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Regional Air Pollution Modelling for Planners

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ABSTRACT

The development of the CSIRO Lagrangian Atmospheric Dispersion Model, LADM, represents a major advance in assessing air pollution impacts. LADM is a synthesis of practical implementations of current scientific knowledge of boundary-layer meteorology, dynamical meteorology in complex geographical regions, plume dynamics, turbulent dispersion in thermally unstable and stable conditions and photochemical smog kinetics. The most startling result from the application of LADM in coastal regions in several studies is the prevalence of recirculations of pollutants back over the emission region later in the day or even during the following day, perhaps then as smog. These and other results are illustrated by recent Australian studies. Most recently, LADM has been extended to permit prediction of dry deposition. Now, dry deposition estimates for complex conditions are possible.

(Key words: Air pollution, Lagrangian, Prognostic, Complex geographies)

1. INTRODUCTION

Air pollution modelling is the key methodology used in Environmental Impact Assessments (EIAs) that permits investigation of the relationships between existing and proposed changes in emissions and their effect on ambient air quality in a region. An audit by Buckley (1991, 1992) of 181 testable predictions in Australian EIAs dated to 1982 showed that over 40% of actual impacts were more severe than predicted, that the predictions where the actual impacts were more severe were on average less accurate than those where they proved less severe, and that these more severe impacts had a much larger range than the less severe impacts. These errors surely must be due primarily to inappropriate assessment methodologies and, hence, modelling.

Recently, CSIRO scientists have made several advances in air pollution meteorology and chemistry. These have been incorporated into a new numerical paradigm called LADM–the Lagrangian Atmospheric Dispersion Model (Physick *et al.*, 1991, 1992, 1994). LADM is rapidly finding acceptance as an advanced air quality planning tool. It has revolutionised the way that EIAs are able to address air pollution impacts in terms of accuracy, site- and

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regional complexities, and pollutant transformations. After a brief consideration of some of the problems of modelling for EIAs, this paper will introduce LADM and describe its strengths and limitations.

2. MAJOR PROBLEMS WITH AIR QUALITY ASSESSMENTS

In the field of air quality assessments, poor predictions in EIAs imply that the results of the concomitant air pollution modelling are poor. There are several possible reasons for this. One relates to the recognition (*eg* Venkatram and Wyngaard, 1988) that modelling science is a lot further advanced than the procedures that many EIA consultants apply. My own observation is that, at least in Australia, most EIAs for development proposals claim to assess air quality impacts by employing grossly inadequate meteorological and air quality data. This often arises from the imposition of unrealistic timescales and the lack of resources from the developer or government agency. Then, inappropriate methods are employed to make predictions.

The workhorse of the air pollution modelling industry continues to be the Gaussian plume model (*eg* Lorimer, 1986) with its assumptions of spatial homogeneity, stationarity and absence of memory in the description of pollutant dispersion. The method is simply inapplicable beyond a distance of ten or more kilometres from sources in the coastal regions of Australia and many other Asian countries where most industrial and urban development occurs. Puff models, which in principle do not require the above assumptions, also usually fail because the reality in Australia (and in most other countries) is that in practically no complex geographic region are there adequate meteorological data to use such models with confidence.

A recognition of the importance of 'whole airshed management' and the general concern with acid deposition and urban haze leads to a need for information on the time history of pollutants from individual sources over several hours, perhaps as long as several days. This point is illustrated in Figures 1 and 2. Figure 1 shows the predicted trajectory of air pollutant particles on a day on which high smog levels were measured to the east of Perth, on the west coast of Australia. The pollutants from the metropolitan area are predicted to first go out to sea in the general large-scale easterly winds. By 1100 h the sea breeze commences, recirculating the pollutants back to the city and further inland. The pollutants continue inland in the sea breeze until late in the evening, by which time the breeze is overcome by the continuing large-scale easterly winds. The pollutants are again brought back to the northern suburbs of Perth, passing over the coast early in the morning. These features are all supported by the measurement data at the Caversham monitoring station, as shown in Figure 2.

An understanding of how different sources interact to cause the cumulative air pollution impact in the airshed is also needed. This point will be illustrated in Section 3.4.

3. LADM–AN AIR POLLUTION ASSESSMENT SYSTEM

Air pollution modelling involves a description of four major features:

(1) transport of pollutants by the wind,
(2) turbulent diffusion (dilution) of pollutants in the air,
(3) chemical reactions of the pollutants among themselves and with other species,
(4) prediction of ground level concentrations and dry deposition rates.

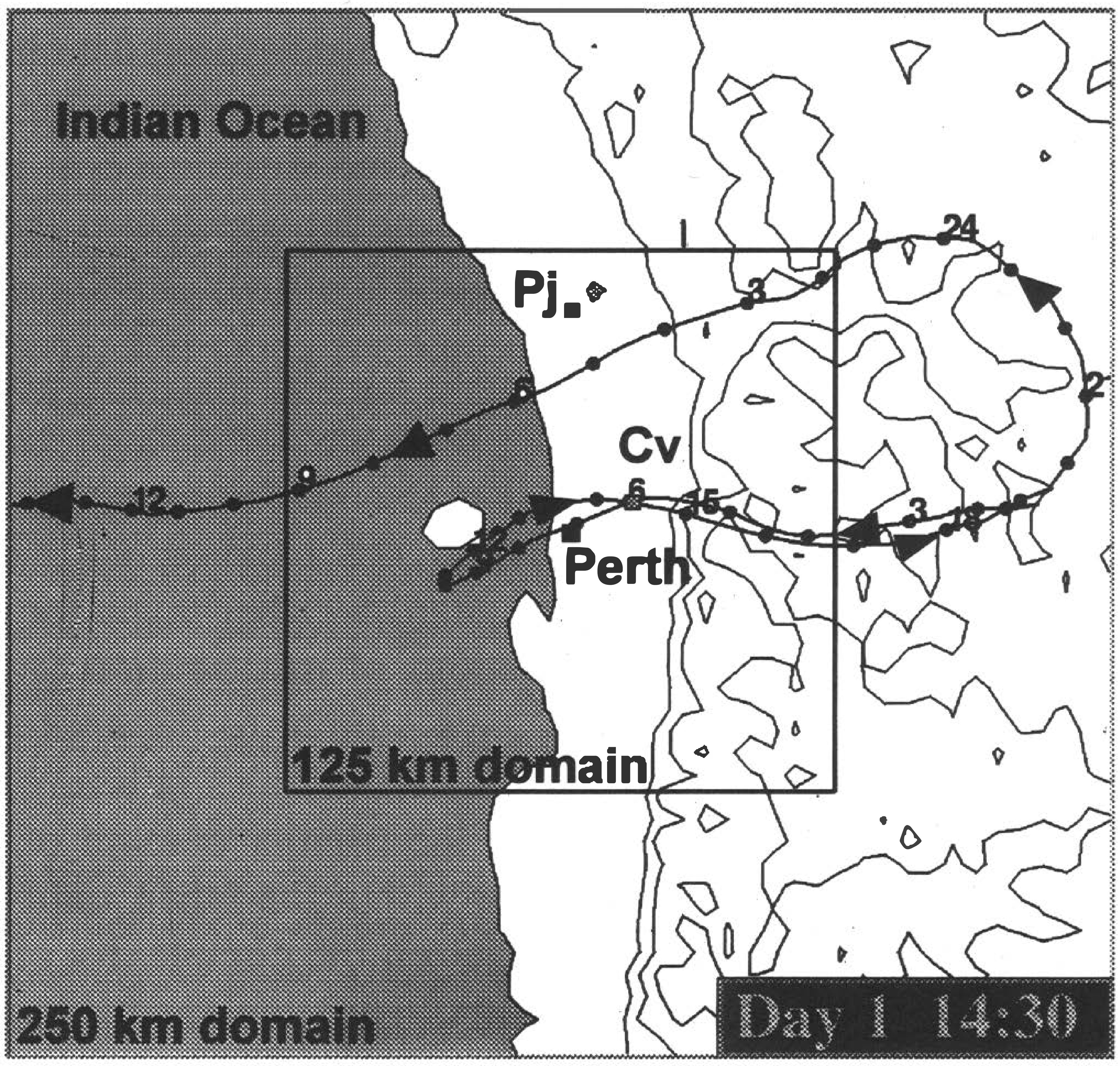

Fig. 1. A predicted trajectory of an air mass over Perth in high-pollution conditions. The air mass passes over Caversham (Cv) at 14.30 hr. Considerable recirculation of Perth air is predicted.

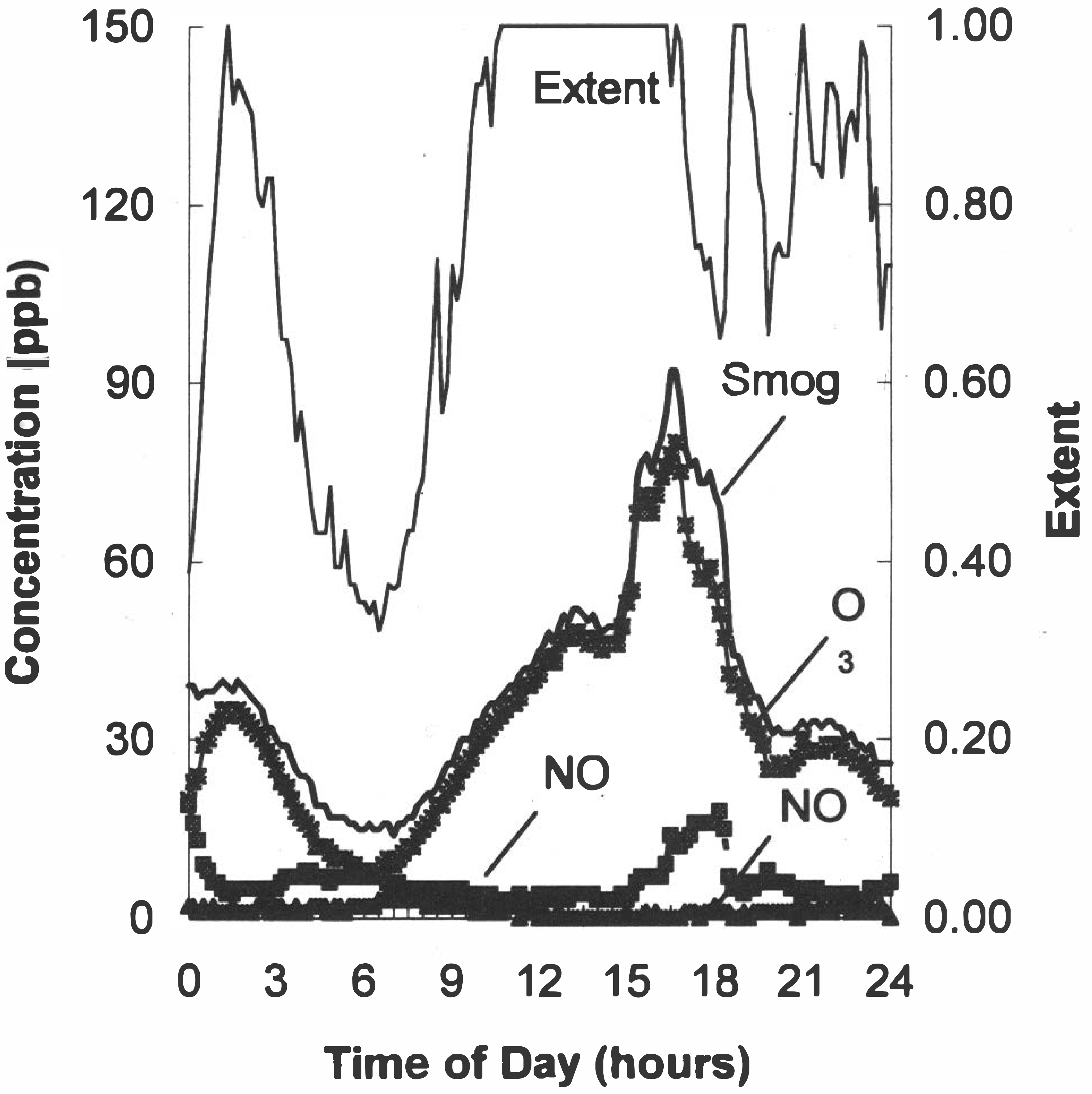

Fig. 2. IER analysis of air monitoring data for 19 January 1991 at Caversham station, east Perth. 'Extents' near 1.0 in the early morning and afternoon mark chemically old recirculated air from Perth.

LADM, the Lagrangian Atmospheric Dispersion Model, is able to obtain a practical solution to these features with the barest minimum of measured data in the region of application. The model consists of two main components: a three-dimensional mesoscale windfield model which predicts the diurnal cycle of winds and turbulence at many gridpoints in the atmosphere, and a Lagrangian particle dispersion model which uses the winds and turbulence to predict the pathways of tracer particles released from any number of locations.

3.1 Pollutant Transport

There are never enough measured wind data in complex topographical regions in practice so LADM takes the approach of predicting all the local winds using only the synoptic winds and temperature data available from standard weather maps for different heights in the atmosphere. This is done by solving the equations of motion on a three-dimensional grid of points every few minutes over two or three days–similar to the approach used by a weather forecasting model. The model first solves for the wind flows in a much larger region to fully account for the gross effects of topography on the smaller domain of interest. The model is then rerun in successively smaller regions, one within the other, until a sufficiently fine grid is used, perhaps as small as 1 km and dependent on the complexity of the terrain but limited by the model's use of the hydrostatic assumption. The domains for two such grids are shown in Figure 1.

This part of LADM uses a simplified but adequate vegetated canopy scheme to allow realistic simulations of surface fluxes over different surfaces (Kowalczyk *et al.*, 1991). The scheme permits a solution for the broad turbulence characteristics of the air flow, as well as for another important output parameter, the height to which surface-generated turbulence extends–the mixing height.

There are many advantages to this approach so long as the model incorporates adequate physical descriptions of the meteorological processes, and adequate computing resources are available. However, modelling a given event can still be subject to considerable uncertainty due to ambiguity in the synoptic conditions and the effects of unresolved motions.

3.2 Turbulent Dispersion

Mixing and dilution of pollutants in the atmosphere is very complex, changing with location in the vicinity of complex terrain and also changing throughout the day as different events occur. It is extremely rare to have observational turbulence data except at a few locations near the ground; for chimney plumes, most of the dispersion occurs hundreds of metres above the surface. In LADM, dispersion is effected using the predictions of the mean wind at every point in the three-dimesional domain, along with a turbulent velocity determined from a Lagrangian stochastic model.

The most natural description of dispersion is to follow different particles emitted from the pollutant sources and to derive the dispersion from the statistics of particle locations at any instant. This is the Lagrangian description of turbulent dispersion (Sawford, 1993) and is the method employed in LADM–the motion of notional particles of pollutant from the sources under study is described using a random-walk technique applied in the calculated turbulent wind field. It has the major advantage of being able to resolve narrow plumes, but for accurate concentration predictions the method is highly computer-intensive.

3.3 Chemical Reactions

Real air pollution problems usually involve atmospheric chemistry, but this is essential for regional impact studies of smog and acid deposition. LADM does not include a comprehensive description of chemical reactions because the necessary data to do this are rarely available and the computing resources required are very large. Instead, LADM only includes the important problem of smog production. The method employs the Integrated Empirical Rate (IER) equations of smog formation (Wratt *et al.*, 1992), which is the basis of the AIRTRAK smog analysis system (Johnson *et al.*, 1990; Johnson, 1991). This methodology permits a simple solution for smog and haze production, as well as giving information on the photochemical 'age' of the pollutants. The IER method can be used to analyse data from a monitoring station to derive important smog properties, as is shown in Figure 2.

3.4 Ground Level Concentrations

In LADM, a sufficient number of emitted particles is used so that by counting them in boxes on the ground, averaged over specified time intervals, predictions of pollutant concentrations may be made.

For example, consider some recent simulations of pollutant dispersion from existing sources and possible industries near Aldoga (Figure 3) in the Gladstone region on the east coast of Australia. Interaction of the emissions with the complex terrain on typical summer and winter days was shown to lead to many effects: a complex transport of pollutants inland by two different sea breezes; plume strikes on the high terrain; and mixing in morning convection conditions to the west of the region. Figure 3 shows one set of predictions just before the sea breeze commences at Gladstone. It is already starting further to the north. At the time shown, the pollutants flow around Mt. Larcom with the highest concentrations predicted in the lee of the mountain due to flow convergence and cumulative impact of emissions from the power station and the cement and lime facility.

3.5 Dry Deposition Predictions

The surface vegetation scheme used in LADM is very suitable for application of the 'Inferential Method' (Baldocchi *et al.*, 1987) for prediction of dry acid deposition moment by moment. The method has been implemented but not applied to practical problems as yet. The required computing resources to obtain predictions of seasonal or annual dry deposition are rather daunting.

3.6 Data Requirements for Operation

The data required to run LADM are minimal:

- Gridded terrain data for the whole region with, *eg*, a resolution of 2.5 km, is needed, as are surface properties such as approximate vegetation height and type, soil type and wetness, and the surface roughness for each grid square. These latter parameters can be estimated by visual examination of the area.
- To predict the winds throughout the day, the model needs to be given a large-scale (synoptic) vertical profile of wind velocity, steady or variable in time; and a profile of temperature and humidity with height. These data are available from national weather services every twelve hours (or more frequently), as synoptic weather maps at different heights in the atmosphere: the most important ones for air pollution work are the

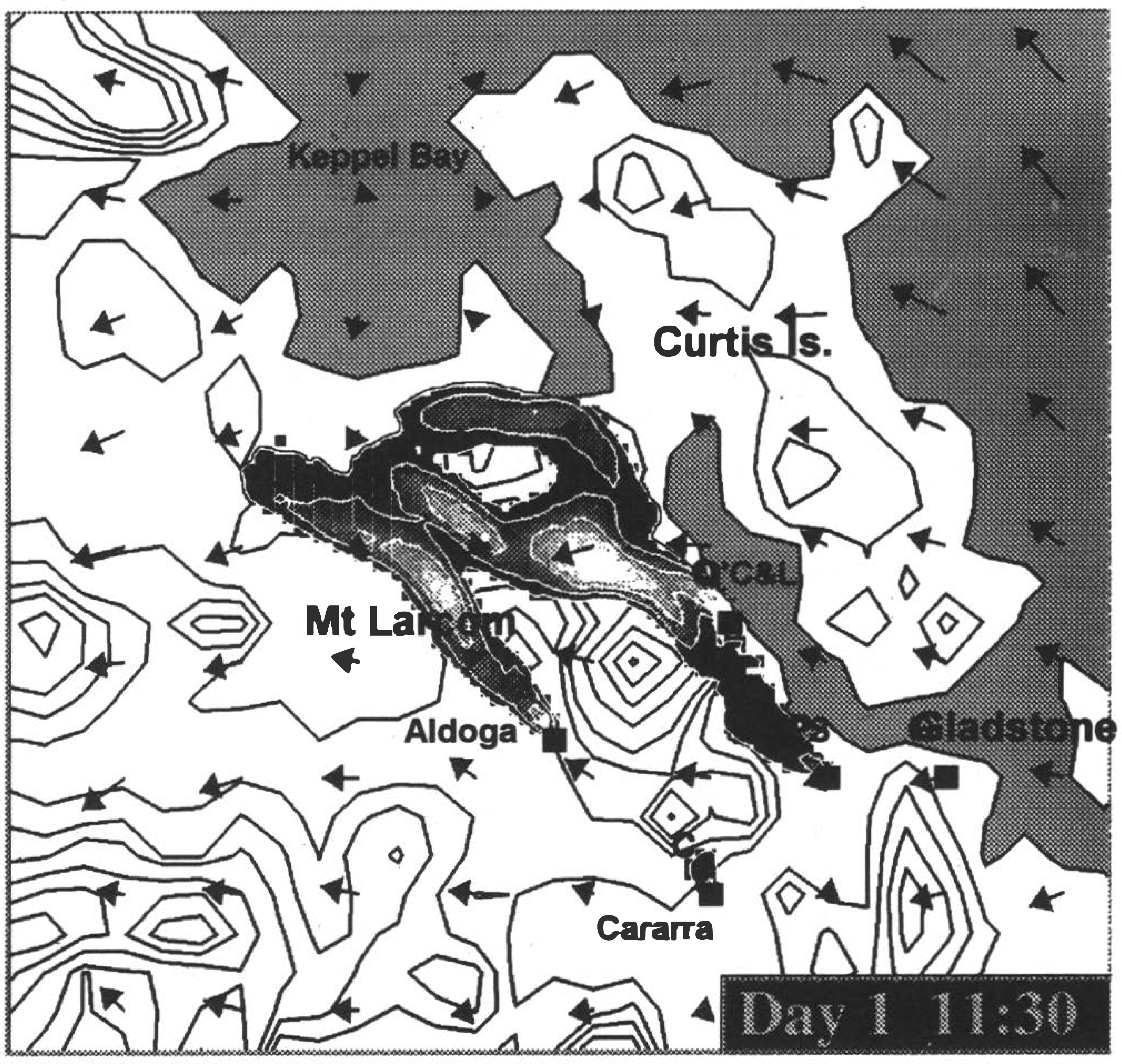

Fig. 3. Predicted ground level impacts from the Gladstone Power Station, Queensland Cement and Lime, and possible industry at Aldoga and Cararra on a typical winter day with SE winds. Terrain contours are at 0, 50, 100, 150, 200, 300, , 600 m; concentration contours are overlain on a shaded background at 100, 250, 500, 750, ... μg/m^3.

pressure and thickness charts for the surface, 1,000 hPa, 950, 900, 850, 800, and 700 hPa if available. Estimates of cloud cover over the region during the day are also required, and these are available from satellite photographs.

- Of course the emissions characteristics of sources are required, including the variation throughout the day if these are important.
- Background concentrations of the pollutant of concern may also be necessary.
- If predictions of NO_2 or ozone are to be made, emissions data are required of both nitrogen oxides and a measure of the photochemical reactivity of the emissions called R_{smog}, which is a single parameter describing the efficacy of emitted hydrocarbons to generate smog. R_{smog} can be measured directly using AIRTRAK or can be estimated from data on the emitted hydrocarbon composition. Also needed are the background concentrations of nitrogen oxides, O_3 and R_{smog}.

4. SOME ADVANTAGES AND LIMITATIONS OF LADM

The difference between being able to investigate the full temporal evolution of dispersion of emissions in complex terrain, following the emissions as they are dispersed in slope-, land- and sea-breezes, and the heretofore very limited picture from Gaussian plume modelling or interpreting data from a small number of measurement points, is truely enormous. Combine the massive quantities of numerical data with a flexible graphical display system featuring animation facilities and the result is an unrivalled system for investigating the regional circulation of pollutants and the discovery of the fate of those pollutants over many hours. Table 1 lists some other important advantages of the LADM approach to EIAs.

There are also several limitations, and some of these are given in Table 1 as well. Perhaps the most important at present is that the computing resources required are large, and growing, as new extensions are incorporated. On the other hand the model can be run on a PC with some restrictions. The most serious scientific limitation is not the assumption of hydrostatic conditions (— 'vertical accelerations must be small'), but rather the turbulence description used in the wind prediction component. A local K-theory mixing scheme is employed there and it is not sufficiently dispersive in thermally stable conditions, nor does it have adequate memory (decay). Our scientific knowledge is insufficient to describe turbulent dispersion in thermally stable conditions in a practical way. Further, vertical resolution in this part of the model is frequently inadequate in determining mixing height, which is a diagnosed parameter in LADM.

As for the good performance of the model compared with observational data, this has been demonstrated in several case studies. Physick *et al.*, (1991, 1992, 1994) show some comparisons, and other recent studies are currently being published (*eg* Hurley and Manins, 1994a, b, c). It may be noted that the very success of the model in making predictions in data-sparse regions has as a consequence that verification tests are difficult to demonstrate. Indeed, the interpretation of Figure 1 compared with Figure 2, discussed only briefly in Section 2, is a major success for the model, as well as for the methods employed in the interpretation of conventional monitoring data.

Table 1. The LADM approach to regional environmental impact assessments for planners.

Advantages	**Disadvantages**
Complex temporal and geographic regions resolved to about 1 km for winds, 250 m for glcs.	Resolution limited by the hydrostatic approximation in strong winds, steep terrain.
Dispersion in complex terrain is simplified by using the Lagrangian particle approach.	A large number of particles is required due to the method of box counting for concentrations.
The particle approach resolves discrete stack plumes, including plume rise, dispersion.	LADM cannot cope with a large number of sources such as in a complex urban area.
Chemically reactive plumes are well resolved, using the IER empirical chemistry model (Johnson 1991).	Expensive demand on computer resources, but modest compared to others. No wet deposition processes.
The worst-case 'defined scenario' approach to Impact Assessments used with LADM can be validated	It is as yet too expensive to investigate a large number of different dispersion classes.
Regional recycling of pollutants is a highly important phenomenon and is readily investigated by LADM.	Only expensive high-resolution Eulerian models are able to approach the power of LADM.

5. CONCLUSION

Our whole way of thinking of EIAs and regional air pollution planning questions has changed with the development of LADM. Now we are able to break away from thinking in terms of pollution impacts on independent hours, limited to short distances, from isolated sources. Now, the fate of chemically active pollutants over periods of, say, 48 hours from interacting sources can be investigated using LADM.

The most startling thing that has been found for common Australian coastal conditions is the prevalence of recirculation of pollutants over the source after a period of 4 to 10 hours. This is in contrast to a general failure to contemplate such a possibility in most EIAs, or to consider only one possibility: that changing weather would clear the air. Instead, we find that if these pollutants are photochemically reactive they may return to the locality, by then transformed into smog (as illustrated in Figures 1 and 2).

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