MESOSCALE NUMERICAL MODELS: COST-EFFECTIVE INPUT TO DISPERSION PREDICTION SCHEMES

Mark R Jury
Oceanography Dept, University of Cape Town
and
Jim M Wilczak
NOAA Wave Propagation Lab Boulder, Colorado

ABSTRACT:
Dispersion prediction schemes which utilise on-line weather data are in increasing use, to predict the concentration distribution of pollutants near an industrial source. In many cases, sharp transitions in plume transport and spread can occur downstream from the source owing to changes in wind direction and mixing properties. These may be observed using costly remote stations or estimated using a mesoscale numerical model. A two dimensional mixed layer numerical model is described and tested for a land-seabreeze scenario in the Cape Town area. Comparisons with previous observational studies are made. It is suggested that these numerical models be used to interpolate meteorological observations from the source, to the wider area influenced by industrial emissions.

INTRODUCTION

The need for predicting the fate of anthropogenic emissions in the lower atmosphere has long been established. To make accurate predictions, information is required on:

- the output and characteristics of the pollutant source,
- the movement of the airmass within which the pollutants are embedded, and
- the horizontal and vertical mixing properties of the lower atmosphere.

A full description of the source is readily available from engineering design information and is generally required by law. The movement of the airmass is often characterised by meteorological measurements near the source, consisting of the horizontal wind speed and direction. Remote stations can be used to provide information on downstream conditions. However, a small meteorological mast and associated equipment will cost upwards of R20 000 (in 1992) and these off-site measurements are often avoided. Hence a dispersion prediction scheme may not account for downstream changes in wind direction and mixing properties.

By analogy, imagine departing a rural location in the morning and driving at 100 km/hr for some distance. On reaching a congested urban area, your vehicle must slow down to account for increasing traffic density. In many cases the air mass may also decelerate downstream from a source in response to changes in pressure and temperature gradients, and to changes in topography and surface roughness. Further, the mixing properties of the atmosphere are less than adequately estimated and may also change downstream, particularly in subtropical, coastal zoes bordering cool seas.

Given the high cost of establishing remote monitoring sites, it is cost-effective to predict the downstream wind field in a sensible manner based on sound theoretical principles. Where pollutant sources are located near steep topography or on the coast (where land-sea thermal contrasts come into play), mesoscale numerical models can provide essential data inputs to dispersion prediction schemes. Here we describe a model which can predict the meteorological environment over a typical urban-industrial complex, given only the most basic of observations at a single point.

MODEL METHODOLOGIES

The mesoscale numerical model described here is a two dimensional, mixed layer type. Turbulence in the planetary boundary layer results in a homogeneous (mixed) layer which can be parameterised with a single level of data. Considering the interactions of this surface mixed layer with the atmosphere aloft and the surface beneath, the wind field can be predicted over a domain of say 100 x 100 km. The mixed layer, which is characterised with a mean wind, is capped by a temperature inversion. The inversion and atmosphere aloft have spatially and temporally varying lapse rates which respond to forcing from the surface mixed layer. Figure 1 illustrates the idealised structure of the atmosphere used in the mixed layer model.

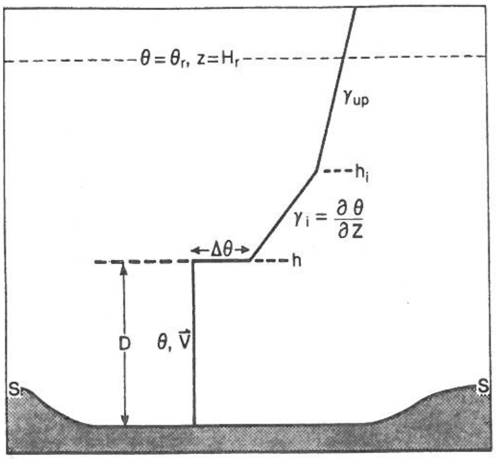

Figure 1 - Schematic view of the vertical profile in the mixed model layer model. 0 = potential temperature, V = wind, h and h_i = inversion base and top respectively, and D is mixed layer depth.

The derivation of the mixed layer equations begins with the dry, hydrostatic Reynolds averaged equations for shallow flow in which the thermodynamic variables have been linearised. Equations are developed for temporal changes in momentum and heat (wind and temperature), continuity of mass, and hydrostatic equilibrium. Wind and temperature are assumed to be homogeneous in the lower mixed layer. Next equations are developed for the depth of the mixed layer and for turbulent mechanical and thermodynamic fluxes. Entrainment across the inversion is parameterised and convective adjustments are catered for. Finally the pressure gradient force is found by taking the horizontal gradient of the integrated perturbation hydrostatic equation.

It is also necessary to consider the response of the overlying atmosphere to forcing from the mixed layer below. The forcing results from motions at the interface which produce thermodynamic changes aloft. These are parameterised by considering the differential density of the upper and lower layers. The lapse rate in the upper layer is modified from the input value, assuming that mesoscale eddies decrease with height.

In many cases nocturnal radiative cooling causes a surface inversion to form and strengthen. A detailed specification of the inversion is necessary to determine the potential for channelling of wind flow in the presence of topography, the intensity of diffusion across the inversion top, and the rate of erosion of the inversion by surface heating after sunrise. The two layer, mesoscale numerical model facilitates such a description. Details of the theoretical basis for the model and all equations are available in Wilczak and Glendening (1988).

MODEL INITIALISATION

To commence operation of the model, a stable land-seabreeze scenario is constructed (Jury *et al* 1990). The geostrophic wind in the upper layer is set equal to zero and the model equations generate an initial wind of 30° at 3 m s^{-1} in the 10 - 30 m layer across the domain. The potential temperature increases from 280°K to 300°K from 100 to 300 m, hence a strong inversion is simulated (as in Figure 1). The drag coefficient increases from a marine value of 10^{-3}, three-fold over land. Diurnal effects are simulated using a surface heat flux applied in a consine function from 0 at 06h00 (sunrise) to a peak of 50 W m^{-2} at 12h00, rather typical of early winter in Cape Town. Topographic values are provided every 1' or 1.8 km, which becomes the model calculation resolution. The domain extends from 33°30' - 34°'S and from 18° - 19°E. In addition to wind flow patterns, parcel trajectories were analysed simultaneously at three points to simulate releases from Koeberg N P S, the Caltex-Kynoch industrial area and the traffic emission peak on the freeway confluence in Woodstock.

RESULTS

The initial wind field at 00h00 is generally from the north (Figure 2). A channel of air flows off the land in the Diep River valley to the north of Cape Town. Northwesterly winds accelerate over the marine areas, most prominently in southeastern False Bay where mountains rise steeply. This acceleration is confirmed by aircraft reports (Jury 1987). Wake effects are evident over the Cape Peninsula and downstream from Tygerberg hill over the industrial area. By 09h00 (not shown) winds become calm across the domain in anticipation of the seabreeze which typically commences about 4 hours after sunrise (Jury and Guastella, 1986).

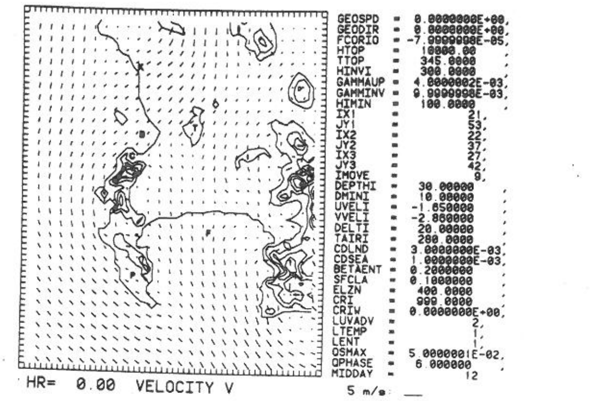

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Figure 2 - Initial wind field for 00h00 illustrating the nocturnal landbreeze draining off the coastal plains. Place names are identified (Cape Town = C, Tygerberg = T, Cape Peninsula = P, Table Bay = B, False Bay = F, Koeberg = K)

By 12h00 winds have turned onto the coast over Table Bay and False Bay (Figure 3), producing a zone of confluence over the central Cape Flats, a phenomenon also found in aircraft-derived wind fields (Jury and Spencer-Smith, 1988). Seabreezes are strongest over the west coast near Milnerton and to the east of Muizenberg on the south coast, although speeds seldom exceed 3 m s^{-1}. Mesoscale wind eddies are generated near Koeberg and west of the mountains of the Cape Peninsula and Cape Hangklip. The seabreeze moves inland over the Cape Flats and reaches the edge of the Paarl valley by 15h00 (not shown).

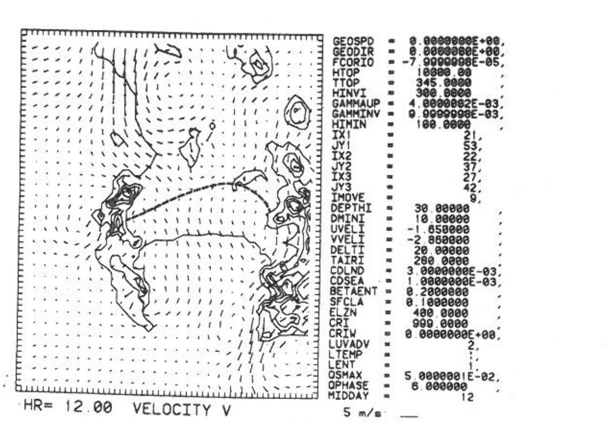

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Figure 3 - Wind field for 12h00 at the time of peak heating illustrating the seabreeze. Confluence line between False Bay and Table Bay circulations is shown by dashed line.

Trajectories of parcels released at 03h00 and 09h00 are shown in Figure 4. Of particular note is the lack of uniformity of trajectories. Also, parcel paths are kinked and move initially southwestwards, seawards, and then towards Cape Town or inland with the advent of the seabreeze. The discrepancy of adjacent parcel paths indicates that pollutant transport is particularly sensitive to source location under land-seabreeze conditions.

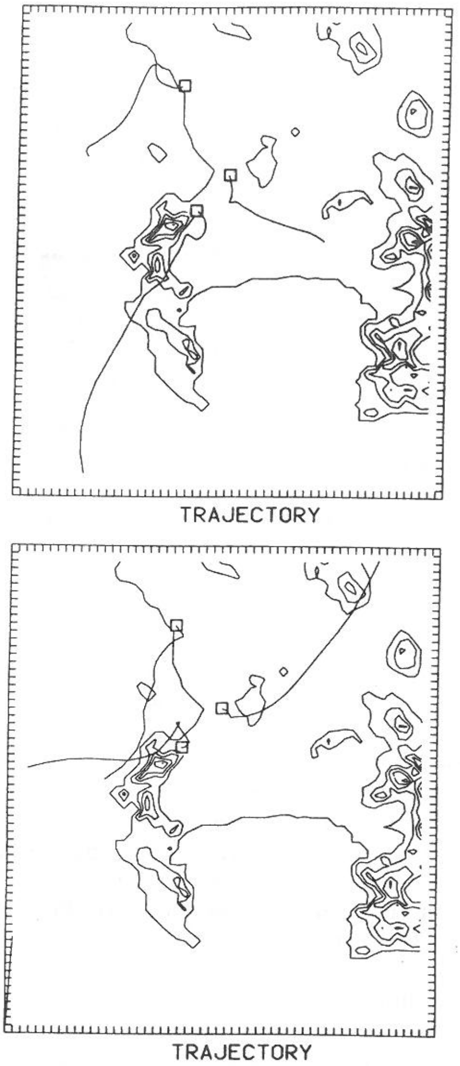

Figure 4 - Parcel trajectory analysis for 03h00 - 09h00 (top) and 09h00 - 15h00 (bottom)

SUMMARY

Numerical simulation of atmospheric boundary layer winds in the Cape town area have been carried out using a two-dimensional mixed layer model. The model incorporates layer-averaged forms of the momentum, thermodynamic, and continuity equations that are obtained by vertical integration over the atmospheric boundary layer. After applying a Reynolds decomposition of velocity and temperature into mean and perturbation components, the latter are neglected to suit a mixed layer scenario. These set of simplified equations were then initialised using a land-seabreeze condition with no geostrophic wind, a low level inversion, and the topography of the Cape Town area.

Results were given for the nocturnal landbreeze and the mid-day seabreeze. The topography, in the presence of a surface inversion, channelled the landbreeze off the coastal plains in the diep River valley north of Cape Town. The Tygerberg hill cast a wake over the high density industrial and traffic areas. Winds became calm at 09h00 as land and sea breezes briefly cancelled. Coincident with mid-day heating, seabreezes were generated over False Bay and Table Bay, producing a zone of confluence over the Cape Flats. A lagrangian parcel analysis demonstrated a divergence of adjacent plume trajectories, a looping of parcel paths and some evidence of pollutant recirculation.

As hardware costs increase, software systems which can accurately predict the environment within which anthropogenic emissions are embedded will become increasingly appealing. In many cases existing dispersion prediction schemes provide linear interpolation of scattered local and remote observations, and do not make use of mesoscale numerical models which can account for time and space varying weather conditions and sharp transition zones. Having simulated the land and seabreeze circulations in a complex area, the next logical step towards the accurate estimation of pollutant concentration distributions is the inclusion of mesoscale numerical models in dispersion prediction schemes.

ACKNOWLEDGMENTS

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