NUMERICAL SIMULATION OF SEA BREEZES OVER THE AUCKLAND REGION, NEW ZEALAND - AIR QUALITY IMPLICATIONS

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Abstract. The air pollution meteorology of a typical sea breeze day is investigated using the Colorado State University Mesoscale Model. Results are qualitatively compared with observations and reveal a complex wind field characterised by migratory sea breeze convergence zones. Associated with these features, the model predicts enhanced upward vertical velocities and 'doming' of the planetary boundary layer (PBL). The diurnal variation in PBL depth is shown to vary markedly at different locations and is dependent on position in relation to the migratory convergence zones. These complex spatial and temporal variations in the wind and PBL depth have important implications for air quality in Auckland and confirm that simple Gaussian or box trajectory approaches are inappropriate for air quality assessment in such environments. The inclusion in the model of variable surface properties, a dynamic synoptic state and improved PBL parameterisations, as well as coupling with a Lagrangian particle model, are recommended if the model is to be used as a tool for further air quality studies in the Auckland area.

1. Introduction

An understanding of variations in both planetary boundary layer depth (hereafter referred to as the PBL) and the three-dimensional wind field is an important requirement for the evaluation of pollutant transport and diffusion within the PBL. This is especially true in complex coastal environments where a variety of phenomena including land-sea breezes, convergence zones and the development of thermal internal boundary layers may markedly complicate dispersion processes (Lyons, 1975; Hsu, 1988; Hanna, 1987). In standard dispersion modelling approaches, both the wind field and the PBL depth are frequently treated very simply. For example, PBL depth is often assumed to be spatially homogeneous and to follow a smooth diurnal variation which is approximated from indirect methods based on radiosonde soundings (Holzworth, 1967). However, previous studies (Glendering *et al.*, 1986; Edinger, 1959) in Los Angeles suggest that marked spatial and temporal variations in PBL depth may occur over coastal regions during onshore flow. Unfortunately, observational networks are usually too sparse to resolve the detailed spatial and temporal variations in both the wind and PBL depth fields that are required for detailed air quality investigations.

One approach to estimating wind and PBL depth fields without resorting to an expensive mesoscale network is the application of a mesoscale numerical model. Current models employ sophisticated PBL parameterisations and are capable of adequately representing the processes which determine wind and PBL depth within a spatial and temporal context. This approach has been demonstrated

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previously by Segal *et al.* (1982) for typical summer daytime conditions over Chesapeake Bay using the Colorado State University (CSU) mesoscale model (Pielke, 1974).

The greater Auckland area (Figure 1), by virtue of its large population, industrial activities and high density of motor vehicles, has significant air pollution potential. This is particularly true in summer when radiation inputs are strongest (Brasell, 1982) and relatively light onshore sea breezes develop over the narrow isthmus. In this investigation, the CSU mesoscale model is used to model a typical sea breeze event over the Auckland region, with the objective of identifying salient aspects of regional air pollution meteorology. Emphasis is placed on the spatial and temporal variations in wind speed and direction and PBL depth over the region that are pertinent to air quality assessments. In particular, the effect on PBL depth of the complex migrating sea breeze convergence lines that have been observed to develop over the isthmus (McGill,

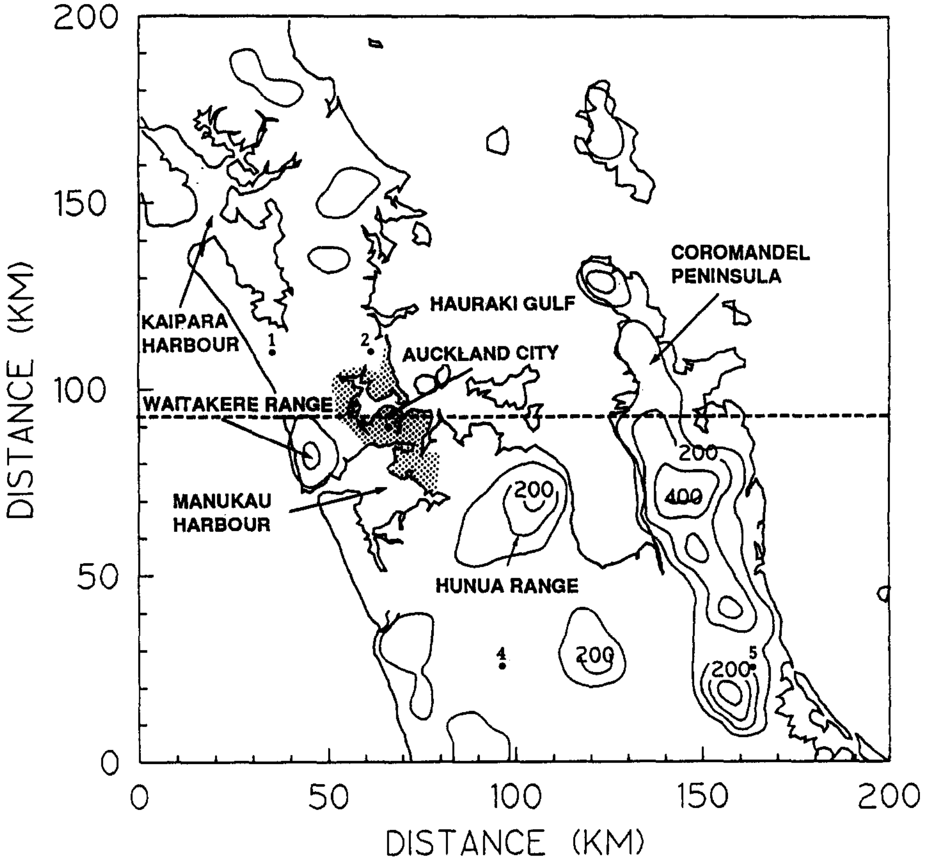

Fig. 1. Map of the modelling domain showing Auckland city, terrain (100 m contours) and five labelled sites referred to in Figure 8. The cross-section used for Figure 5 is denoted by a dashed line.

1987) is examined. Although convergence lines have been studied at larger scales (Noonan and Smith, 1987; Pielke, 1974), little attention has been given to the air quality implications of local-scale convergence features. Such features have been observed to influence the diurnal variation in PBL depth at Fullerton in the Los Angeles basin (Edinger, 1959). The day chosen for simulation has been investigated in detail by McGill (1987) as part of an observational study of Auckland sea breezes. Model predictions are compared with these observations to give a qualitative evaluation of model performance.

2. Model and Input Data

The CSU mesoscale model has been described in detail by Pielke (1974), Pielke and Mahrer (1975, 1978) and Mahrer and Pielke (1976, 1977, 1978). In summary, the model, which was developed for the study of thermally-forced, terrain-induced mesoscale phenomena, is hydrostatic and consists of the equations of motion, moisture and continuity written in a three-dimensional terrain-following coordinate system. It also includes a surface heat budget and detailed PBL parameterisation.

This model has been used widely for a broad range of applications. Previous studies in Australasia include sea breeze investigations by Abbs (1986) for the Melbourne area, Noonan and Smith (1987) for the Cape York Peninsula and McKendry *et al.* (1988) for the Cantebury plains. Verification studies have been carried out by Pielke and Mahrer (1978), Segal *et al.* (1982) and Steyn and McKendry (1988) while notable air quality applications of the model include studies by Segal *et al.* (1982), Arritt *et al.* (1988), Segal *et al.* (1988) and Pielke *et al.* (1983).

PBL depth (above ground level) is calculated in the model by a semi-empirical prognostic formula developed by Deardorff (1974). This equation is necessary to close the parameterisation scheme for vertical turbulent mixing in the convective PBL. In Deardorff's equation, the heated PBL grows in proportion to the surface heat flux and mesoscale vertical velocity, and in inverse proportion to the overlying stability. This formulation was developed under assumptions of flat terrain and horizontal homogeneity (Wangara day 33) and has been shown to be very realistic under daytime conditions when the variation of PBL depth is strongly influenced by surface heating (Pielke and Mahrer, 1975: Yu 1977: Steyn and McKendry, 1988). However, it is not considered to be valid under conditions of significant cumulus cloud development (Pielke and Mahrer, 1975). This is not a major limitation in the present study as only scattered stratocumulus was observed on the day simulated (McGill, 1987). Synoptic-scale subsidence was included in the model to account for the presence of a high pressure ridge over the region. The method used is outlined by Steyn and McKendry (1988).

The day selected for analysis was 29 January, 1981. A ridge of high pressure extending over the model domain from an anticyclone to the north-east (Figure

2) gave north-westerly gradient flow over the Auckland region. The vertical profiles of potential temperature and specific humidity used to initialise the model were derived from the 1100 New Zealand Standard Time (NZST) radiosonde ascent from Auckland Airport. The temperature profile at this time was characterised by a 2°C temperature inversion from 1.15 to 1.6 km. The initial profiles at 0600 NZST (after dynamic initialisation) are shown in Table I.

The terrain used in the model is shown in Figure 1 and was derived from a 1 km resolution digital terrain model obtained from Geophysics Division, Department of Scientific and Industrial Research. Maximum terrain heights are found on the Coromandel Peninsula (600–800 m), the Hunua ranges (450–600 m) and the Waitakere ranges (250–500 m).

Computations were performed on a 49 × 42 × 13 (x, y, z) grid with a horizontal

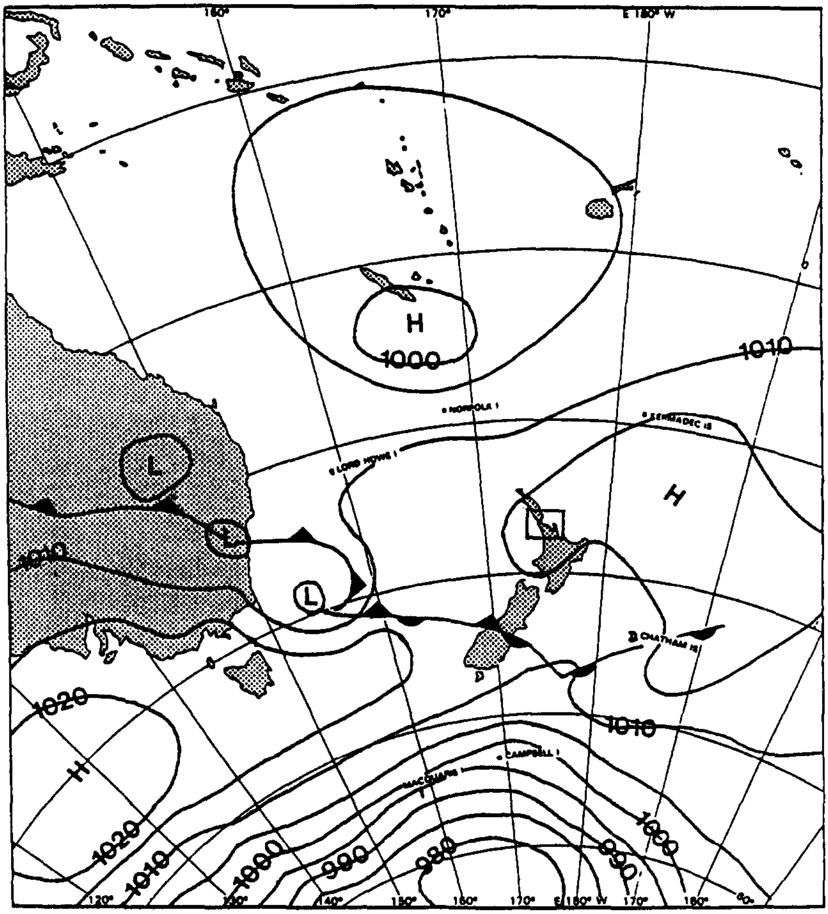

Fig. 2. Synoptic sea level pressure analysis of 0000 UTC (1200 New Zealand Standard Time) on 29 January, 1981. The modelling domain is represented by the boxed area.

TABLE I

Initial vertical profile of potential temperature (θ) and specific humidity (q) at model levels at 0600 NZST

Z (m)	θ (K)	q (kg kg^{-1})
10	290.7	0.0102
40	290.9	0.0101
100	291.3	0.0099
250	292.5	0.0097
500	292.6	0.0093
750	293.2	0.0090
1000	295.3	0.0089
1500	301.5	0.0040
2000	304.9	0.0032
3000	310.6	0.0016
4000	317.0	0.0012
5000	319.5	0.0010
6000	322.9	0.0006

grid spacing of 5 km, except at the four outermost grid points where it expands linearly to 20 km (only the innermost grid is shown in the subsequent figures). Vertical grid spacing was variable with greatest resolution near the surface (Table I). An absorbing layer was included above level 10 to control the reflection of vertically propagating wave energy (Klemp and Lilly, 1978; Mahrer and Pielke, 1978). Input parameters used to initialise the model are listed in Table II.

TABLE II

Input parameters used to initialise the model

Timestep	60 s
Horizontal Filter Coefficient	0.02
Mean latitude	37.0 °S
Land Surface:	
(a) albedo	0.23
(b) roughness length	0.20 m
Initial PBL depth	150 m
Initial surface pressure	101.6 kPa
Synoptic wind direction	315°
Synoptic wind speed	3 m s^{-1}
Free atmospheric lapse rate	6 K km^{-1}
Soil characteristics	
(a) density	1300 kg m^{-3}
(b) specific heat	1549.4 J kg^{-1} K^{-1}
(c) diffusivity	5×10^{7} m^{2} s^{-1}
(d) wetness*	0.3

* A parameter between 0 and 2.

The simulation commenced at sunrise and was preceded by a 4 h period of dynamic initialisation in which surface cooling was permitted to occur. This procedure enabled nocturnal flow features to be represented at sunrise and thereby permitted a more realistic initial state. Initial PBL depth over land was set at 150 m, a depth recorded by acoustic sounder near Auckland city and considered to be reasonably representative of the whole region.

3. Results

In the following analysis, one horizontal level (10 m) and one vertical east-west cross-section (through Auckland city) are used to display wind speed and direction results. In addition, the horizontal vertical velocity field at level 4 (250 m) and the contoured field of PBL depth are displayed. Results are presented for the four daytime hours of 0900, 1200, 1500 and 1800 LST. Where possible, qualitative comparisons with McGill's (1987) observations are made.

3.1. THE WIND FIELD

The evolution of the low level wind field throughout the simulation is presented in Figure 3. At 0900 LST, sea breezes are predicted along eastern coastlines producing distinct convergence lines especially along the Coromandel Peninsula, to the south-west of the Hauraki Gulf and to the north of Auckland. At this time, sea breeze penetration is of the order of 5–10 km. Sea breezes are well developed along all coastlines by 1200 LST and result in four distinct convergence lines. Over the centre of the Coromandel Peninsula, marked convergence is predicted between the easterly sea breeze and the sea breeze augmented gradient flow from the Hauraki Gulf. To the north of Auckland, convergence occurs between the east coast sea breeze, the gradient northwesterly flow (itself augmented by sea breeze effects) and what happens to be a more local circulation developed in the Kaipara Harbour. Finally, two convergence lines are predicted to the south of Manakau harbour. One is associated with the sea breeze from the east coast penetrating westward and one with the sea breeze from the west coast penetrating eastward. Between these convergence lines, relatively light north-westerlies prevail. By midafternoon, the two convergence lines to the south of Auckland city have merged while the convergence line to the north of Auckland has pushed farther westward. At this time, wind speeds at 10 m are of the order of 5–6 m s^{-1} over land and 3–4 m s^{-1} over the Hauraki Gulf. Finally, by 1800 LST the convergence line to the north of Auckland has penetrated to within 10 km of the west coast. Elsewhere the dominance of the sea breeze circulation appears to be diminished with a backing of the winds in the Hauraki Gulf and a return to northwesterly flow over the Coromandel Peninsula as thermal forcing decreases in late afternoon.

The model predictions are in general agreement with observations by McGill (1987) for similar synoptic conditions (Figure 4). Although observed winds were

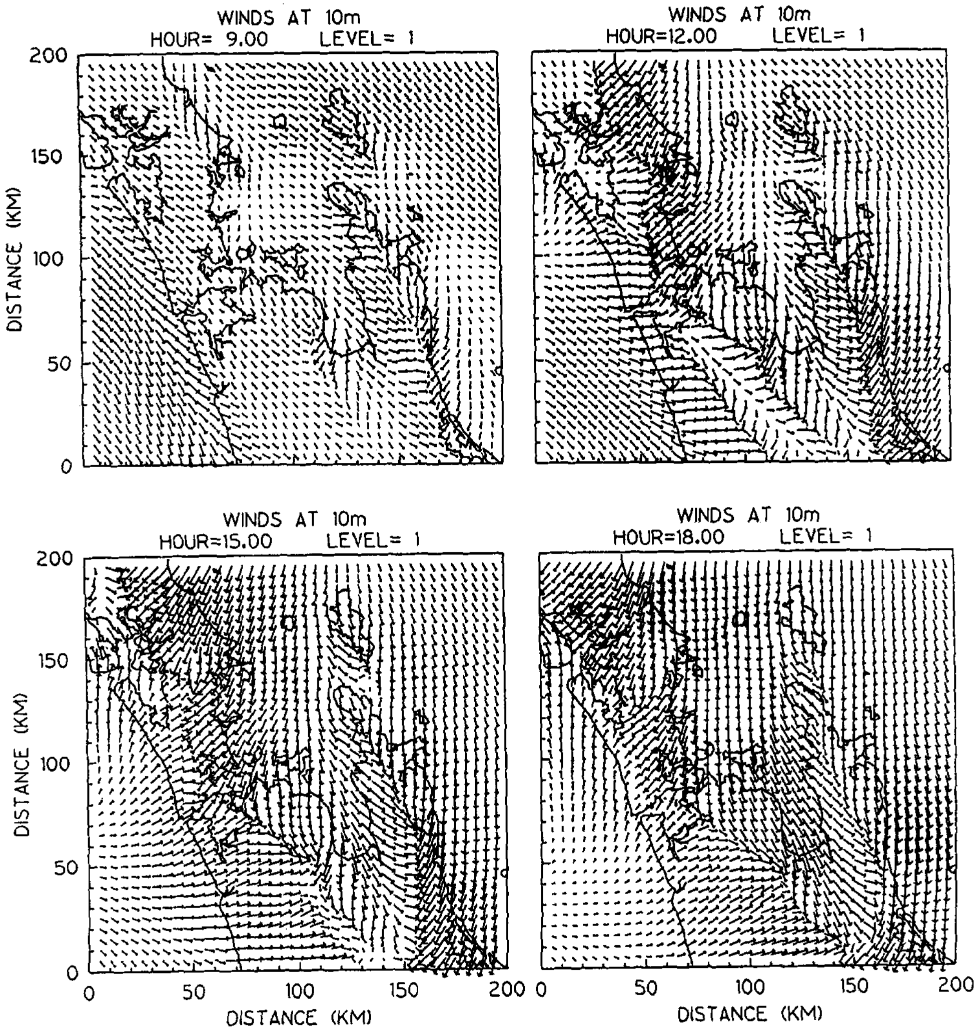

Fig. 3. Predicted horizontal wind fields at 10 m above ground level for 0900, 1200, 1500 and 1800 LST (A wind vector of 4 grid lengths represents 10 m s^{-1}).

lighter and more variable than predicted at 0900 LST, by 1200 LST there is remarkable agreement between predicted and observed fields over the region covered by McGill's (1987) study. Not only are surface wind speeds of a similar magnitude but also the observations suggest the presence of the twin convergence lines south of Auckland city predicted in the simulation. The predicted evolution of the wind field through to mid-afternoon is also in agreement with observations. However, late in the afternoon the convergence line of the centre of the isthmus was observed to migrate eastward to an offshore position. This development may have been a result of the evolving synoptic situation. If this

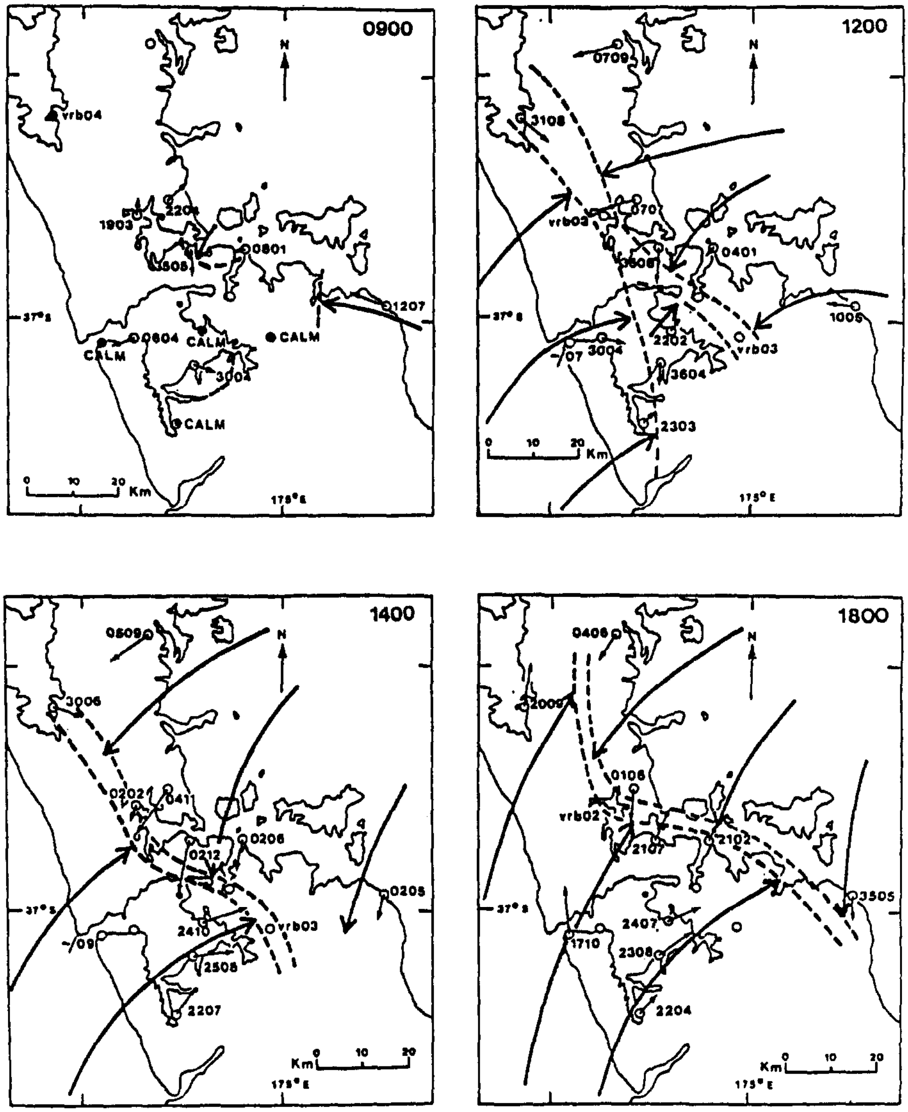

Fig. 4. Observed evolution of the low-level wind field and convergence zones around Auckland on 29 January, 1981 (after McGill, 1987). Times are Local Standard Time. (Notation: 2403 represents a wind of 3 knots from 240°; 1 knot = 0.51 m s^{-1}). Large arrows represent the general low level flow.

was the case, the eastward movement of the convergence zone could not be represented in the simulation as the synoptic state was assumed to be static.

In Figure 5 contoured values of the east-west (U) component of the horizontal wind vector for a cross-section through Auckland city are used to display significant features of the vertical wind structure (shaded areas represent easterly flow). At mid-morning, easterly flows associated with the sea breeze inflow

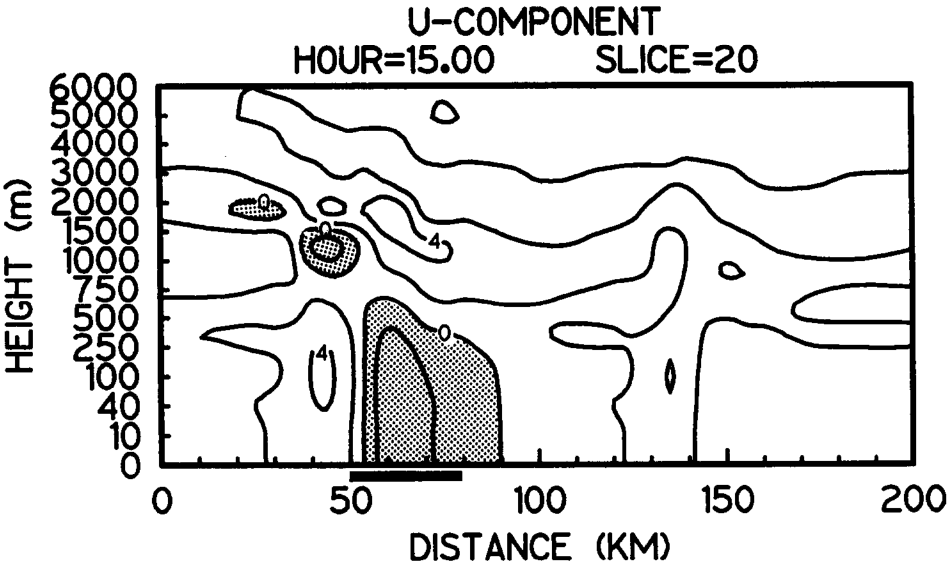

Fig. 5. Predicted east-west cross-section (shown in Figure 1) through Auckland city showing contoured values (contour interval 2 m s^{-1}) of the east-west (U) horizontal velocity component at 1500 LST. (Shaded areas represent winds having an easterly component. Underscore on X-axis denotes Auckland city).

developing over eastern coastlines are predicted to reach a depth of 250 m over the isthmus. At this time, there is little evidence of return flow associated with the circulation. However, by midafternoon the cross-section shows considerable vertical structure. Sea breeze inflow depths are predicted to reach 500–750 m over the isthmus with marked return flows between 1000 and 2000 m for both the westerly and easterly sea breezes. For the case studied, McGill (1987) observed sea breeze inflow depths over Auckland city of 320 and 480 m at 1310 LST and 1500 LST, respectively. Although in broad agreement with the observations of sea breeze inflow, the model appears to overpredict the depth of the sea breeze return flows. Limited observations by McGill (1987) suggest a return flow between 320–830 m around midday.

The evolving horizontal field of vertical velocity is presented in Figure 6. The level chosen (250 m) for display is at the level of maximum predicted vertical velocities. At 0900 LST, vertical velocities are generally small and positive over land with little organisation in the field. However, by 1200 LST the field is considerably more organised with upward velocities (positive) in excess of 20 cm s^{-1} associated with uplift in the convergence zones shown in Figure 3. Between the convergence lines to the south of Auckland and around concave coastlines (e.g., the Kaipara Harbour), divergent flow results in subsidence. As expected, the regions of maximum uplift migrate with the convergence lines. By

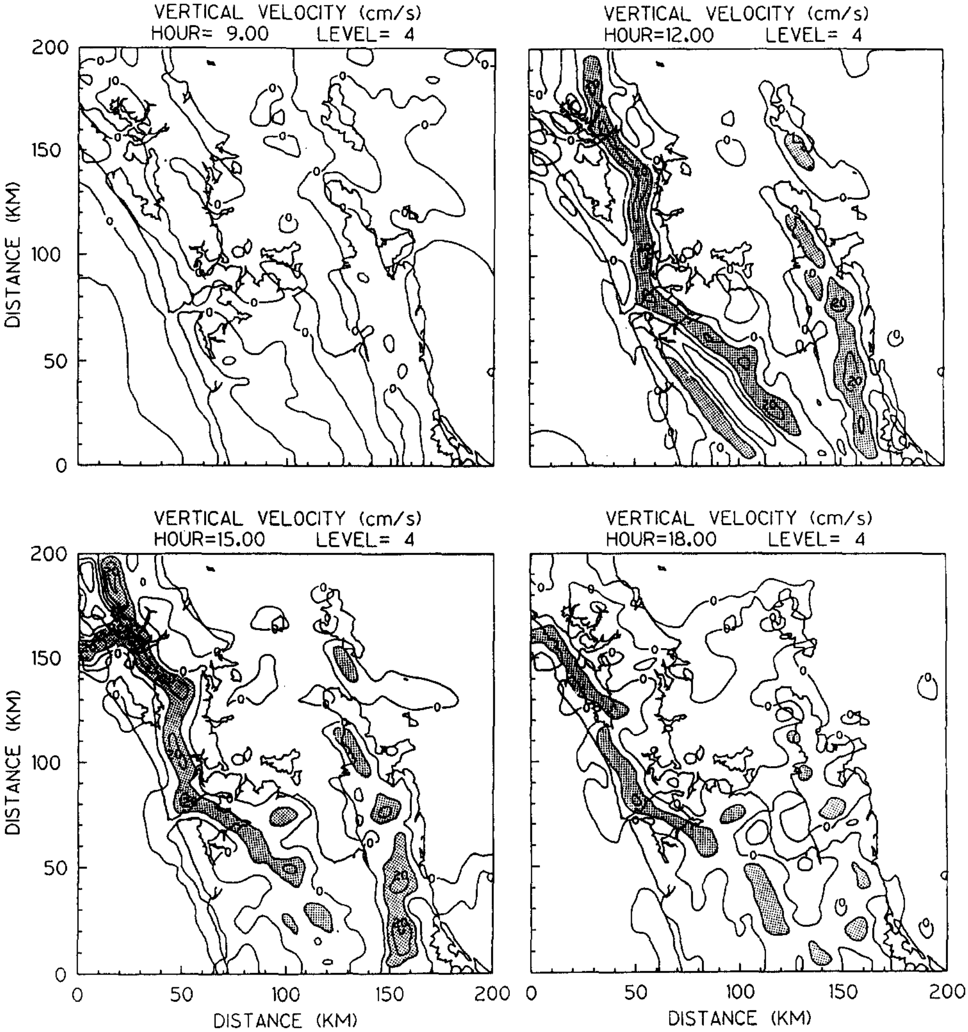

Fig. 6. Predicted horizontal fields of vertical velocity (*w*) at a height of 250 m at 0900, 1200, 1500 and 1800 LST. (Contour interval 10 cm s^{-1}. Shaded areas represent upward vertical velocities of greater than 10 cm s^{-1}).

1800 LST, maximum vertical velocities are generally less than those predicted in the middle of the day. This may be attributed to the reduction in thermal forcing in late afternoon. Consequently the sea breezes and the associated convergence lines are less vigorous at this time.

3.2. The PBL depth field

In Figure 7, the evolution of the field of PBL depth is presented. At 0900 LST, PBL depths are predicted to reach 400–800 m over land with greatest depths

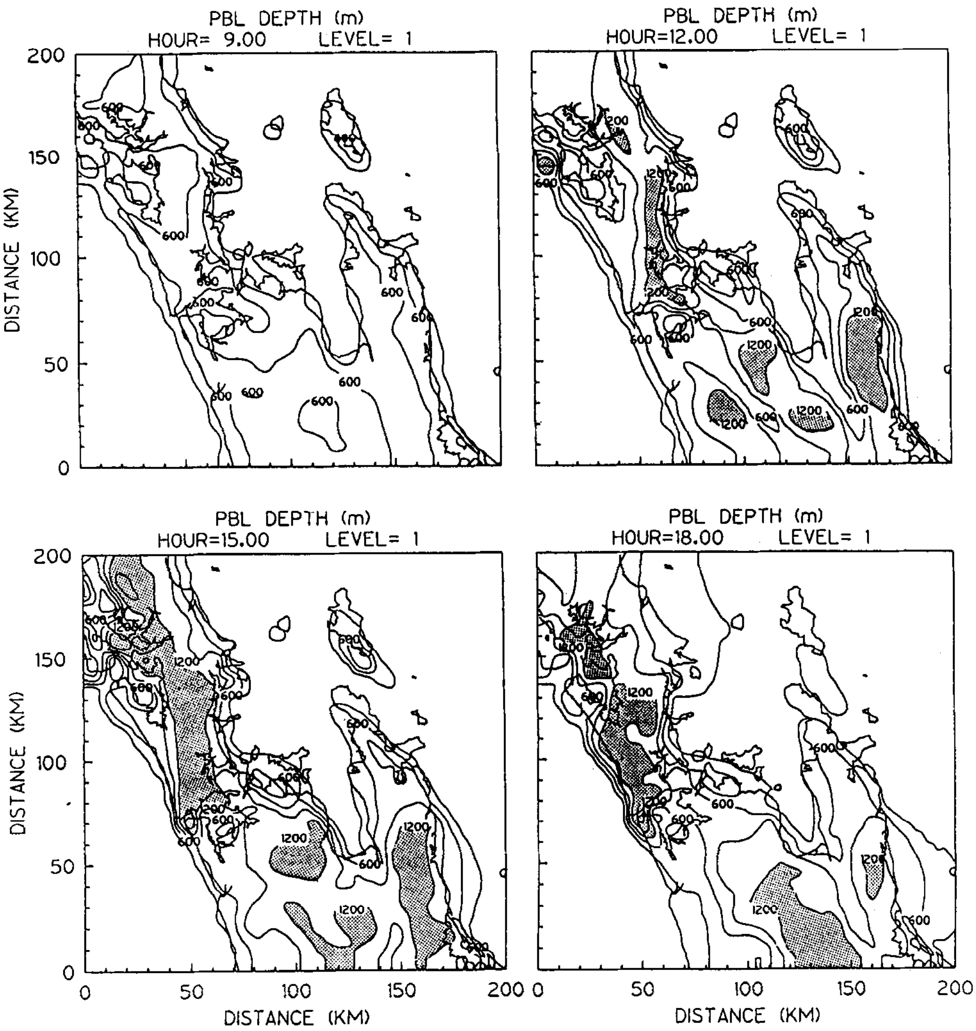

Fig. 7. Predicted horizontal fields of planetary boundary layer depth (m) for 0900, 1200, 1500 and 1800 LST. (Contour interval 300 m. Shaded areas represent PBL depths of greater than 1200 m above ground level).

associated with those areas where there is convergence between the sea breeze and gradient flow (e.g., the east coast of Coromandel Peninsula). Strong gradients in PBL depth are predicted along all coastlines reflecting the contrast between the stable marine boundary layer and the convectively driven heated boundary layer over land. By 1200 LST, the PBL field strongly reflects the patterns of vertical motion shown in Figure 6. In regions of uplift (e.g., the convergence zones) the PBL is pushed to heights of 1200 m or more. In areas of subsidence (e.g., around the harbours and between the convergence lines) the depth of the

PBL is considerably lower. With the movement of the convergence line to the north of Auckland from east to west, maximum PBL depths at 1800 LST are predicted to occur on the west coast to the north of Manakau Harbour. The PBL depths predicted over Auckland are in good agreement with the 1150 m height derived from the 1100 LST radiosonde sounding at Auckland Airport (McGill, 1987). They are also in agreement with climatological values determined from radiosonde data from Auckland Airport (Capuano and Atchison, pers. comm.) using the method described by Capuano and Atchison (1984). These indicate a mean monthly maximum PBL depth for Auckland of 1369 m in January.

The spatial and temporal variations in PBL depth outlined above can be more clearly appreciated by consideration of 5 separate locations over the model domain (Figure 8). Between locations (shown in Figure 1), there are significant differences which may be attributed primarily to the movement of the sea breeze convergence lines. At the west coast site (1), PBL depths are generally low until midafternoon as a result of the predominantly onshore flow advecting low marine PBL depths across land. The arrival of the easterly breeze and convergence line at 1500 LST results in a marked increase in PBL depths at a time when PBL depths are decreasing at other sites. In contrast, PBL depths farther east (site 2) reach a peak near midday and decrease thereafter. At the Auckland city site (3), the proximity of ocean on both sides and the static position of the convergence line result in a relatively smooth diurnal variation in PBL depth with a maximum value of approximately 1000 m. To the south (sites 4 and 5), maximum PBL depths reach 1300 m. At the western site (4), maximum depth is reached near

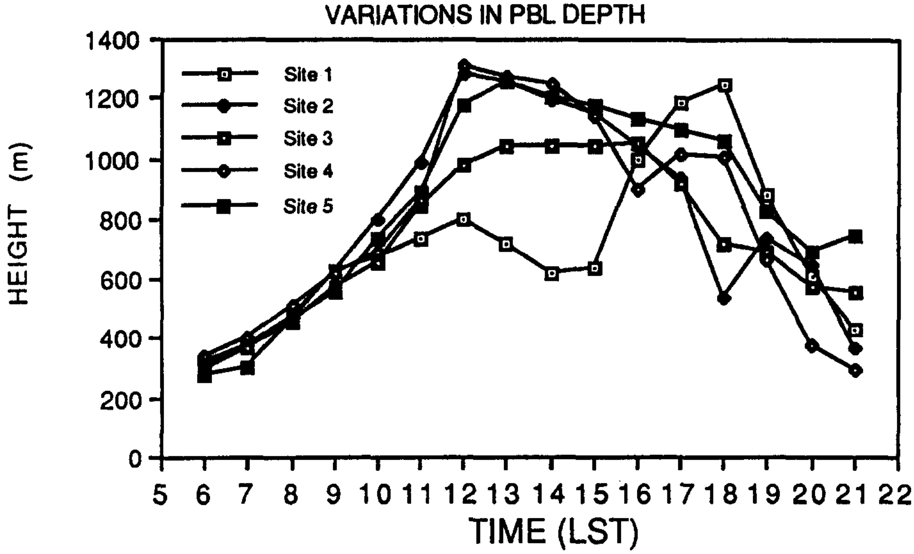

Fig. 8. Predicted evolution of PBL depths (m) at the 5 sites (labelled in Figure 1).

midday and is associated with the passage of the convergence line from the westerly sea breeze. At site 5, the static position of the convergence line over the Coromandel Peninsula results in the maintenance of relatively high PBL depths until late afternnoon.

4. Discussion and Conclusions

The results outlined above are in general agreement with previous observational studies by McGill (1987) and Brasell (1982) which suggest that the summertime air pollution meteorology of the Auckland region is strongly influenced by local sea breeze effects. In this study, migratory sea breeze convergence lines are identified as the principal features contributing to marked spatial and temporal variations in wind and PBL depth. Such convergence zones have been investigated at a larger scale by Noonan and Smith (1987) for the Cape York Peninsula and by Pielke (1974) for South Florida. However, little attention has been given to the air quality implications of such a regime at the local scale. In the Auckland area, it is likely that these features strongly influence the dispersal and transport of pollutants. The predominance of onshore flow around the entire regional coastline also suggests that fumigation effects may be an important factor influencing local air quality where emission sources are located near the coast. Such effects have been noted in coastal environments elsewhere by Keen and Lyons (1978) and McCraw *et al.* (1981). Furthermore, the dominance of sea breeze circulations over the region suggests that recirculation of pollutants may be an aspect of the local air pollution meteorology that is worthy of further investigation.

The complex spatial and temporal variations in wind and PBL depth highlighted in this study suggest that standard air quality assessment procedures based on Gaussian principles and 'box' approaches may be wholly inadequate for the Auckland case. Certainly, considerable care should be taken in the application of such models. This applies particularly to the determination of pollutant trajectories and PBL depths where due consideration to the complex three-dimensional wind field and spatial and temporal variations in PBL depth should be given. An approach worthy of future consideration for the Auckland case is the numerical evaluation of the transport and diffusion of pollutants using modelled wind and turbulence fields. This has been successfully demonstrated by Segal *et al.* (1988) and Pielke *et al.* (1983) and involves the tracking of a large number of particles in a Lagrangian framework.

In general terms, this study adds further weight to the study by Segal et al. (1982) in demonstrating the potential of mesoscale models as tools for identifying regions of diminished/enhanced air quality based on consideration of preferred zones of convergence/divergence, light/strong winds and increased/decreased PBL depths. In addition to the air quality assessment applications, simulations may be utilised as a guide in optimal network design. For example, siting of acoustic sounders may be based on consideration of modelled PBL depth fields.

Despite the realistic appearance of the fields predicted by the CSU model, several limitations of the study should be emphasised. Firstly, the simulation does not take into account variations in surface properties. These are likely to influence surface energy fluxes significantly and hence the turbulent intensities which govern PBL growth. For example, Hjelmfelt (1982) using the CSU model, has shown that 'doming' of the PBL may occur downwind of St. Louis. It is likely that Auckland city influences PBL depths in the surrounding area in a similar fashion. Although the CSU model permits the input of variable surface properties, it is often difficult to specify surface and soil properties reliably over a large region on a grid square basis. Secondly, recent work by Physick *et al.* (1989) suggests that Deardorff's (1974) prognostic equation for PBL depth does not provide an accurate representation of thermal internal boundary-layer growth during onshore flow. For the Auckland case, this suggests that predicted PBL depths near the coastline may be an overestimate of true values. Evaluation of alternate approaches (e.g., Physick *et al.*, 1989) to the formulation of the thermal internal boundary layer in the CSU mesoscale model for applications in the Auckland region is required. Finally, the inability of the model to accommodate variations in boundary conditions associated with the evolving synoptic situation may have been a limiting factor in the present study. This deficiency may have contributed to the inability of the model to simulate the late afternoon eastward migration of the sea breeze convergence zones. To remedy this, a nested approach should be adopted for future modelling studies in the region.

Without more rigorous validation studies, these results must be regarded as preliminary. However, the level of agreement between the simulation and available observations is encouraging and adds further weight to previous studies advocating the use of mesoscale models for air quality applications. Before this is attempted, it is recommended that intensive observational studies be carried out in order to test the veracity of mesoscale models for this purpose.

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