PERGAMON

AE International – Australasia

Atmospheric Environment 37 (2003) 443–454

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Recirculation of coastal urban air pollution under a synoptic scale thermal trough in Perth, Western Australia

Yimin Ma[a,b,*], T.J. Lyons[a]

[a] Environmental Science, Murdoch University, Murdoch, WA 6150, Australia
[b] School of Computational Sciences, George Mason University, Fairfax, VA 22030, USA

Received 15 January 2002; received in revised form 17 October 2002; accepted 1 November 2002

Abstract

Air pollutant recirculation is a common feature of coastal cities as a result of the diurnal variation of the land/sea breeze circulation. On the western coast of Australia, a thermally induced synoptic scale trough interacts with this local circulation to enhance the sea breeze flow, allowing pollutant to penetrate further inland. As well a low wind speed zone formed offshore near the trough axis leads to increased ozone concentrations and the rotation of the trough axis during its onshore movement spreads these higher concentrations of air pollutant over a larger area.

Keywords: Recirculation; Coastal urban; Ozone; Vehicle emissions

1. Introduction

Many coastal cities experience a recirculation of air pollution (e.g. Lyons et al., 1995; Lu and Turco, 1994; Hurley and Manins, 1995). The basic mechanism of the recirculation is not difficult to understand. If there is no strong or transitional synoptic forcing, the diurnal heating and cooling differences between the land and sea will determine the local wind circulations which affect the transportation and diffusion of emissions from both surface and elevated sources (Manins et al., 1994). Early morning emissions are swept out to sea by the land breeze only to be brought back over land by the developing sea breeze. Being constrained within the sea/land breeze circulation, pollutant may be caught up in the evening flow of the land breeze and returned over the sea the following evening.

The situation in Perth (32°S, 116°E) is quite complex. The city lies on an essentially north/south coastline in the southwest corner of Australia (Fig. 1). Its metropolitan area covers a relatively featureless sandy coastal plain and the 300 m high Darling Scarp is some 25 km from the coast paralleling the coast line (Ma Yimin and Lyons, 2000). Perth's climate is characteristically Mediterranean with hot, dry summers and mild wet winters (Tapper and Hurry, 1992). During the austral summer, the subtropical highs in the southern hemisphere are located in the vicinity of 30°–35°S and constantly move eastwards under the influence of an upper westerly wind. Simultaneously, a surface heat low is an almost permanent feature of north-western Australia, which protrudes into the gap between successive highs or even cuts into a high to form a low pressure trough, known locally as the West Coast Trough (Tapper and Hurry, 1992). The trough dominates local Perth weather patterns from late spring to early autumn, especially during the summer season (Watson, 1980; Tapper and Hurry, 1992). Because of the subtropical highs, Perth experiences prevailing surface easterly winds, blowing across the inland desert and the trough tends to be a shallow system being generally confined below 700 hPa in this easterly wind regime (Watson, 1980).

Diurnal variations in surface heating between the land and ocean lead to the trough line oscillating around the coast, whereas its more general eastward movement is

*Corresponding author.
E-mail address: yma@scs.gmu.edu (Y. Ma).

1352-2310/02/$ - see front matter
PII: S 1 3 5 2 - 2 3 1 0 (0 2) 0 0 9 2 6 - 3

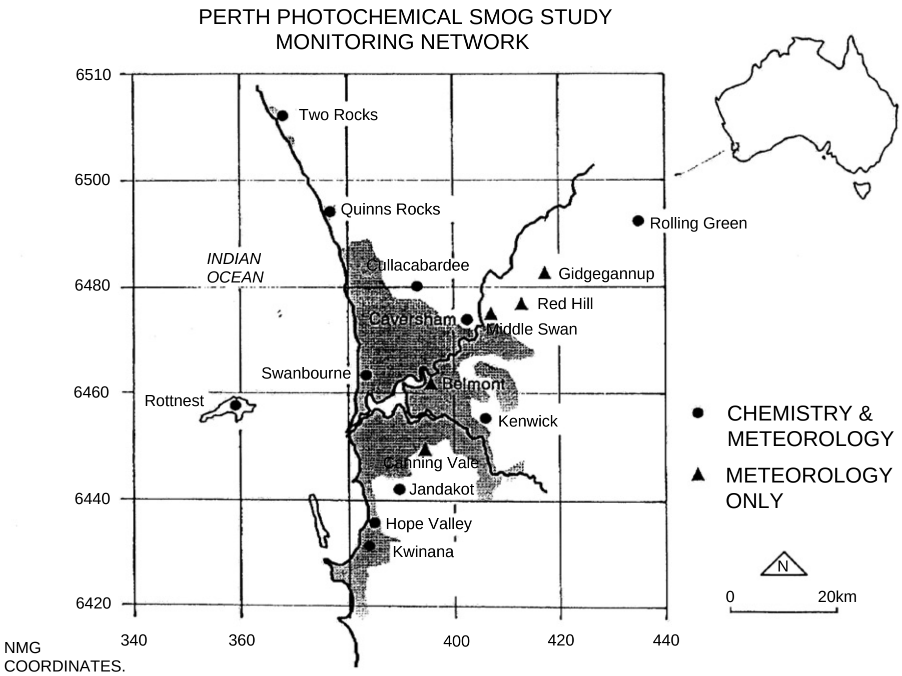

Fig. 1. The Perth photochemical smog study monitoring network (after PPSS, 1994). Sonde observations were available at Rottnest, Swanbourne and Belmont.

synoptically controlled (Ma Yimin et al., 2001). The significance of the trough lies in its interaction with the sea/land breeze circulation, which strongly controls Perth weather during the summer season (Kepert and Smith, 1992; Ma Yimin and Lyons, 2000). This interaction may in turn lead to a recirculation of the coastal air mass which has important implications for Perth urban air quality (Hurley and Manins, 1995).

The position of the trough relative to the coast, its intensity, and the process of its ultimate movement inland strongly influences these local flow patterns (Ma Yimin and Lyons, 2000; Ma Yimin et al., 2001). That is, if the trough stays off the coast, the pressure gradient force generally prevents a sea breeze from reaching the land early, or at all; if the trough stays inland, the pressure gradient force enhances early sea breeze formation; and if the trough moves across the coast, it leads to a change in wind direction from offshore to onshore. Any sea breeze or onshore wind has the potential to bring air pollution which has been emitted from the city in the morning or even during the previous evening and blown out over the ocean following a land breeze or easterly wind, back over the city. Especially, it has been shown that high ozone events are associated with the trough moving across the coast (PPSS, 1996).

Although a number of studies have contributed to addressing pollution dispersion across the Perth metropolitan area (i.e., Kamst and Lyons, 1982; Rayner, 1987; Pitts and Lyons, 1992; Manins et al., 1994; Rye, 1994; Hurley and Manins, 1995; PPSS, 1996), they have tended to address particular episodes or only considered stationary synoptic conditions without incorporating the dynamic impact of the trough on changing synoptic forcing. For example, Hurley and Manins (1995) simulated possible recirculation routes under stationary synoptic conditions. Rye (1994) focused on the role of the trough in controlling pollutant recirculation, but did not simulate the trough or its dynamic nature, particularly with respect to its movement across the coast.

Therefore, in this paper an attempt has been made to study air pollutant recirculation and dispersion in Perth under the dynamic framework of the trough. A Lagrangian particle diffusion model, based on Pitts and Lyons (1992), has been coupled with a mesoscale model to highlight pollutant transport and dispersion across the coastal plain and the respective roles of the coastal trough and sea breeze circulation on pollutant diffusion. As our focus is on meteorological factors, the full urban chemistry has not been incorporated in the model.

2. Numerical model

A three-dimensional version of RAMS, the Regional Atmospheric Modelling System, was employed (Pielke et al., 1992). This model incorporates a vegetation parameterisation scheme (Avissar and Mahrer, 1988) and the full characteristics and options are given by Pielke et al. (1992) and Nicholls et al. (1995). Three nested grids were used to simulate the flow: the domain of grid 1 covering most of the Australian continent and its contiguous ocean at a horizontal resolution of 100 km; grid 2 is nested to grid 1 to cover a large area of the southwest of Western Australia and its surrounding oceans with a horizontal resolution of 25 km and grid 3 covers the Perth metropolitan area and its adjoining sea at a horizontal resolution of 5 km. A similar map explaining the grids can be found in Ma Yimin and Lyons (2000). Grid 2 is a transitional grid which avoids a large ratio of horizontal grid spacings between the inner and outer nested grids. The vertical grid is stretched from 8 m at the surface to 2000 m at around 20 km, the top of the domain (Ma Yimin and Lyons, 2000). A diffusion model was incorporated in this inner grid with a relatively large area of $200 \times 200\ \mathrm{km}^2$, to allow for the recirculation of pollutant. This domain is comparable with the domains used by Hurley and Manins (1995) who had an inner domain of $125 \times 125\ \mathrm{km}^2$ and an outer domain of $250 \times 250\ \mathrm{km}^2$.

Following Pitts and Lyons (1992), a particle Lagrangian diffusion model was coupled to the mesoscale model. Pitts and Lyons (1992) validated the diffusion model against the well-mixed criterion and results from the water tank experiments of Willis and Deardorff (1978) under convective atmospheric conditions using Wangara day 33/34. A similar validation has been performed for this configuration (Ma Yimin, 2001).

Following Ma Yimin et al. (2001) we have employed the four-dimensional data assimilation available in RAMS (Pielke et al., 1992) and used analysis fields of the US National Meteorological Centre (NMC) gridded at 2.5° and 12 hourly intervals as boundary conditions to nudge the model towards the analysis at the lateral and top boundaries of the coarse grid. This ensures that broad scale synoptic forcing is present and allows the modelling to focus on the mesoscale interactions.

The model was initialised with NMC gridded data at 00 GMT (08 local standard time) and all simulations were run for at least 36 h. Emissions were started at 1200 h (LST) on the first day and continued until the model run was completed. Emissions on the first morning were not included, as delaying emissions allowed the output from the mesoscale model to stabilise as was also done by Hurley and Manins (1995).

NO_x (nitrogen oxides), the major contributor to an ozone event, were selected as the tracer to study the transport and dispersion of pollutant rather than incorporate the full urban chemistry. Emissions of NO_x are mainly from motor vehicle exhausts in the metropolitan area centred on the Perth CBD (Central Business District) and industrial emissions from the Kwinana industrial area (Fig. 1). Emission rates were adopted from PPSS (1996) and are listed in Table 2. During the morning (0700–0900 LST) and evening (1600–1800 LST) traffic peak periods, motor vehicle emissions are dominant at more than double the industrial emissions over the same period or traffic emissions in the offpeak period (Lyons et al., 1990; PPSS, 1996).

As the Kwinana industrial area is confined within a few square kilometres, it was treated as a point source compared with the whole study area of $200 \times 200\ \mathrm{km}^2$. Based on Lyons et al. (1990), the vehicle traffic emissions have been grouped to approximately 43 spots scattered over an area of $15 \times 15\ \mathrm{km}^2$ centred on the Perth CBD. Particles were released at rates of 10 each time step of 60 s from the Kwinana industrial area and 1 from each representative source for the automotive emissions with varied particle masses, representing the temporal and spatial distribution of the emission (Ma Yimin, 2001). Particles leaving the domain of grid 3 were dumped.

3. Data description

The Perth Photochemical Smog Study was conducted from 1992 to 1995. A major aspect of the study was designed to acquire base information about the incidence of photochemical species and understand the transport of pollution across the region (PPSS, 1994, 1996). During the study, an intensive observation period ran from 27 January to 12 February 1994 and data collected during this period have been utilised within this paper.

A total of 25 monitoring stations were set up over a 100 km × 100 km region centred on the Perth Central Business District (Fig. 1). All these stations made measurements of surface wind speed and direction at a height of 10 m above ground. As well some stations incorporated chemistry monitoring which included O_3 (Ozone), NO (nitrogen monoxide), NO_2 (nitrogen dioxide). The data at the surface stations were recorded every 10 min, 24 h a day.

The west coast trough displayed its normal pattern during the intensive study period, consistent with its climatology (Tapper and Hurry, 1992; Watson, 1980). The daily weather maps from the intensive study period exhibit sequences of the development, movement and ultimate disappearance of troughs during these 17 days (Ma Yimin, 2001). In particular, there are three trough sequences of note during the period. Two troughs formed offshore and passed the coast on 31 January and 12 February, respectively. One formed inland near the coast on 4 February (Ma Yimin et al., 2001). Six case studies of both sea breezes and transitional troughs (see Table 1) which occurred during the intensive study period were selected to study pollution dispersion. The term "transitional trough" refers to the situations when the trough moves across or emerges around the coastline.

4. Results

Ma Yimin et al. (2001) showed that the RAMS model is able to simulate the main features of the West Coast Trough and related synoptic systems. Although there are mismatches between trough intensity and the position of the trough axis, the model was able to simulate the movement of the trough axis and the rotation of its orientation (Ma Yimin et al., 2001). Fig. 2 shows an example of the analysed and simulated trough movement for case 5 (Table 1).

Compared with the normal sea breeze circulation under stationary synoptic conditions, the marine atmospheric boundary layer is more stable in the transitional case, accompanying a weak offshore wind before the onshore wind starts. Fig. 3 show the cross-shore potential temperature and cross-shore wind component for cases 5 and 3 representative of a transitional trough and late sea breeze situation, respectively, before and after the onshore wind or sea breeze started near the coast. Before the onshore wind starts, an easterly flow extended up to 2.5 km in the later sea breeze case while the layer above 500 m has a westerly wind in the transitional trough case. After the onshore wind starts, however, a thick onshore wind layer penetrates inland almost without a return flow in the transitional trough case, compared with the small onshore wind zone in the later sea breeze.

Luhar et al. (1998) analysed the coastal atmospheric boundary structure within the Kwinana Coastal Fumigation Study (KCFS) (Sawford et al., 1998), selecting

Table 1
Summary of selected cases during the intensive study in 1994 to simulate the pollution recirculation and dispersion. Ozone peaks (ppb) are noticed

Case 1	Feb 3	Early sea breeze, No trough	60 ppb at Rolling Green, 45 ppb at Caversham
Case 2	Jan 28	Late sea breeze, weak trough offshore	60 ppb at Two Rocks, 55 ppb at Rottnest
Case 3	Feb 11	Late sea breeze, weak trough offshore	55 ppb at Two Rocks and Rottnest
Case 4	Feb 12	A trough passing the coast	40 ppb at Rottnest, Two Rocks, Caversham and Rolling Green
Case 5	Jan 31	A trough passing the coast	Over 60 ppb at Rottnest, Two Rocks, Caversham and Rolling Green
Case 6	Feb 4	A trough forming in land near coast	70 ppb at Rolling Green and 60 ppb at Caversham

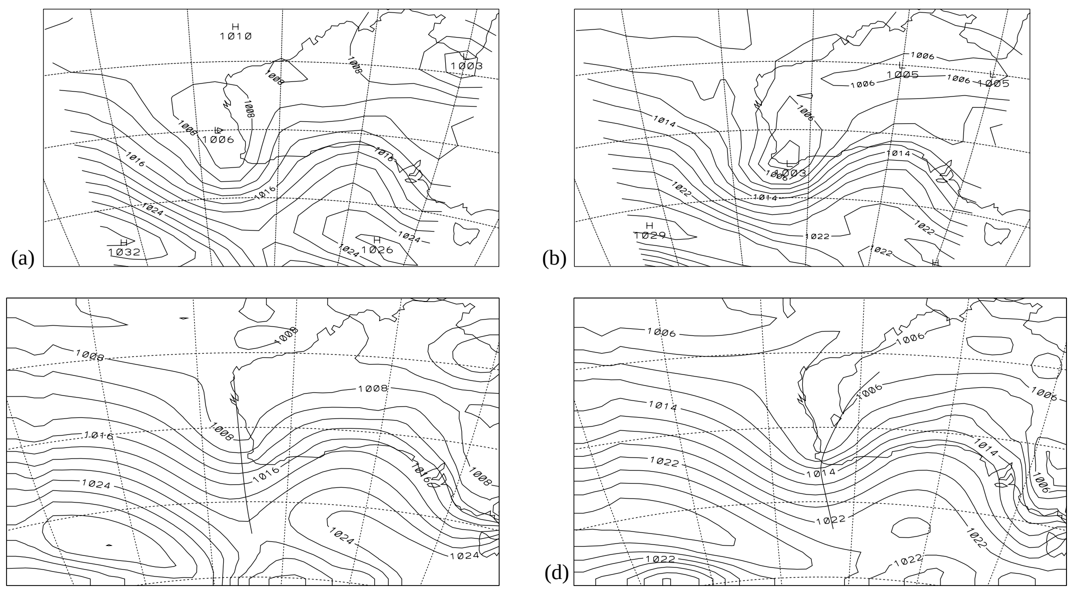

Fig. 2. Sea surface pressure charts and the simulations for case 5. Observations: (a) 00 GMT January 31, (b) 12 GMT January 31, Simulation (c) 00 GMT January 31, (d) 12 GMT January 31. The thick lines in the simulations indicate the trough lines.

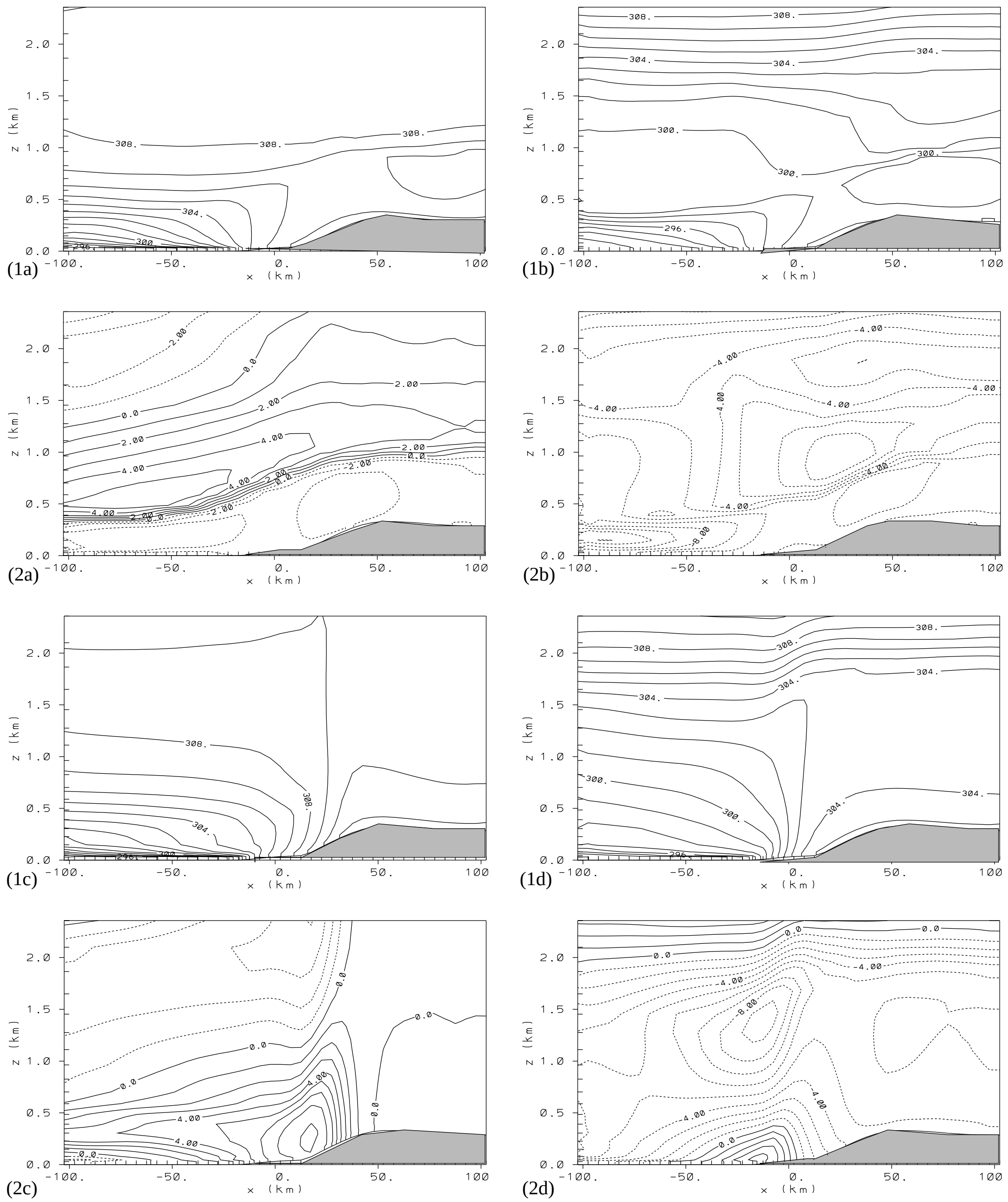

Fig. 3. Simulated cross-shore contours of meteorological fields. (1) Potential temperature (contour interval: 1 K) and (2) cross-shore wind component (contour interval 1 m s^{-1}) for case 5 (a) and 3 (b) at 1100 LST and for case 5 (c) and 3 (d) at 1400 LST on the second day.

four sea breeze cases, and indicated that a neutral or stable layer of about 200 m deep capped a super-adiabatic layer extending about 50 m above the water surface, under onshore flow. This neutral layer in the present simulation can be seen near the coast when the onshore wind started (Fig. 3) for both cases.

The recirculation of the morning peak emissions to the metropolitan area happened in all six cases, while the recirculation of the previous evening's emissions only occurred in case 6 when the automotive emissions from the evening peak moved to the northern part of Perth during the next day. Fig. 4 shows two examples of the

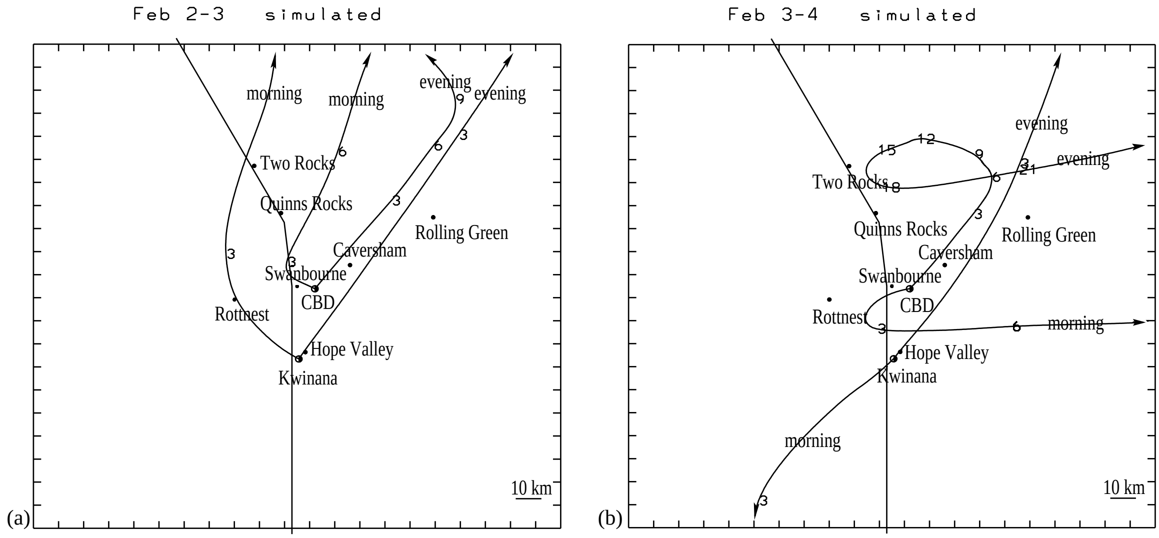

Fig. 4. Examples of recirculation routes simulated for (a) the sea breeze (case 1) and (b) the transitional trough (case 6). Each parcel is released from the surface in CBD and the elevated point in Kwinana at 1700 LST of the evening and 0800 LST of the morning traffic peaks (marked as "evening" and "morning" on the trajectories). The parcel follows mean flow and the numbers on the line indicate the hours after it is released.

model trajectories for the morning (0800 LST) and evening (1700 LST) peaks of automotive emissions from the city centre, along with emissions from the elevated sources of the Kwinana industrial area, incorporating the effects of vertical velocities. Fig. 4a represents a sea breeze situation (case 1) and Fig. 4b is a transitional trough situation (case 6). This recirculation is consistent with the suggestion that high air pollution episodes are associated with both transitional trough (PPSS, 1996) and sea breeze circulations (Petford, 1995).

Fig. 5 show the simulated and observed time variations of NO_x at Caversham (Fig. 1) from 2000 LST on the first day to 2000 LST on the second day. Overall, although there are significant differences among the timing and magnitude of NO_x occurrence, most of the main features of the time variation of NO_x are represented. This is consistent with observations at other stations (Ma Yimin, 2001) (Table 2).

Both elevated and surface emissions contribute to the daytime NO_x occurrences at the stations, consistent with the analysis of Rye (1994). Next day recirculation, as shown in the trajectories (Fig. 4), only happens in case 6 and contributed to the NO_x observed at Two Rocks. This transported plume arrived at the site between 0100 and 0900 LST, and mainly contained fresh NO_x that has not been involved in any photochemical reactions (Ma Yimin, 2001).

The recirculation of the plume can also be seen in the simulated NO_x horizontal distribution as for example shown for case 5 (Fig. 6). The diurnal movement of the plume is quite obvious wherein the pollution is blown out over the ocean during the first night and early morning of the second day, and moves back to the metropolitan area on the second afternoon. This recirculation occurs over a larger area and more directions with the combined effect of trough movement and land/sea contrast, compared to the earlier studies of pollution transport caused only by the land/sea contrast (Pitts and Lyons, 1992).

5. Discussion

The stable marine boundary retains air pollution from the vertical mixing which occurred over the land. Liang and Jacobson (2000) simulated ozone production efficiency with a photochemical model and concluded that air pollution dilution rapidly reduces ozone productivity. The still and stable marine boundary layer could enhance this reaction, provided the other conditions are satisfied. It has been suggested that the wind near Perth tends to be lighter than normal when the trough is just off the coast before it moves inland (PPSS, 1996). These simulations illustrate a low wind zone ($\leqslant 5$ m s^{-1}) in the transitional trough cases 4–6, lasting for a period of up to 4 h in case 5 and extending some 100 km off the coast. There is a much shorter period for the low wind zone with less offshore extension simulated for cases 1–3 of the stationary trough situation. This low wind zone is located around the trough axis region where the horizontal pressure gradient force is negligible, and corresponds to a strongly stable marine

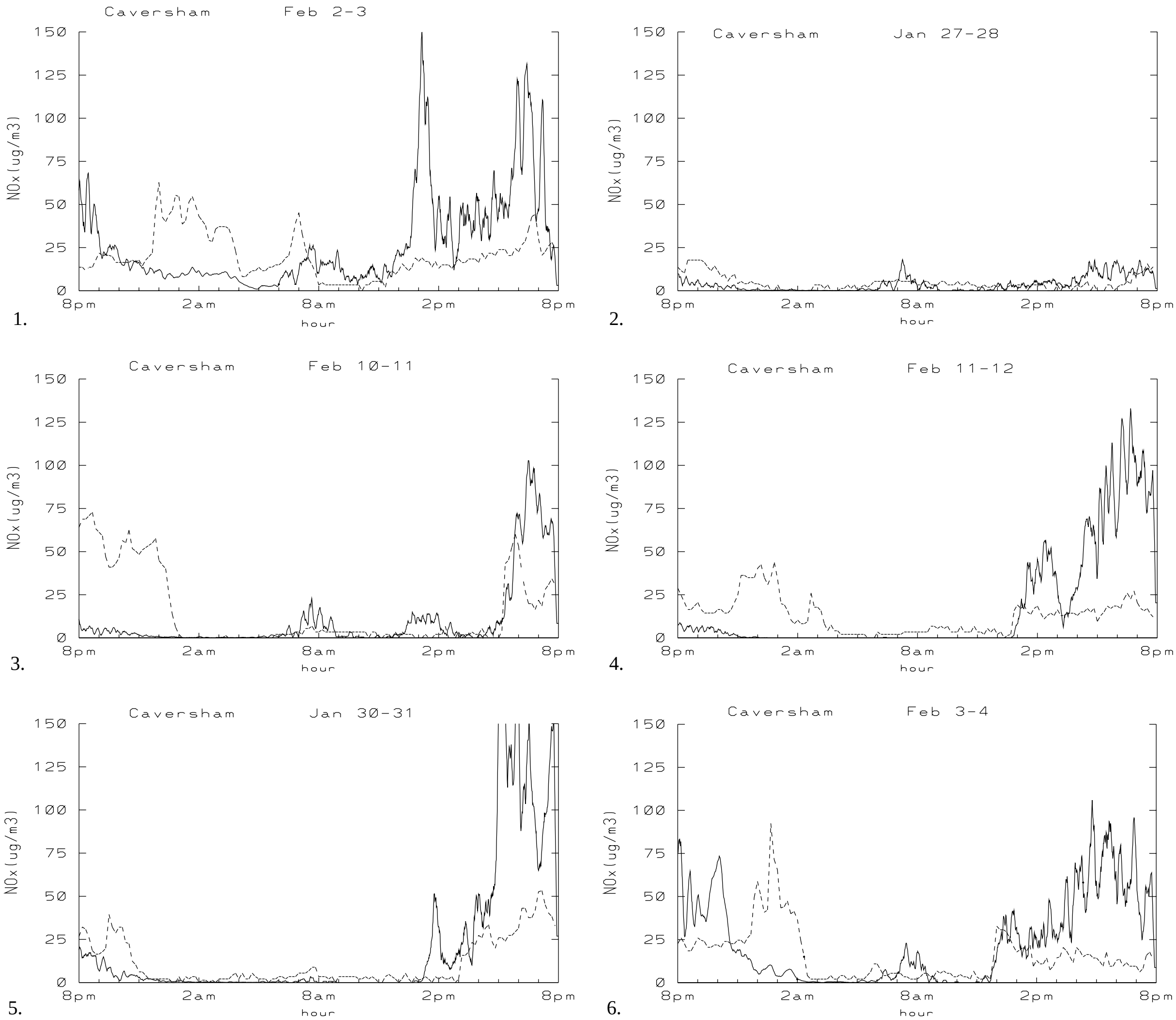

Fig. 5. Time variations of NO_x at Caversham for the six cases. Solid line is the modelled NO_x and dashed line the monitored NO_x.

Table 2
NO_x emissions input to the model

	Emissions (ton day^{-1}) (after PPSS, 1996)	Emissions (ton h^{-1})	Mean source height (m, AGL)
Motor vehicle	63.3	2.64	2
Peak		5.52	
Off Peak		2.06	
Industrial	55.6	2.32	50

atmospheric surface layer. The zone is considered to be favourable to photochemical reaction because the mixing or pollution dilution is weak within it (Liang and Jacobson, 2000). The strong stable marine atmospheric boundary layer in the trough transitional situation is also indicated in Fig. 3.

The weak wind within the trough axis zone would lead to a weak friction velocity in the surface layer and minimal mixing. Secondly, compared with the sea breeze situation, a shallower offshore wind layer exists off the coast before the transitional trough moves/emerges inland, capped with a upper westerly wind driving the surface trough eastward (Fig. 3) (Annette, 1978). This shallow offshore wind would have less effect in destabilising the marine atmosphere. Hence under these conditions higher concentrations of O_3 are expected with the corresponding NO_x.

Over the large scale domain representing the trough axis movement towards the coast, Fig. 7 displays the time variation of the pressure and wind fields during the whole simulation period in case 5. It shows the

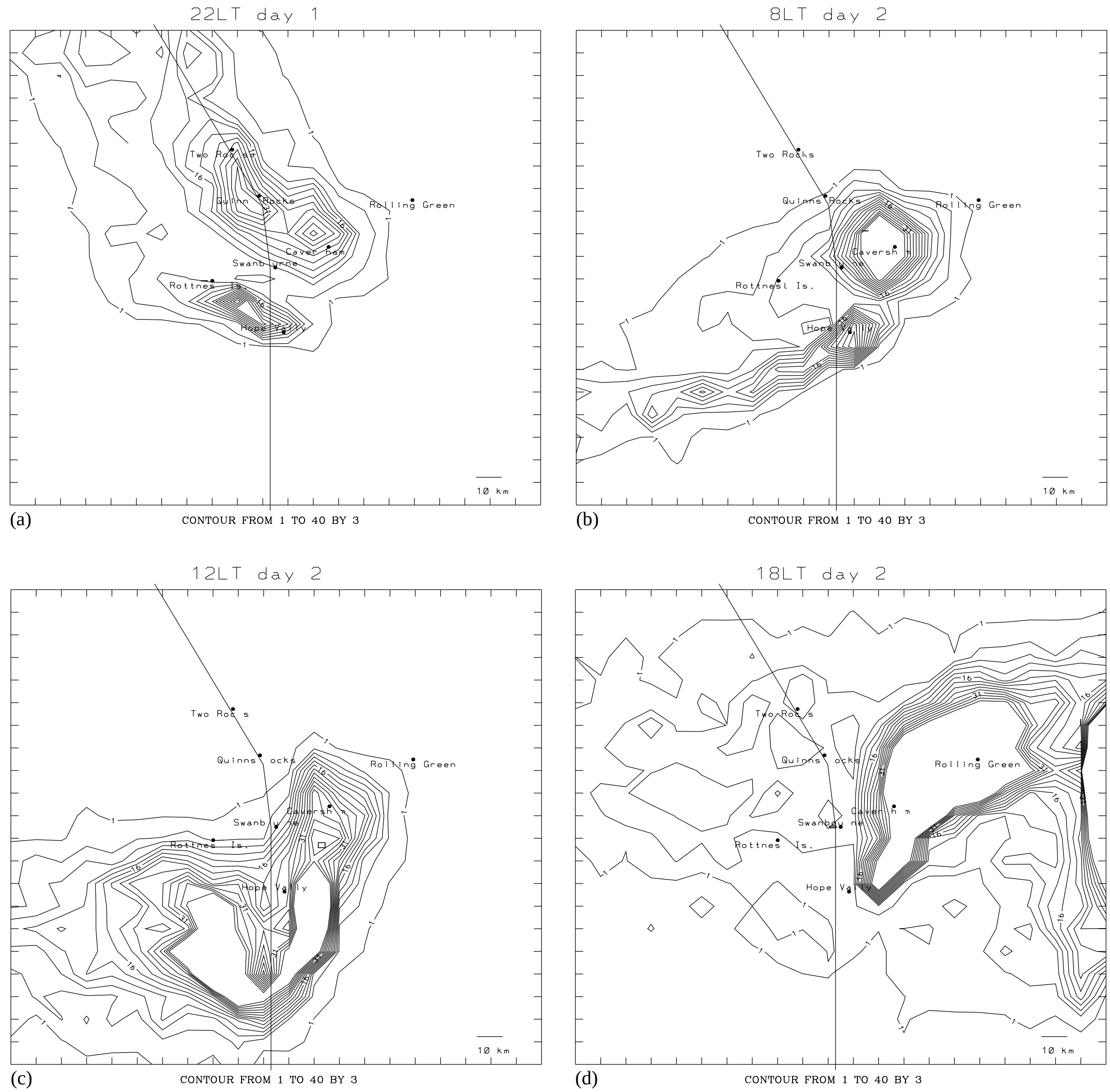

Fig. 6. Modelled NO_x surface distribution (contour lines with interval of 3 μg m^{-3}) for case 5 over the grid 3 area.

correspondence between the low speed zone (Fig. 7b) and the low zone of the sea level pressure (Fig. 7a) on the morning of the second day. This zone, however, would only exist when the onshore wind has not commenced, during which the photochemical reaction can fully proceed. The offshore wind on the second morning is bounded with an onshore wind around 300 km off the coast under the influence of the trough (Fig. 7c). As the trough moved across the coastline, a sea breeze started first near the coast before the whole domain became a westerly flow. Ma Yimin and Lyons (2000) argued that the sea breeze could initiate trough movement across the coastline.

Let us compare how pollution recirculation behaves with an onshore wind arriving at the coast under stationary and transitional trough situations. In both cases 3 and 5, the onshore wind arrived at the coast in the afternoon, bringing higher ozone episodes to the coastal station Two Rocks, while in case 3 the high ozone event is not observed at the inland stations of Caversham and Rolling Green. Although in case 5 of the trough moving across the coast, the onshore wind

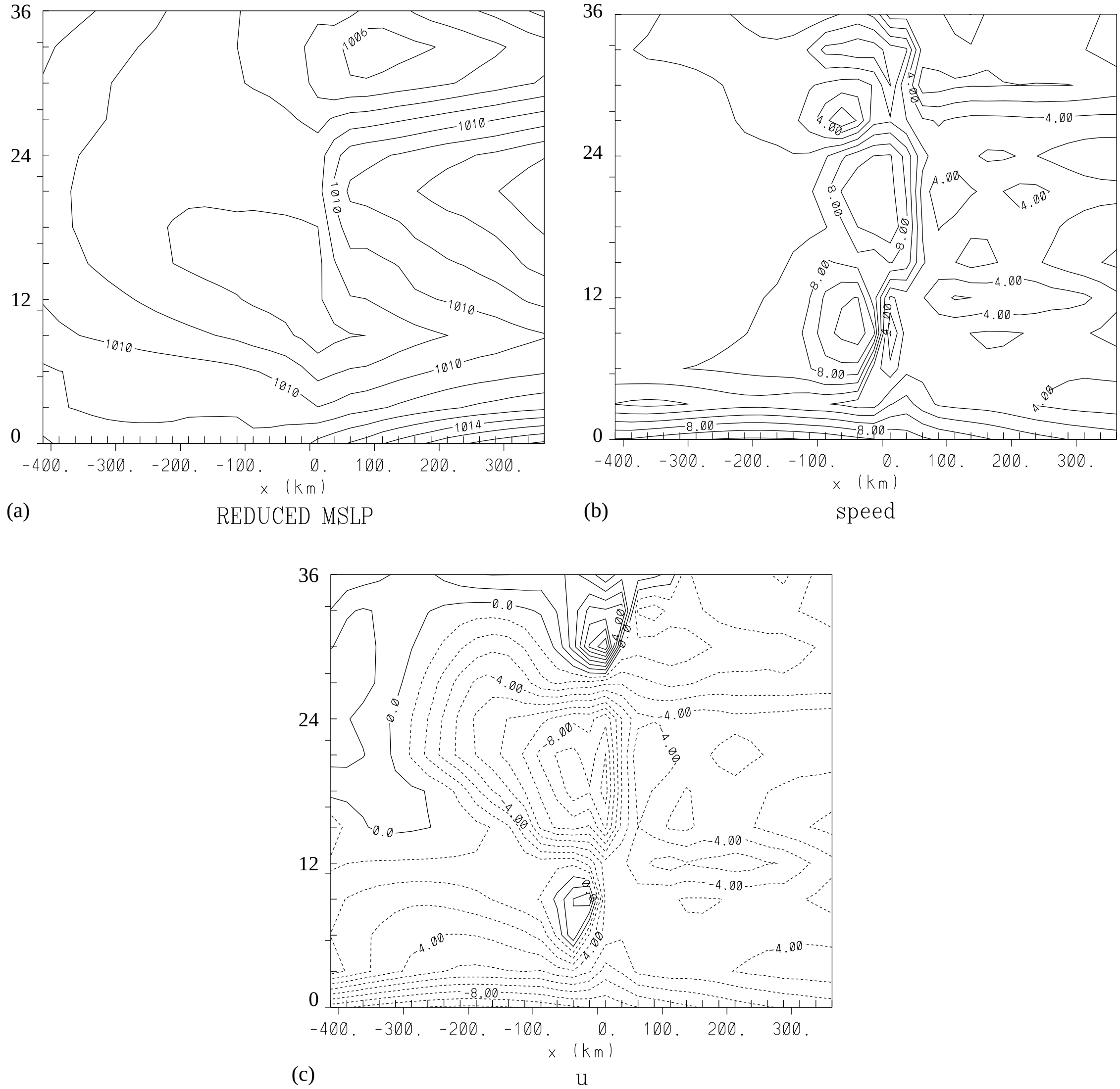

Fig. 7. Time variation of reduced sea surface pressure (hPa) (a), wind speed (m s^{-1}) (b) and u-component of the wind speed (m s^{-1}) (c) across the coastline at 1000 hPa level during the case 5 in grid 2. The vertical axis is the time (h).

occurred in the afternoon, it is quite different from the late sea breeze case in terms of pollution dispersion, though both situations allow the morning traffic emissions to stay over the stable marine atmospheric boundary layer for most of the day generating ozone. Under stationary synoptic influence, a later sea breeze tends to occur within a narrow region near the coastline with a shallow onshore wind and a upper offshore return flow (i.e., Abbs and Physick, 1992). However, the onshore wind in case 5 has a higher wind speed and a thicker westerly wind layer covering a larger area from the ocean extending further inland, and brings a larger amount of pollution back to the metropolitan area than in case 3 (Fig. 3). Figs. 8a–c displays a time series of the normalised vertical cross-shore wind component profile (Ma Yimin and Lyons, 2000) before, around and after the beginning of the onshore wind at Swanbourne (Fig. 1). Before the start of the surface onshore wind, an upper layer westerly flow penetrates to the surface (Fig. 8a, combined with Fig. 3(2a)), which is in accord with the suggestion that the upper synoptic system drives the trough's eastward movement (Annette, 1978; Leslie and Skinner, 1994; Ma Yimin et al., 2001). Around the start of the onshore surface wind, Perth is close to the trough axis and the trough's horizontal pressure gradient force is negligible. The normalised profile displays the features of a pure sea breeze (Ma Yimin and Lyons, 2000) based on Steyn's (1998)

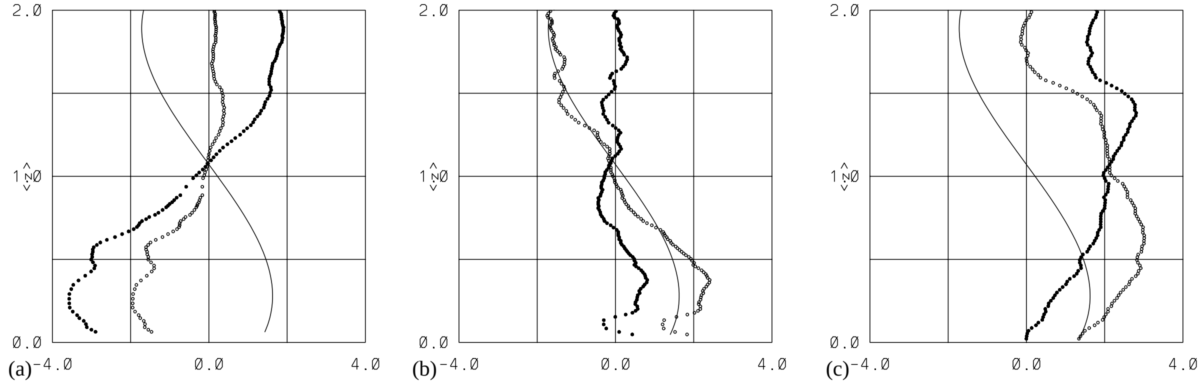

Fig. 8. Dimensionless profile of the cross-shore sea breeze velocity component observed in case 5 at Swanbourne at 1200 (a), 1500 (b) and 1630 (c) with before, around and after the onshore wind started at the station. The curve represents a pure sea breeze (Steyn, 1998), the open circles the observed profiles and the closed circles the difference between the two.

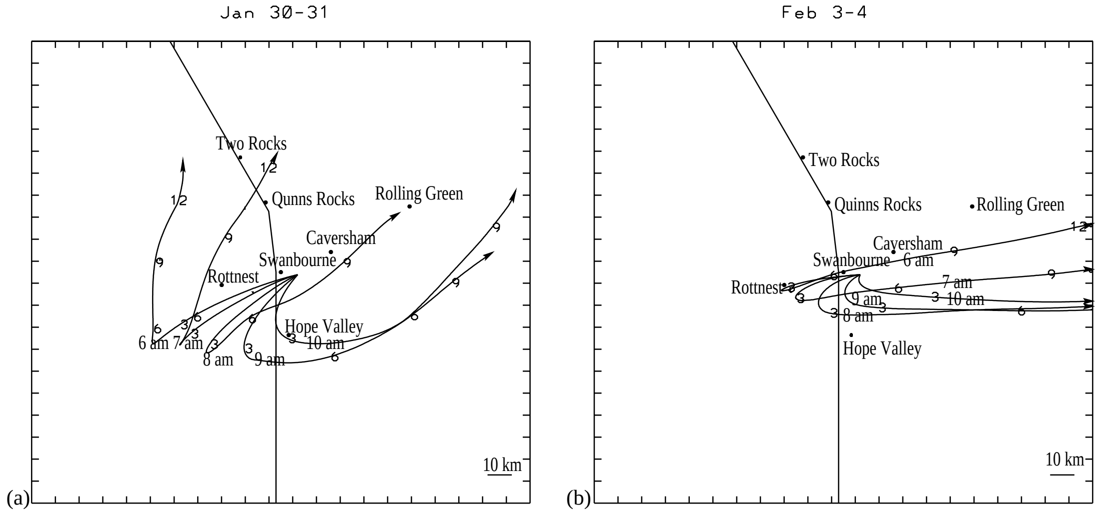

Fig. 9. Simulated recirculation routes for the case 5 (a) and 6 (b) with the air parcel released from 0600 to 1000 of the traffic morning peak the second day. The releasing time are marked on the curves and other conventions are the same as in Fig. 4.

analysis of the sea breeze under no synoptic influence. After the start of the onshore surface wind, there is a thick layer of onshore wind and the sea breeze return flow is almost invisible. This causes the marine air to spread and allows air pollution to penetrate further inland.

The wind structure also impacts on the vertical distribution of the recirculated plume. Under a stationary synoptic situation, part of the pollution has been injected into the return flow of the sea breeze because of the upward flow in the sea breeze front (i.e., Abbs and Physick, 1992), whereas in the transitional trough cases the return flow is not present and the plume advances further inland (Fig. 3).

Horizontal spreading of pollutant also occurs under the transitional trough, according to the movement and orientation of the trough axis. In case 5, most of the monitoring stations observed high ozone peaks (Table 1) and the trough axis changed its orientation during the transitional period (Fig. 2). This spreading of the pollutant can be explained with the trajectory analysis (Fig. 9) where for the first few hours the air mass has a small displacement over the ocean, wherein the plume meets the low speed zone before turning from offshore to onshore. Secondly, the fluctuating wind directions during the transitional period ensures that the high ozone containing air mass spreads over a large area. The affected areas of recirculated air pollution are different among the transitional trough cases, as shown in Fig. 9b of case 6 that the possible transported high ozone caused by morning emission could accumulate in the southern part of the city.

The transport pattern is a combination of the effects of trough movement and sea breeze circulation. The trough movement can be divided into trough axis movement with respect to the coast and trough axis orientation. When the trough line stays off the coast, the horizontal pressure gradient force exerted leads to strong easterlies which tend to prevent sea breezes from forming. After the trough line moves across the coast, the synoptic flow reverses tending to enhance the sea breeze circulation. That is why the process of the trough moving across the coast is invariably accompanied by an onshore wind front as the simulations indicated. This is consistent with the observations wherein the occurrence of minimum surface pressure and onshore wind were within 3 h.

6. Conclusions

The dynamics and structure of the trough and its interaction with the local land sea breeze circulation affects pollutant transport and dispersion. Under a transitional trough, a low wind speed zone with strong atmospheric stability corresponding to the trough axis develops off the coast and enhances photochemical reactions over the ocean. Compared to the normal sea breeze, the onshore wind associated with the advance of the trough spreads pollutant over a wide region, penetrates further inland and does not have a return flow. The transport route when the trough moves across the coast while changing its axis orientation is conducive to the widespread dispersion of pollutant across the Perth area. Thus the prediction of high ozone events across the Perth metropolitan area is critically dependent on forecasting the movement of the trough (Ma Yimin et al., 2001).

Acknowledgements

The RAMS code was provided by Professor Roger Pielke, and RAMS was developed under the support of the National Science Foundation and the Army Research Office. Ma Yimin was supported by an Australian Overseas Postgraduate Award as well as a Murdoch University Studentship. Meteorological data was supplied by NCAR and the Commonwealth Bureau of Meteorology as part of the Perth Photochemical Smog Study, which was supported by Western Power and the West Australian Department of Environmental Protection. All of this assistance is gratefully acknowledged.

References

Abbs, D., Physick, W.L., 1992. Sea breeze observation and modelling—a review. Australian Meteorological Magazine 41, 7–19.

Annette, P., 1978. Some aspects of the troughs in the easterlies over southern hemisphere continent. Meteorological Note 100, Bureau of Meteorology, Australia, pp. 1–5.

Avissar, R., Mahrer, Y., 1988. Mapping frost-sensitive area with a three-dimensional local-scale numerical model. Part I: physical and numerical aspects. Journal of Applied Meteorology 27, 400–413.

Hurley, P., Manins, P., 1995. Meteorological modelling in high-ozone days in Perth, Western Australia. Journal of Applied Meteorology 34, 1643–1652.

Kamst, F.H., Lyons, T.J., 1982. A regional air quality model for the Kwinana industrial area of Western Australia. Atmospheric Environment 16, 401–412.

Kepert, J.D., Smith, R.K., 1992. A simple model of the Australian west coast trough. Monthly Weather Review 120, 2042–2055.

Leslie, L.M., Skinner, T.C.L., 1994. Real-time forecasting of the western Australian summertime trough: evaluation of a new regional model. Weather and Forecasting 9, 371–383.

Liang, J., Jacobson, M.Z., 2000. Effects of subgrid segregation on ozone production efficiency in a chemical model. Atmospheric Environment 34, 2975–2982.

Lu, R., Turco, R.P., 1994. Air pollutant transport in a coastal environment. Part I: two-dimensional simulations of sea-breeze and mountain effects. Journal of Atmospheric Science 51, 2285–2308.

Luhar, A.K., Sawford, B.L., Hacker, J.M., Rayner, K.N., 1998. The Kwinana coastal fumigation study: II-growth of the thermal internal boundary layer. Boundary-layer Meteorology 89, 385–405.

Lyons, T.J., Pitts, R.O., Blockley, J.A., Kenworthy, J.R., Newman, P.W.G., 1990. Motor vehicle emission inventory for Perth airshed. Journal of the Royal Society of Western Australia 72, 67–74.

Lyons, W.A., Tremback, C.J., Pielke, R.A., 1995. Applications of the regional atmospheric modelling system (RAMS) to provide input to photochemical grid models for the Lake Michigan Ozone Study (LMOS). Journal of Applied Meteorology 34, 1762–1786.

Ma Yimin, 2001. Modelling Perth urban air pollution. Unpublished Ph.D. Thesis, Murdoch University, Perth, Australia. Available from Library, Murdoch University, Murdoch, WA 6150, Australia, pp. 176.

Ma Yimin, Lyons, T.J., 2000. Numerical simulation of a sea breeze under dominant synoptic conditions at Perth. Meteorological Atmospheric Physics 73, 89–103.

Ma Yimin, Lyons, T.J., Blockley, J.A., 2001. Surface influences on the Australian West Coast Trough. Theoretical and Applied Climatology 68, 207–217.

Manins, P.C., Physick, W.L., Hurley, P.J., Noonan, J.A., 1994. The role of coastal terrain in the dispersion of pollutants from Australia's major cities. Clean Air'94, Proceedings of the 12th International Conference of the Clean Air Society of Australia and New Zealand INC., Vol. 2, Perth, Western Australia, pp. 179–188.

Nicholls, E.N., Pielke, R.A., Eastman, J.L., Finley, C.A., Lyons, W.A., Tremback, C.J., Walko, R.L., Cotton, W.R., 1995. Applications of the RAMS numerical model to dispersion over urban areas. In: J.E. Cermak, et al. (Eds.), Wind Climate in Cities, Kluwer Academic Publishers, The Netherlands, pp. 703–732.

Petford, P.J., 1995. The relationship between synoptic meteorology and episodes of high pollution in the Kwinana region. Honours Thesis, Murdoch University, Perth, Australia. Available from Library, Murdoch University, Murdoch, WA 6150, Australia, pp. 196.

Pielke, R.A., Cotton, W.R., Walko, R.L., Tremback, C.J., Lyons, W.A., Grasso, L.D., Nicholls, M.E., Moran, M.D., Wesley, D.A., Lee, T.J., Copeland, J.H., 1992. A comprehensive Meteorological Modelling System-RAMS. Meteorological Atmospheric Physics 49, 69–91.

Pitts, R.O., Lyons, T.J., 1992. A coupled mesoscale/particle model applied to an urban area. Atmospheric Environment 26b (3), 279–289.

PPSS, 1994. The Perth photochemical smog study. Department of Environmental Protection, Study Description and Compendium of Data, Perth, Western Australia. Available from Department of Environmental Protection, Westralia Square, Perth, WA 6000, Australia.

PPSS, 1996. The Perth photochemical smog study. Department of Environmental Protection, Report 16, Perth, Western Australia. Available from Department of Environmental Protection, Westralia Square, Perth, WA 6000, Australia, pp. 94.

Rayner, K.N., 1987. Dispersion of atmospheric pollutants from point sources in a coastal environment. Unpublished Ph.D. Thesis, Murdoch University, Perth, Australia. Available from Library, Murdoch University, Murdoch, WA 6150, Australia, 249pp.

Rye, P.J., 1994. Modelling smog events for the Perth 1994 summer season. Clean Air'94, Proceedings of the 12th International Conference of the Clean Air Society of Australia and New Zealand INC., Vol. 2, Perth, Western Australia, 327–336.

Sawford, B.L., Luhar, A.K., Hacker, J.M., Yang, S.A., Yoon, I.-H., Noonan, J.A., Carras, J.N., Williams, D.J., Rayner, K.N., 1998. The Kwinana coastal fumigation study: I-program overview, experimental design and selected results. Boundary-layer Meteorology 89, 359–384.

Steyn, D.G., 1998. Scaling the vertical structure of sea breezes. Boundary-layer Meteorology 86, 505–524.

Tapper, N., Hurry, L., 1992. Australia's Weather Patterns: An Introductory Guide. Dellasta Pty. Ltd., Australia, pp. 130.

Watson, I.D., 1980. A dynamic climatology of the Australian West Coast Trough. Unpublished Ph.D. Thesis, University of Western Australia, Perth, Australia. Available from Library, University of Western Australia, Crawley, WA 6008, Australia, pp. 246.

Willis, G.E., Deardorff, J.W., 1978. A laboratory study of dispersion from an elevated source within a modeled convective planetary boundary. Atmospheric Environment 12, 1305–1311.