FORMULATION OF THE THERMAL INTERNAL BOUNDARY LAYER IN A MESOSCALE MODEL

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Abstract. Mesoscale models using a non-local K-scheme for parameterization of boundary-layer processes require an estimate of the planetary boundary layer (PBL) height z_i at all times. In this paper, two-dimensional sea-breeze experiments are carried out to evaluate three different formulations for the advective contribution in the z_i prognostic equation of Deardorff (1974).

Poor representation of the thermal internal boundary layer in the sea breeze is obtained when z_i is advected by the wind at level z_i. However, significantly better results are produced if the mean PBL wind is used for the advecting velocity, or if z_i is determined simply by checking for the first 'sufficiently' stable layer above the ground.

A Lagrangian particle model is used to demonstrate the effect of each formulation on plume dispersion by the sea breeze.

1. Introduction

Glendening *et al.* (1986) have evaluated the various mechanisms controlling the planetary boundary layer (PBL) height under conditions of marine air incursion in the Los Angeles Basin. Advection and divergence were found to contribute significantly to the large spatial and temporal variations in PBL depth observed over the region. Accurate prediction of these depths is important for the prediction of boundary-layer winds and temperatures, and also for air-quality forecasts.

Mesoscale models using a non-local K scheme for boundary-layer parameterization usually employ a prognostic equation for PBL height. An example is the formulation developed by Deardorff (1974) from laboratory and numerical studies, and which is used in the Colorado State University (CSU) mesoscale model (Pielke and Mahrer, 1975; McNider and Pielke, 1981). In the following sections, the CSU model is used to evaluate this formulation under sea-breeze conditions in southeast Australia. Two different, but equivalent, modifications to the Deardorff scheme are also tested and found to improve the results considerably. The effect of the original and modified schemes on simulations of pollutant dispersion in the coastal region is also discussed.

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2. The Numerical Model and Modified z_i Formulations

The CSU mesoscale model has been used extensively during the past 15 years to study flow over complex terrain. It is hydrostatic, incompressible, with dry thermodynamics, and employs a terrain-following coordinate system. Surface temperature is obtained from an energy balance equation and a Businger-type similarity formulation is used for fluxes in the surface layer. A summary of the model characteristics, with references, can be found in Table 1 of Segal *et al.* (1988) and details of model validation studies are given in Pielke (1984).

Under unstable conditions, the PBL height z_i in the model is computed from a prognostic equation suggested by Deardorff (1974). This rate equation was found to simulate well the growth and mean structure of the unstable PBL for Day 33 of the Wangara experiment (Pielke and Mahrer, 1975). It can be written as

$$\frac{\partial z_i}{\partial t} = -\mathbf{V} \cdot \nabla z_i + w_i + 1.8(w_*^3 + 1.1 u_*^3 - 3.3 u_*^2 |f| z_i) \Big/ \left(g \frac{z_i^2}{\theta_s} \frac{\partial \theta^+}{\partial z} + 9 w_*^2 + 7.2 u_*^2 \right), \quad (1)$$

where w_i is vertical velocity at z_i, w_* is the mixed-layer convective velocity scale, u_* is friction velocity, f is the Coriolis parameter, g is gravitational acceleration, θ_s is surface-layer potential temperature and $\partial\theta^+/\partial z$ is stability immediately above z_i. Discussion on a representative value for the advecting velocity $\mathbf{V}$ follows.

Observations show that the penetration of relatively shallow cool air into a warmer and deeper convective layer as a sea breeze moves inland leads to the formation of a thermal internal boundary layer (TIBL) within the original PBL. In a numerical model employing Equation (1), this reduction in z_i can only occur through the advection term $-\mathbf{V} \cdot \nabla z_i$ as all other terms (except w_i) will increase z_i, as long as sensible heat is being added at the ground. In the conventional representation of advection, currently used in this mesoscale model, $\mathbf{V}$ is the velocity at level z_i. However, in the rate equation for z_i derived by Glendening *et al.* (1986) from the Boussinesq continuity equation, the mean PBL wind is used as the advecting velocity. In this paper, both representations are evaluated, with the former being referred to as scheme A and the latter as scheme B (see Table I).

Following a suggestion by Physick (1988), a further scheme (C) in which the advection term is omitted from Equation (1), and its contribution calculated in an alternative manner, is also tested. In formulation C, the stability of each layer in a column is checked every timestep, from the ground upwards, to find the first layer with a lapse rate greater than a critical value. If such a layer exists within the current PBL, the PBL height is reduced to the top of that layer. However, the PBL is allowed to grow according to Equation (1) (minus advection) if no such layer is found. The critical stability value was set to 1 K km^{-1}, following Anthes

TABLE I

Schemes used for prediction of PBL height

PBL height z_i scheme	Comments
A	Advection of z_i by wind at z_i
B	Advection of z_i by mean PBL wind
C	No advection, but z_i adjusted according to stability

(1978) who used such a criterion to define the PBL top in a sea-breeze model.

Under unstable conditions in the model, the vertical profiles of exchange coefficients for momentum, heat and moisture are obtained by fitting a cubic polynomial between coefficient values at the top of the surface layer and negligibly small values at z_i (O'Brien, 1970). Thus in such a non-local scheme, the value of PBL height can be expected to have a significant effect on turbulent transport throughout the mixed layer.

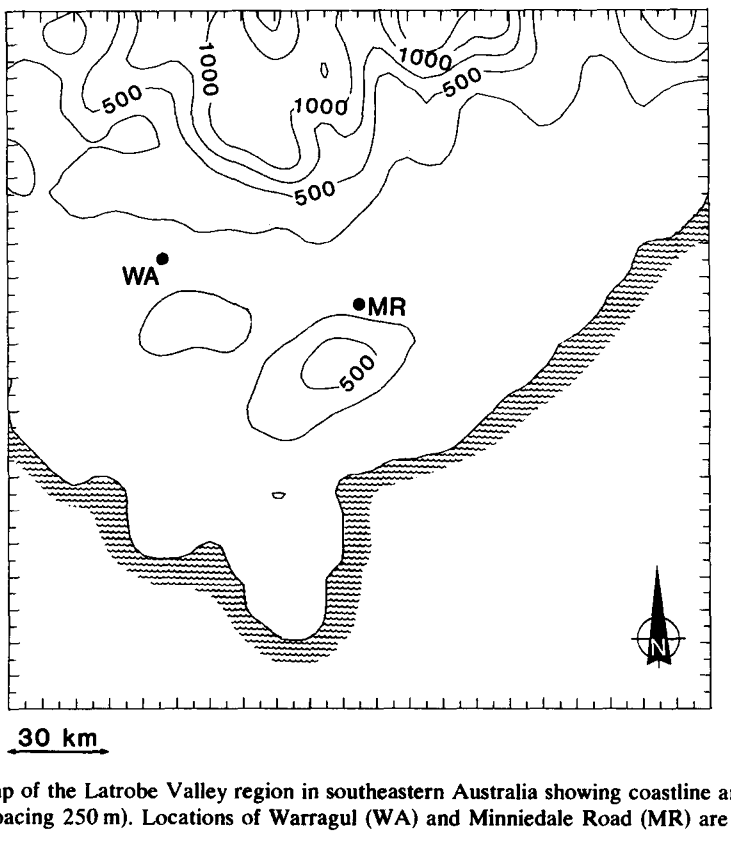

Fig. 1. Map of the Latrobe Valley region in southeastern Australia showing coastline and elevation contours (spacing 250 m). Locations of Warragul (WA) and Minniedale Road (MR) are also shown.

3. Initial Conditions

Numerical results are compared to data from a radiosonde station (Minniedale Road, latitude 38° 12.5′ S, longitude 146° 35.1′ E) in the Latrobe Valley of southeastern Australia. Flat bottomed and about 15 km wide on average, the Latrobe Valley runs from Warragul 100 km east of Melbourne to the coastline, a further 130 km to the east (Figure 1). Further details of its geography can be found in Physick (1982).

In the summertime, sea breezes regularly arrive at Minniedale Road, 50 km up the Valley from the coastline, between 1500 and 1600 Eastern Standard Time (EST = Greenwich Mean Time + 10 h). On 9 March, 1985 under clear skies and a weak synoptic pressure gradient in the lowest 3 km, a sea breeze reached Minniedale Road at 1550 EST. Figure 2 shows potential temperature profiles from 1500 and 1700 EST radiosonde ascents. A mixed layer more than 2000 m deep at 1500 EST has been undercut by the incoming sea breeze (onshore flow 1200 m deep), with the accompanying TIBL extending to about 350 m. These data were obtained during a special two-week observing period. Over this time, TIBL depths of 400, 450 and 650 m were observed on three further occasions.

The model integrations are started at 0200 LST (Local Solar Time) with a

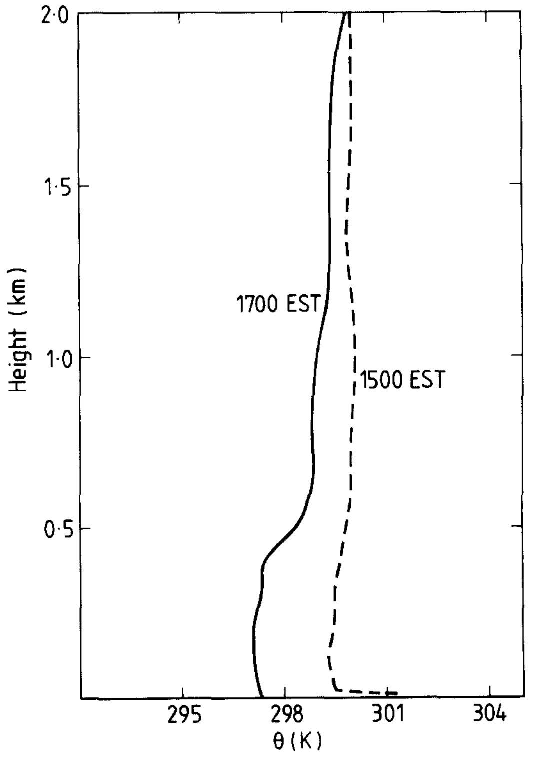

Fig. 2. Potential temperature profiles from Minniedale Road, at 1500 and 1700 EST, 9 March, 1985.

potential temperature profile based on the 0800 EST sonde ascent at Minniedale Road on 9 March, 1985. The latter contains a superadiabatic profile to 40 m, but this was removed for the model profile by extrapolating from the higher-level stable layers to the ground. This gave a land surface temperature of 281.7 K, compared with 290 K (observed) for the sea. Observed winds in the Valley ahead of the sea breeze were light and variable, although predominantly parallel to the coast. The synoptic wind in the numerical runs was set to zero.

There is no terrain included in the model, and the simulation is two-dimensional with a grid length of 5 km and time step of 30 s. The model top is at 7 km and there are 17 levels in the vertical.

4. Results

4.1. PBL HEIGHT

Figure 3 shows the horizontal distribution of z_i at 1700 LST. In the coastal region, scheme A generates values of z_i which are not very different from those ahead of the sea breeze (gridpoint 21 at this time). Values obtained with schemes B and C appear far more realistic and give much better agreement with the observed values of the previous section. Advection in schemes A and B is performed by upwind interpolation using a cubic spline, with the application of a selective spatial filter to the z_i field each timestep. When no filter is applied in scheme B, the z_i curve is very similar to that of scheme C, apart from moderately

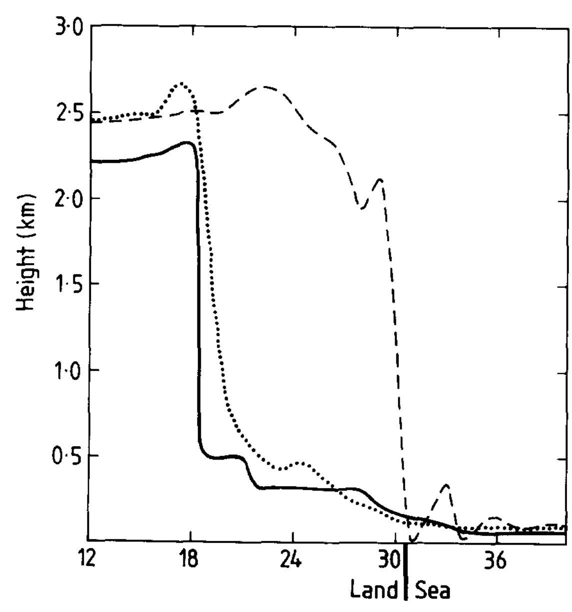

Fig. 3. Horizontal distribution of PBL height at 1700 LST for runs incorporating schemes A (dashed line), B (dotted line) and C (solid line). Grid point numbers are indicated on the abscissa. Use $\Delta x = 5$ km to convert to distance.

large oscillations upwind of the sea-breeze front. However, use of the filter is necessary as these oscillations affect the velocity and temperature fields. No filter is used in scheme C.

4.2. Temperature and Wind Fields

The observed potential temperature profile 50 km inland at 1700 EST is shown in Figure 4. Also shown are model profiles at grid point 21, 50 km from the coast. A TIBL of about 297 K with a top near 325 m is obtained with schemes B and C, in good agreement with the observations. At higher levels, the model results are 0.5 to 1.0 K warmer than the data. At this time, the sea-breeze front is at grid point

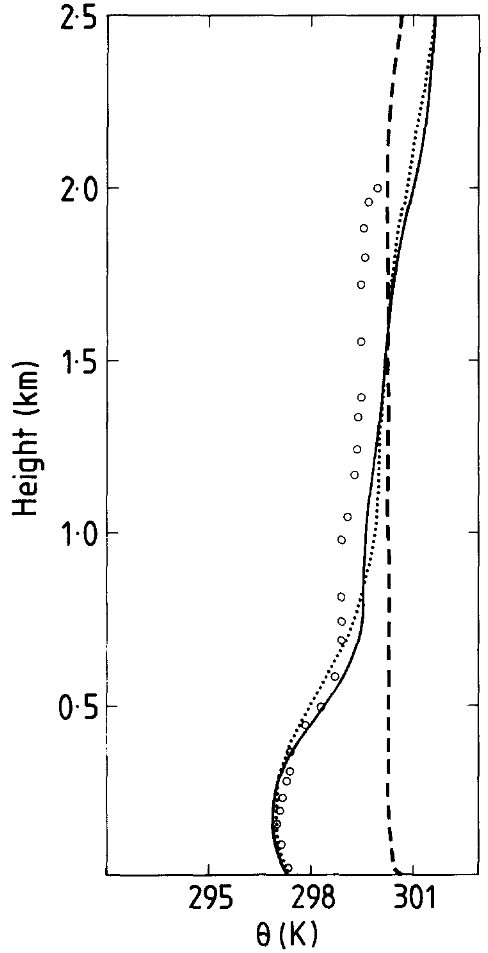

Fig. 4. Vertical profiles of potential temperature at 1700 LST for schemes A (dashed line), B (dotted) and C (solid) at gridpoint 21, 50 km from the coast. Also shown are observations from Minniedale Road, 50 km inland, at 1700 EST on 9 March, 1985 (open circles).

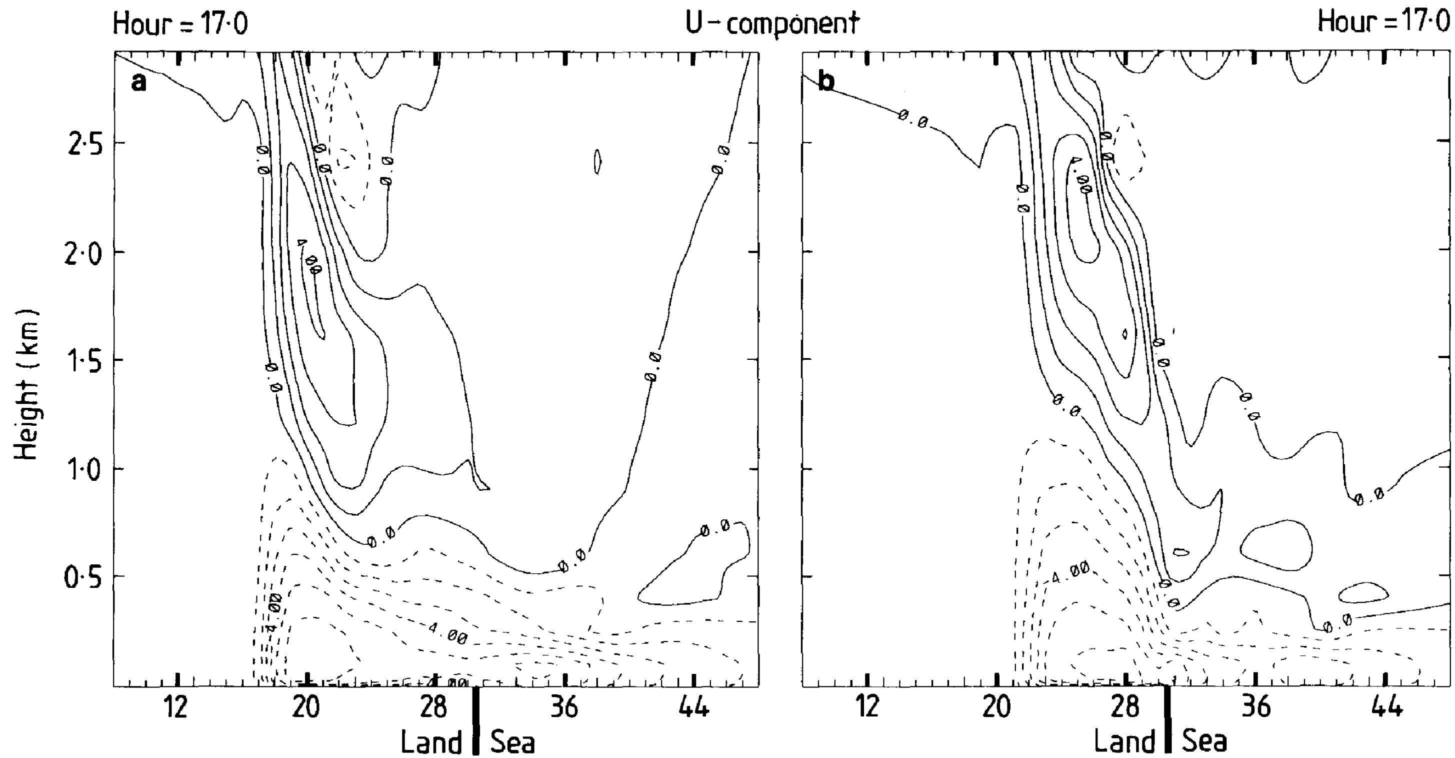

Fig. 5. Vertical cross-section of wind component normal to the coast at 1700 LST for (a) C, and (b) A PBL height prediction schemes. Contour interval is 1 m s^{-1}. Grid point numbers are indicated on the abscissa. Using $\Delta x = 5$ km to convert to distance.

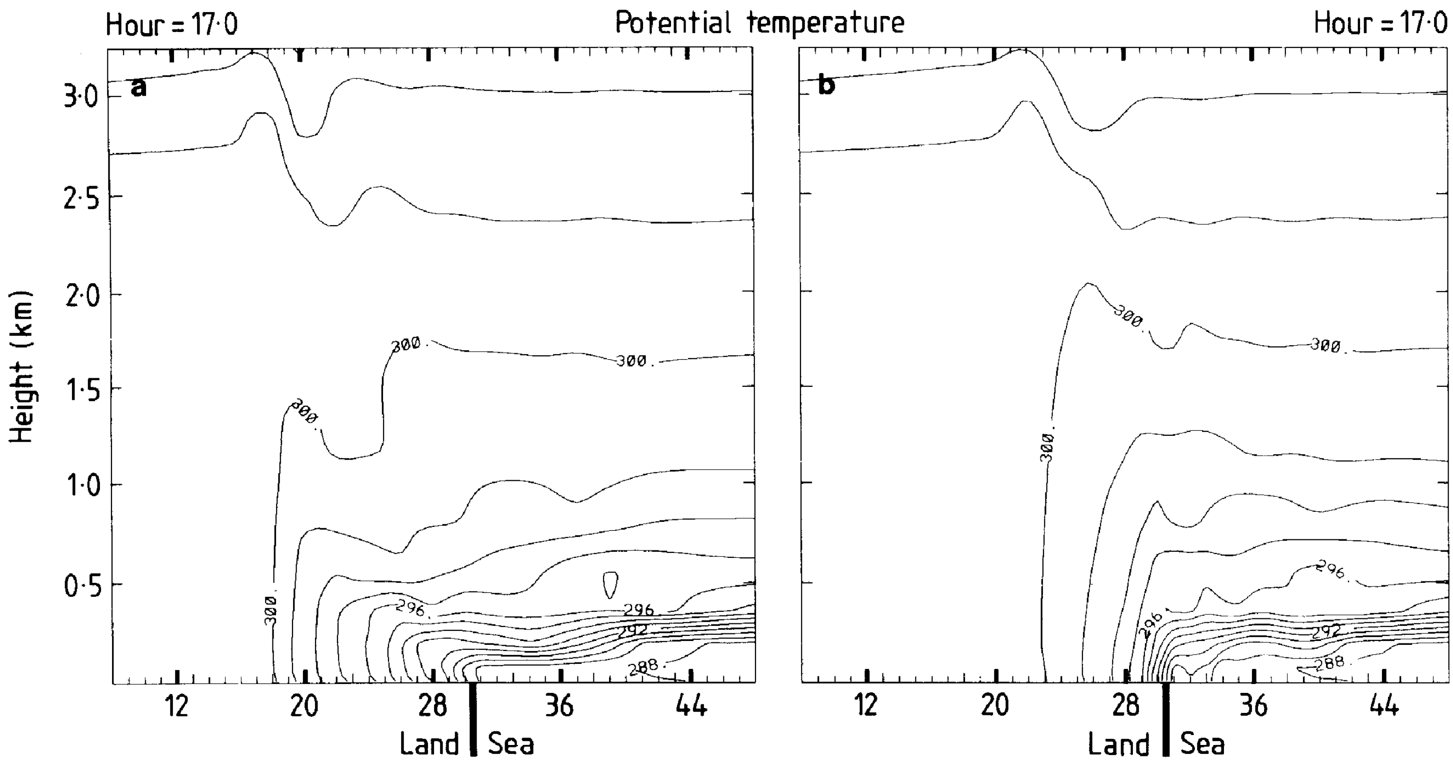

Fig. 6. Vertical cross-section of potential temperature at 1700 LST for (a) C and (b) A PBL height prediction schemes. Contour interval is 1 K. Grid point numbers are indicated on the abscissa. Use $\Delta x = 5$ km to convert to distance.

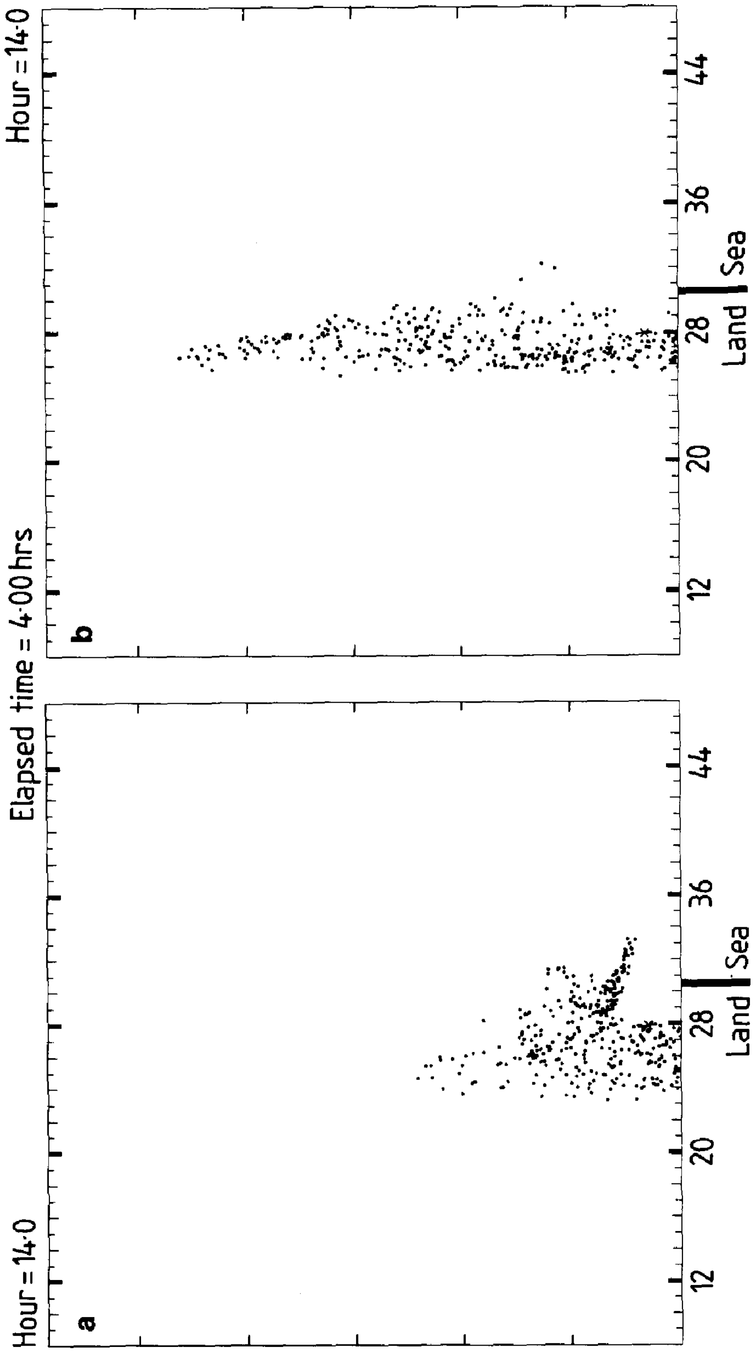

Fig. 7. Particle distribution for (a) C and (b) A PBL height schemes at 1400 LST. Particles were released every 40 seconds, beginning at 1000 LST, at a height of 150 m and 15 km inland from the coast. Grid point numbers are indicated on the abscissa. Use $\Delta x = 5$ km to convert to distance.

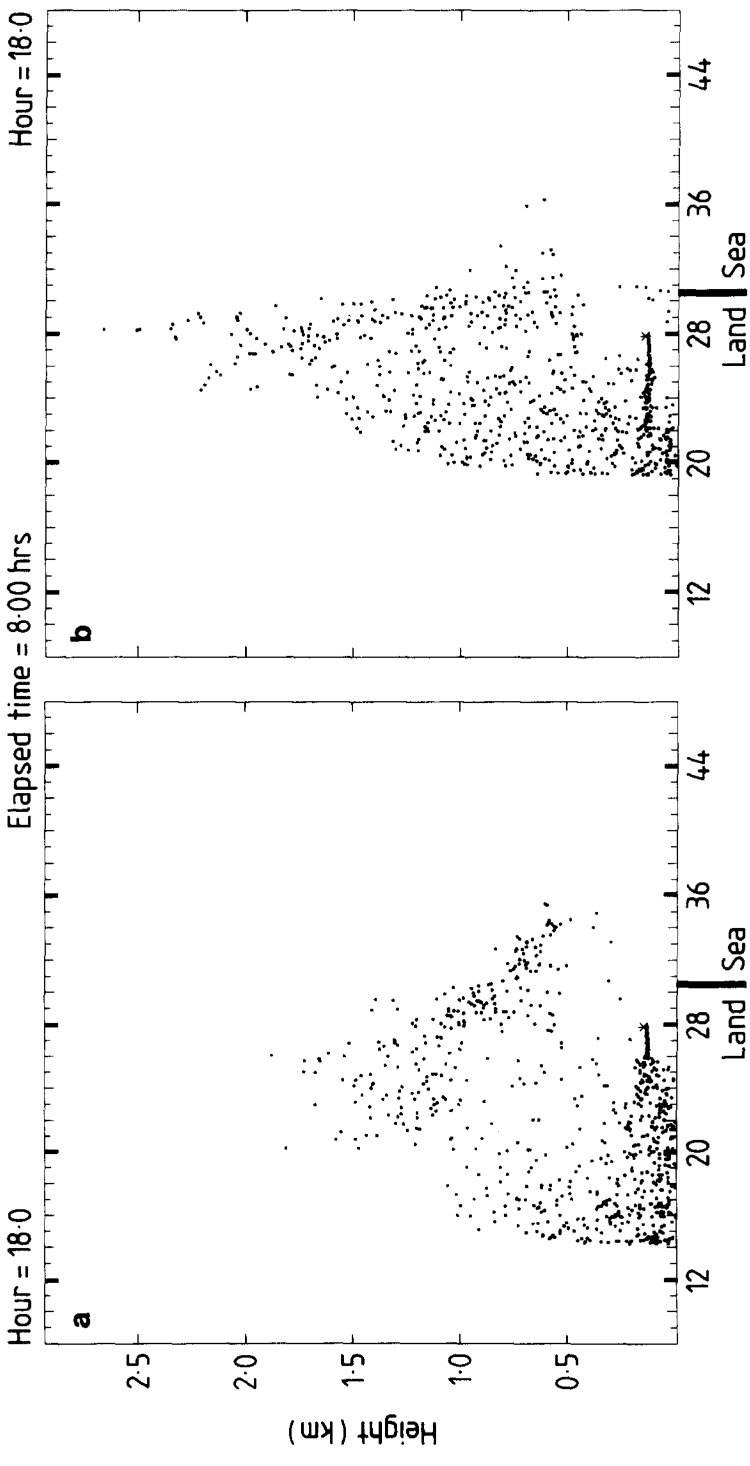

Fig. 8. As in Figure 7, but at 1800 LST.

17, 20 km farther inland, whereas the scheme A sea breeze is just about to reach grid point 21: hence, the deep well-mixed layer shown in Figure 4 for scheme A. Low-level (below 400 m) temperatures which agree with the 1700 EST data can be obtained using scheme A if an onshore wind of 3 m s^{-1} is specified, but this is not representative of the synoptic situation. Also, for this wind-speed scenario, predicted temperatures between 400 and 1400 m are cooler than observed by up to 2 K, and the sea-breeze arrival time is 3 h earlier than observed.

The slower penetration rate of the scheme A sea breeze, compared to B and C, is a direct result of the relatively high values of mixing depth in the incoming sea air (Figure 3). Low-level easterly momentum of the sea breeze is 'diluted' with upper return flow westerly momentum to a greater extent in this scheme and so a weaker sea breeze results.

The depth and penetration rate differences discussed above can also be seen in the wind and temperature cross-sections at 1700 LST for schemes C and A (Figures 5 and 6). Negligible differences exist between schemes B and C and only results from C are presented here and in the following section. Note that a weak TIBL develops with scheme A (Figure 6b), but its depth is not represented by the predicted z_i values (Figure 3) used in the model's turbulent mixing scheme.

4.3. Particle Dispersion

The wind and turbulence fields from the model runs were used to drive a Lagrangian particle dispersion model (for details, see Pielke *et al.*, 1987). A source releasing a particle every 40 s at the 150 m level from 1000 LST onwards, was located 15 km landward of the coastline. Figure 7 shows the particle distribution for the two schemes at 1400 LST. Quite different patterns result, with scheme C confining the particles to lower levels, as expected from the previous discussion. This result is due not only to the TIBL produced in scheme C, but also to the fact that this scheme brings about a faster penetration rate for the sea breeze. Convective mixing in the boundary layer prior to the later sea-breeze arrival with scheme A has lifted particles to higher levels in Figure 7b than in Figure 7a.

From the 1800 LST distribution (Figure 8), it is clear that particles released into the sea breeze are confined within the TIBL until they reach the front, a region of convergence, where they both rise and congregate. Convection has ceased by this time; and in the following hours, particles are trapped in the lower levels. With scheme A (Figure 8b), the unrealistically large values of PBL height in the sea breeze allow particles released into the marine air to be mixed to depths much greater than those of scheme C and also greater than the depth of the inflowing sea air.

5. Sensitivity Studies

Several sensitivity tests have been performed. When a value of 2 K km^{-1} was used for the critical stability value in scheme C (instead of 1 K km^{-1}), it was found that PBL heights near the leading edge of the sea breeze did not decrease quickly enough after frontal passage.

Reducing z_i to the *bottom* of the first stable layer (instead of the top) produced slightly lower PBL heights which were also spatially noisier. This noise was also present in the warm air inland ahead of the sea breeze, with adjacent values occasionally differing by up to 200 m. Consequently, wind and temperature fields were also a little noisier, but the general structure and values remained the same.

The schemes have also been tested over a region of complex orography and coastline. With scheme C, large differences were found between values of z_i above ridges and valley floors (e.g., 2500 m compared to 400 m) due to vertical motion associated with upslope winds, but the solution showed little sign of noise, and velocity and temperature fields were very similar to those with scheme A, except in coastal regions. Scheme B produced similar results to C, except that the difference between values of z_i over ridges and valleys was not as great, due to the use of a filter on z_i for each time step in B. Consequently, velocity and temperature fields appeared a little smoother than those of scheme C. R. Kessler (Systems Applications Inc., California, personal communication) has also found improved results using scheme B after noting that the use of scheme A caused deep PBLs on ridgetops to be advected down slopes by the return flow of upslope circulations.

6. Concluding Remarks

It has been shown that unrealistic PBL heights z_i are obtained in sea-breeze simulations when advection in the prognostic equation for z_i is carried out by winds at the PBL top (scheme A). Much improved results are obtained when advection of z_i is assigned to a wind averaged over the PBL depth (scheme B). An alternative scheme (C) in which no advection is carried out, but in which z_i is assigned to the first level above the ground at which a critical value of stability is exceeded, produces very similar results to scheme B. Differences in z_i predictions between scheme A and scheme C (or B) also significantly affect pollutant distribution when the mesoscale model provides wind and turbulence fields for a dispersion model.

In comparing schemes B and C, a sharper gradient between PBL heights in land air and modified sea air may be an advantage of scheme C, although in complex orography the smoother z_i fields of B, due to filtering, may be preferred. However, differences in the general structure of wind and temperature fields are small.

Our findings are relevant to the results of Steyn and McKendry (1988) who evaluated the ability of the CSU model, using scheme A, to simulate a sea breeze in complex terrain. While their comparison of wind and temperature fields with data was good, predicted PBL heights in coastal locations were considerably higher than observed. Steyn and McKendry attributed this behaviour to numerical smoothing in the model, but our results suggest that the TIBL formulation is the more likely cause.

It should be noted that the modifications suggested in this paper are only necessary for boundary-layer schemes requiring a PBL height for use in a non-local convective mixing formulation. Local, and the increasingly popular turbulent kinetic energy schemes should generate their own TIBL, as demonstrated by Arritt (1987) in a numerical study of lake-breeze characteristics.

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