the UK Met Office Cardington monitoring station (in Bedfordshire) for August, September and November 2005 were used (see http://badc.nerc.ac.uk/data/cardington/instr_v7/index.html#intro for data details). The data available include sonic-anemometer winds at heights of 10, 25 and 50 m; temperatures at 1.2, 10, 25 and 50 m; humidity; radiation; and sub-soil measurements. The data were averaged over hourly periods. There are two large airship hangars north of the site that may have a major influence on the air flow; therefore, we omitted the hours for which the observed winds were between 355° and 35°.

CASES-99 dataset

CASES-99 (Cooperative Atmosphere-Surface Exchange Study–1999, USA) was an intensive field experiment that took place over the period October 1–31, 1999 in southeast Kansas, and was directed principally towards making a comprehensive investigation of the stable boundary layer (*Poulos et al.*, 2002; http://www.eol.ucar.edu/projects/cases99/). The primary data used in the present study were collected on a 60-m tower. Six sonic anemometers were positioned at heights of 10, 20, 30, 40, 50, and 55 m for wind and temperature measurements. Four prop-vane anemometers were deployed at heights of 15, 25, 35, and 45 m, and temperature and relative humidity measurements were made at 5, 15, 25, 35, 45, 55 m. Additional sonic anemometers at 1.5 and 5.0 m were deployed on a small tower placed 10 m away from the 60-m tower. The data, given as 5-min averages, were averaged over hourly periods.

MODEL SETUP

TAPM is a three-dimensional, nestable prognostic meteorological and air pollution model developed by CSIRO Marine and Atmospheric Research, and is widely used in Australia for air quality management and research applications (see *Hurley et al.*, 2005; http://www.cmar.csiro.au/research/tapm for model details). The model includes a complete set of equations governing the behaviour of the atmosphere and dispersion of pollutants, and employs an *E-e* turbulence closure, where the turbulent kinetic energy (*E*) and its dissipation rate (*e*) are determined using prognostic equations. The MOST is used for determining fluxes at the surface. The model uses large-scale synoptic analyses, typically obtained from the Australian Bureau of Meteorology's GASP (Global AnalySis and Prediction) system at a horizontal grid spacing of 1° × 1° (about 100 km × 100 km) at 6-hourly intervals, as input boundary conditions for the outermost nest. Other inputs to the model include global databases of terrain height and land use (both given at a horizontal grid spacing of approximately 1 km, finer resolution for Australian regions), databases of soil type and monthly-varying Leaf Area Index (LAI) and sea-surface temperature. The model predictions are typically obtained at resolution of 0.5 km for meteorology and 250 m for dispersion.

For Cardington, the model setup involves four nested grid domains at 20, 7, 2, 0.5 km resolution for meteorology (31 × 31 grid points), centred on 00° 25.5' W, 52° 06' N. The lowest five of the 25 vertical levels are 10, 25, 50, 100 and 150 m, with the highest level at 8000 m. For CASES-99, four nested grid domains at the same resolution are used. These are centred on the location 96° 44' W, 37° 39' N, which is almost the location of the 60-m tower. The other model settings are the same as for Cardington.

MODEL RESULTS

The observed and modelled (in parentheses) frequencies (%) of hourly-averaged wind speed at 10 m AGL (above ground level) for various wind-speed classes are given in Table 1. For Cardington, TAPM severely underpredicts the frequency of low winds (< 2 m/s) during the nighttime, only around 18% of the time as opposed to the observed 41%. The model performance for the daytime hours is much better. For CASES-99, the model underpredicts the frequency of low winds during both daytime and nighttime, but the model performance is slightly better in the daytime. The overall wind-speed correlation (*r*) is 0.52 at night and 0.65 during the day for Cardington, and 0.74 and 0.87, respectively, for CASES-99.

Table 1. Observed and modelled (in parentheses) frequencies (%) of the hourly-averaged wind speed at 10 m AGL during daytime (0800–1900 h) and at night (2000–0700 h).

Station	Time	0–2 m/s	2–4 m/s	4–6 m/s	6–8 m/s	>8 m/s
Cardington	Day	15.3 (12.4)	31.6 (33.8)	29.7 (31.9)	15.9 (17.1)	7.5 (4.8)
	Night	40.8 (17.5)	29.9 (45.8)	17.3 (25.2)	8.8 (8.7)	3.2 (2.8)
CASES-99	Day	12.5 (9.0)	25.3 (35.3)	19.9 (30.4)	19.9 (20.5)	22.4 (4.8)
	Night	13.5 (9.0)	45.2 (42.3)	23.7 (36.9)	14.7 (11.8)	13.9 (0)

The model performance for winds becomes progressively better for higher levels.

OTHER OPTIONS AND MODIFICATIONS

To investigate the reason(s) for the poor performance of TAPM at predicting light winds, a number of options and modifications were tried including: (1) a finer model resolution (at

0.2 km); (2) a finer terrain resolution (at 0.25 km, for CASES-99 only); (3) a more comprehensive land-surface scheme called CABLE developed by *Kowalczyk et al.* (2006); (4) use of the US NCEP synoptic analyses, given at a resolution of 2.5° × 2.5°, rather than the default GASP analyses; (5) a Richardson-number based surface flux scheme in place of TAPM's x (= z/L)-based one, specifically the scheme as used in the MM5 model (*Grell et al.*, 1995), to deal with issues such as the problem of self-correlation with gradient functions for momentum and heat (*Klipp and Mahrt*, 2004), where z is height above ground and L is the Obukhov length; and (6) refinements to the original Businger-Dyer-Hicks flux-gradient relationships carried out by various researchers as well as those derived from an analysis of the present datasets.

None of the above options and changes produced a substantially better model performance for low wind stable conditions than that reported earlier. This result highlights the difficulty in parameterising strongly stable conditions in a prognostic model and suggests that there is a fundamental problem with the way the surface fluxes are determined via the MOST under such conditions.

DATA ANALYSIS

A more in-depth analysis of the datasets was carried out, focussing on the MOST relationships for stable stratification, which are directly or indirectly used in most meteorological models, including TAPM. According to the MOST, the flux-gradient relationships for momentum in the surface layer at height z are:

$$\frac{k\,z}{u_*}\frac{\partial U}{\partial z} = f_m, U(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_o}\right) - y_m\right], y_m = \int_{z_o}^{z} \frac{1 - f_m(z')}{z'}\,dz', \qquad (1)$$

where u_* is the friction velocity, k the von-Karman constant, U the wind speed, and z_o the roughness length. There are equivalent equations for heat exchange. For stable conditions, it is common to use $f_m = 1 + 5x$ (as in TAPM), and assume that the heat exchange is the same as the momentum exchange, yielding a critical Richardson number (gradient or bulk) of 0.2.

Both bulk and gradient Richardson numbers were determined at 10-m AGL using the Cardington and CASES-99 data. Here we examine the variation of various observed parameters in terms of the bulk Richardson number (R_{ib}) (the variation is qualitatively very similar when the gradient Richardson number is used instead). It was found that as the wind speed decreases R_{ib} increases (plot not shown) and approaches values as large as 10 for very low wind speeds (~ 0.3 m/s). While this indicates that there is no critical Richardson number as such, the observations do indicate that there is a threshold Richardson number, above which low wind conditions persist and the MOST relationships are not valid. This is evident from Fig. 1, which presents the non-dimensional wind speed kU/u_* as a function of the stability parameter x, and shows that there are two different turbulent regimes separated by a threshold R_{ib} ~ 0.25. When the flow is weakly stable (Fig. 1a), which corresponds to moderate to high winds with strong, fully developed turbulence, the observations are consistent with commonly used similarity curves. However, when the flow is strongly stable (Fig. 1b), which largely corresponds to light winds with weak and intermittent turbulence, the data points show a larger scatter and deviate substantially from the plotted similarity parameterisations derived within the framework of the MOST.

Despite the large scatter in Fig. 2a, it is apparent that the observed turbulent Prandtl number Pr (= f_h/f_m ≡ a ratio of momentum exchange to heat exchange) remains more-or-less constant with R_{ib} when $0 < R_{ib} \leq 0.25$, but increases in the intermittent turbulence regime ($R_{ib} > 0.25$), suggesting that the exchange of heat is far less efficient than the exchange of momentum in this regime. The data plotted in Fig. 2b demonstrate that the turbulence becomes strongly anisotropic beyond the threshold R_{ib}.

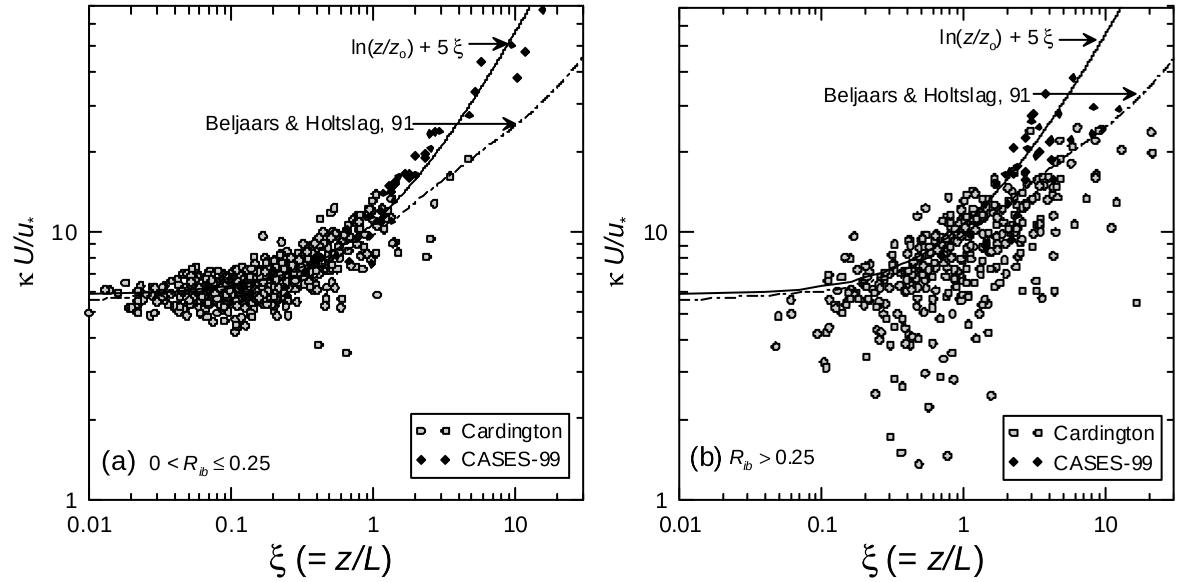

Fig. 1; Observed non-dimensional wind speed (kU/u) as a function of the stability parameter x (= z/L) for (a) weakly stable conditions (0 < R_{ib} £ 0.25), and (b) strongly stable conditions (R_{ib} > 0.25). Commonly used parameterisation curves are also shown.*

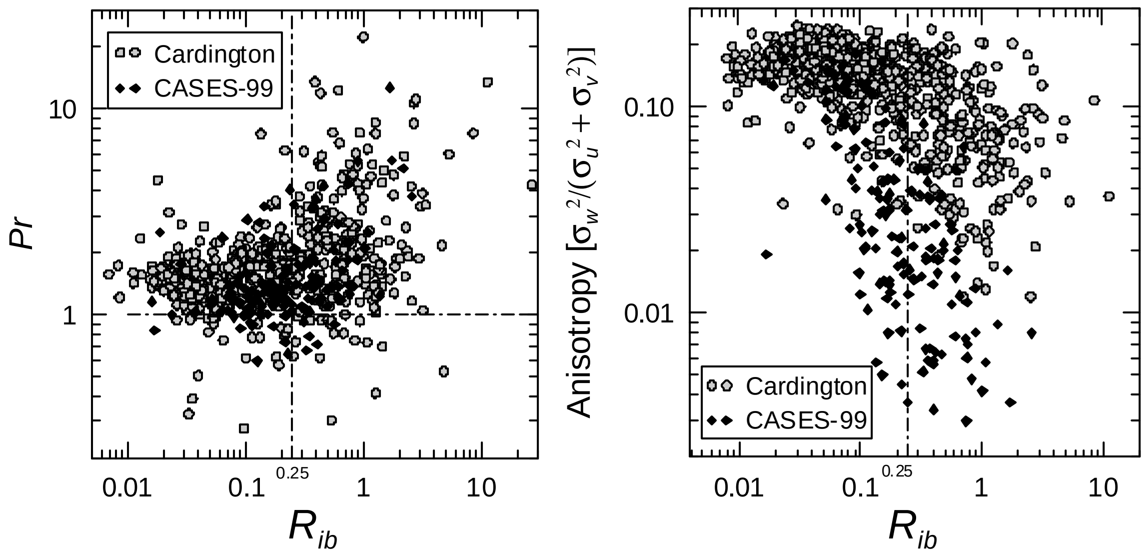

Fig. 2; Observed variation of (a) turbulent Prandtl number and (b) anisotropy with the bulk Richardson number (R_{ib}).

The existing MOST relationships, as used in most models, do not describe the flow behaviour when the winds are light, with weak and intermittent turbulence, under strongly stable conditions. The results presented in this section are consistent with a study by *Zilitinkevich et al.* (2007) in which the validity of differentiating between turbulent and non-turbulent (laminar) regimes via a critical Richardson number (R_i) value is questioned. It is proposed instead that a threshold value (0.2–0.3) separates two turbulent regimes: fully developed, chaotic turbulence at low R_i, and weak, highly anisotropic turbulence at large R_i.

Clearly, a better approach than the traditional MOST is necessary to describe low wind, strongly stable conditions in TAPM. In this regard, we are exploring alternative surface scalings, such as the *z*-less approach.

CONCLUSIONS

Highest ground-level concentrations of air pollutants are often encountered when wind speeds are low (< 2 m/s). We assessed CSIRO's prognostic meteorological and air pollution model TAPM for its performance for low wind-speed predictions near the ground using the Cardington (UK) and CASES-99 (USA) datasets. The model performs well for low winds under daytime conditions when the atmosphere is unstable with vigorous convective and/or mechanical mixing, but it performs poorly when the ambient stratification is strongly stable with little turbulence. It was also revealed that simply changing various model options, for example increasing the terrain or model resolution, or using different synoptic input, does not improve model performance for low winds under stable conditions. This is also the case when modifications, such as the inclusion of a more sophisticated land-surface scheme are made in the model. These results highlight the difficulty in parameterising strongly stable conditions in a prognostic model via the Monin-Obukhov similarity theory (MOST), which as the data analysis carried out here shows, is not valid under such conditions. Alternative surface scalings need to be devised.

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