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Contribution by bushfire smoke to photochemical smog

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ABSTRACT

Visibility reductions in the Perth region, due to smoke from bushfires and controlled burns, have at times been measured by the Western Australian Department of Environmental Protection to be in excess of accepted standards. The smoke has been observed to include high concentrations of hydrocarbons, with the potential to contribute to the formation of photochemical smog.

During the spring and summer of 1992-1993, two photochemical smog events occurred which were clearly associated with the passage of smoke from controlled burns. The background to these events, and some implications, are discussed.

INTRODUCTION

Since the beginning of 1990, the Department of Environmental Protection of Western Australia (subsequently termed the DEP) has monitored haze events in the Perth region using nephelometers. Instruments have been located at the DEP's Caversham, Queen's Buildings (Perth) and Hope Valley sites. (See Fig. 1)

Two major classes of visibility impairment have been identified. One occurs during winter nights, and appears to be due to the accumulation of smoke from domestic fires. The other occurs during early summer evenings, with a moderate sea breeze still present.

A major source of the latter class of episode was found to be controlled burns conducted by the State's Department of Conservation and Land Management. The need to manage the impact of smoke from controlled burns has since been accepted by that department. Their summer burn program now includes enhanced smoke management methods, drawing heavily on specialized forecasting provided by the Bureau of Meteorology.

While the most immediately apparent effect of the smoke was on visibility, chemical contaminants were also present. At the Hope Valley site, levels of both methane and other hydrocarbons have been measured. (The latter are conventionally termed non-methane hydrocarbons, abbreviated NMHC.)

During the summer smoke episodes, non-methane hydrocarbon levels were observed to rise to extreme levels, in almost exact time correspondence with the scattering coefficient measured by the nephelometer. Collected smoke samples were analysed using chromatography, but the analysis showed a mass of peaks, with no clearly identifiable species.

The presence of hydrocarbons at such concentrations was of concern to the DEP, because of their potential to contribute to the formation of photochemical smog, and because some smoke episodes were seen to extend through the morning of the following day.

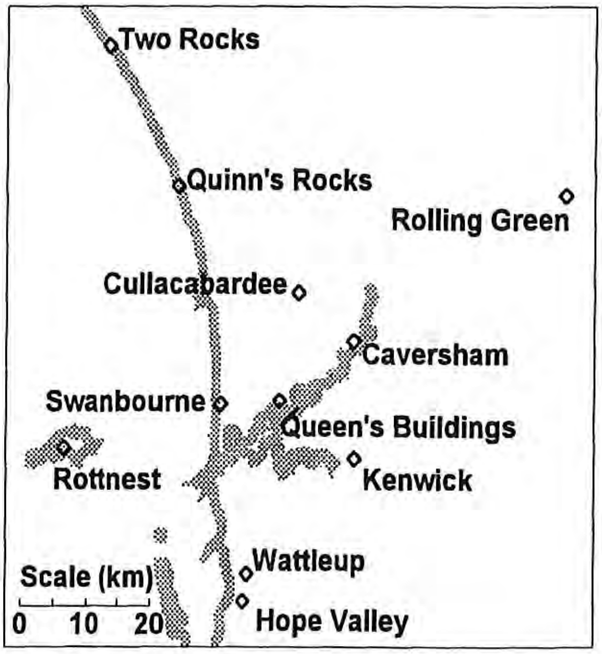

Figure 1. Air quality monitoring sites currently operated by the DEP. Sites other than Hope Valley, Wattleup, Queen's Buildings and Caversham are components of the Perth Photochemical Smog Study.

PHOTOCHEMICAL SMOG PROCESSES

The term 'photochemical smog' refers to a combination of chemical species in the atmosphere, which is the product of reactions involving initially a mix of nitrogen oxides and hydrocarbons with normal atmospheric gases.

The principal components of concern are ozone and a range of oxidated nitrogen species, which are bronchial irritants and corrosive to varying extents. The maximum hourly average concentration for ozone considered acceptable by the United States Environmental Protection Agency and Victorian Environmental Protection Authority is currently 120 ppb (parts per billion). However, as a result of recent epidemiological studies, the recommended hourly average limit for ozone has decreased, with most recommendations in the 75-90 ppb range. A review of these is given by Streeton (1990).

Ozone is produced naturally in the atmosphere by the reactions

$$NO_2 + h\nu \rightarrow NO + O^*$$

$$O^* + o_2 \rightarrow o_3$$

where 'h' represents the energy of a photon of ultraviolet light, and O^* indicates an oxygen atom in an excited state. The NO produced is re-oxidized slowly in the clean atmosphere to NO_2, maintaining an equilibrium that leads to a low background level of O_3 of about 15-25 ppb.

The rate of NO_2 regeneration, and consequently ozone production, is considerably accelerated by the presence of reactive volatile organic compounds ('VOC'), and by the presence of nitrogen oxides from anthropogenic sources (i.e., those originating from human activities). In these circumstances, the progress of photochemical smog reactions in strong sunlight leads to a significant increase of ozone concentrations, peaking typically in the mid-afternoon period.

Emissions inventories generally show that the major sources of volatile organic compounds are motor vehicles and industry, but that biogenic emissions - those from vegetation - are also significant. Carnovale *et al.* (1991) estimated that for average Melbourne summer temperatures around 25°C, about 10 per cent of total emissions arose from this source, but that emissions may rise by 60 per cent for a temperature increase from 25 to 30°C. The VOC's emitted from vegetation tended to be of high reactivity, further enhancing their influence.

OBSERVATIONS

Figure 2 shows an example of an overnight smoke episode, in which both visibility and non-methane hydrocarbon values exceeded the full scale measurement capacity of the recording system. The pattern shown, with an initial rise in levels between 9.00 p.m. and midnight, and a decreasing trend towards dawn on the following day, is typical of these events.

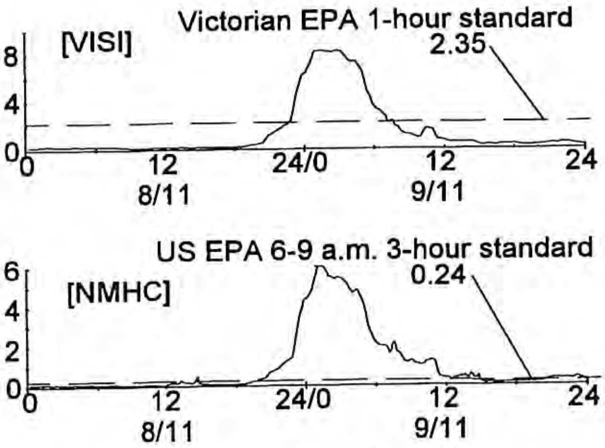

Figure 2. Visibility ('[VISI]', units of 10^{-4} m^{-1}) and non-methane hydrocarbon ('[NMHC]', parts per million) at Hope Valley, during 8-9 November 1990. The horizontal axes represent two days of time, from midnight to midnight, and hours through the day.

In previous summers of recording, smoke levels have cleared before the afternoon ozone peak might have developed. But during the spring and summer of 1992-93, two ozone events occurred in association with bushfire smoke. Figure 3 presents time sequences of visibility and ozone measurements, obtained at the DEP's Caversham site, for the first event, on 22 October 1992.

In this case, and the other on 13 January 1993, the visibility standard was approached, but not exceeded during the period of increased ozone concentration. Also in both cases, the range of standards currently recommended for ozone was exceeded.

The DEP is monitoring ozone and nitrogen oxide levels across the metropolitan area, as a major component of a study funded by the State Energy Commission of WA. At the time of the October 1992 event, equipment was operational at Caversham, Swanbourne, Kenwick and Quinn's Rocks (See Fig. 1 for locations). The peak hourly averages measured were 107, 106, 86 and 74 ppb respectively, showing that increased photochemical smog levels occurred across the whole metropolitan region, both upwind and downwind of the urbanized area. (Winds at the time were from the south-west.)

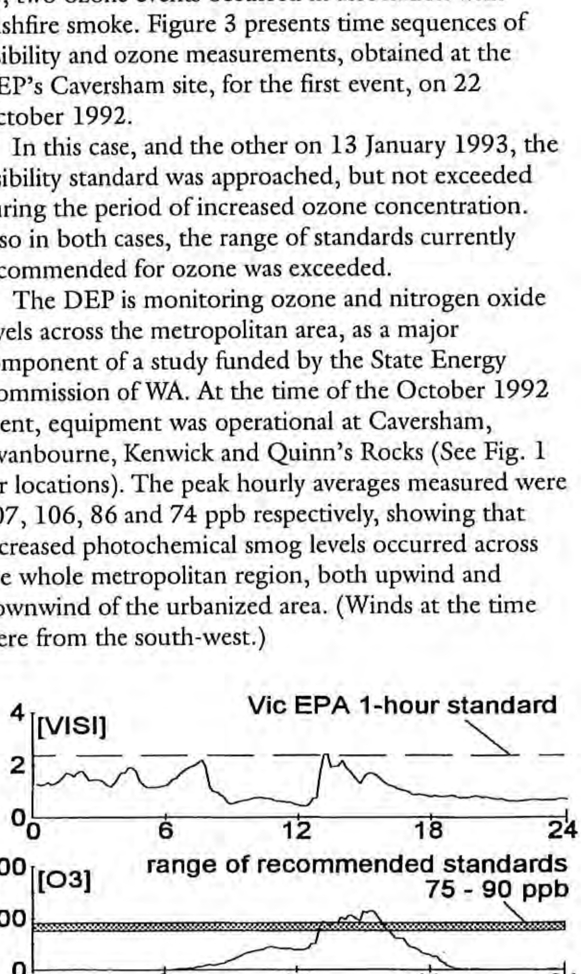

Figure 3. Visibility ('[VISI]', units of 10^{-4} m^{-1}) and ozone ('[O3]', parts per billion) at Caversham, during 22 October 1992. The horizontal axis unit is hours through the day.

While ozone levels did not vary greatly across the metropolitan area in the October episode, the January event showed large variations. Peak levels measured the DEP's sites were as follows:

Rottnest Island	28	ppb at	11.30 a.m.
Swanbourne	36		11.40
Quinn's Rocks	35		11.50
Two Rocks	23		11.50
Cullacabardee	85		12.10 p.m.
Kenwick	62		12.20
Caversham	85		12.10
Rolling Green	112		2.20

Highest values occurred inland, and to the north of the city. Winds at noon were 7-8 m s^{-1} from about 210° at the coast, and 4-5 m s^{-1} from 230-240° inland. At these speeds, the time of travel of an air mass from Swanbourne to Cullacabardee (about 20 km downwind) would have been close to an hour. During this time the ozone concentration in the air mass rose by about 50 ppb. This represents a high rate of reaction, compared with normal Perth experience.

The differences between the two events may be linked to the differing meteorology of the two days. On 22 October, there was an initial light easterly wind at the coast, with a light southerly at Rottnest. The southerly wind was due to the presence of a common feature of Perth's summer climate, the 'west coast trough', a low-pressure trough that forms offshore with its axis parallel to the coast. The occurrence of southerly winds at Rottnest shows that its axis lay between there and the coast.

This pattern, during summer, is the most common one leading to a photochemical smog episode. Morning urban emissions of VOC and nitrogen oxides are carried offshore by the easterly, but held close to the coastline by the effects of the coastal trough. Reactions within the offshore air mass permit increased ozone concentrations to form, before the air is returned onshore by the sea breeze. Levels of nitrogen oxides measured at Swanbourne on 22 October were consistent with values preceding such an event.

It therefore seems likely that the increased ozone levels arose from the mixing of normal urban emissions with VOC in the offshore smoke. The probable high reactivity of the mix would have compensated for the lower reaction rates in spring, resulting in ozone concentrations more typical of summer events.

By contrast, the 13 January winds were initially light southerly, with an onshore trend developing during the morning. These conditions do not normally lead to increased ozone levels. A steady southerly would carry morning emissions well out of the metropolitan area before increased ozone concentrations could form.

The moderate levels of ozone and low concentrations of nitrogen oxides measured at the coast on 13 January were consistent with these conditions. The development of high ozone concentrations inland could only be ascribed to much higher reactivity of VOC in the smoke.

ILLUSTRATION OF SMOKE TRAJECTORIES

To the best of the DEP's knowledge, the October and January events originated from different sources. The sole major burn conducted before the first event was on private land, north-east of the city. Other minor burning-off operations were also in progress in the northern suburbs. Before the second event, the Department of Conservation and Land Management had conducted a significant controlled burn in the far south-west of the state.

It was believed that in both cases, a major factor in common was the presence offshore of a coastal low-pressure trough. Circulation of air southward to the east of the trough, and northward to its west, creates the potential to trap smoke for an extended period. This trapping may be enhanced when a closed low forms in the trough, as happened at least for the October event.

To illustrate the potential effects of the trough, a three-dimensional mesoscale model was run from an initial easterly-wind condition, typical of the start of a period of trough development. The model used was an extension of a two-dimensional one developed for both forecasting and analytical purposes (Rye 1989) which had been extensively validated in the Perth region, and has recently been applied for sea breeze and trough studies related to the current Perth Photochemical Smog Study. In the most representative case so far, the trough formed and deepened over a period of three days, the fourth and fifth day of model time being used in the work quoted here.

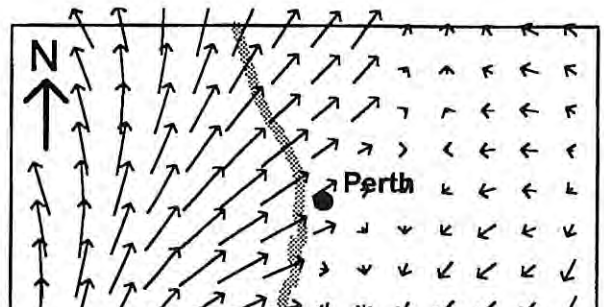

Figure 4. Wind vectors for 9.00 a.m. on the fifth day of model time, showing circulating wind flow.

Figure 4 shows a wind vector plot for a subsection of the modelled region at 9.00 a.m. on the fifth day, as the trough was passing inland. The closed circulation near Cape Naturaliste is a common component of the trough.

The calculated hourly meteorological fields, from which Figure 4 is an extract, were used to estimate the movement of smoke that might have been released from a location in the south-west forest region.

In the modelled case the trough passed inland slightly later than the time that would have brought the smoke trajectories to Perth. Therefore, to illustrate the type of event that was observed on the 13 January, a slight shift of smoke emission time was required.

Normally, controlled burns are conducted during the daytime, but in this exercise it was necessary to shift the period to cover the times 12.00 noon to 8.00 p.m.

The complications evident in the trajectories shown in Figure 5 are probably typical. A particle emitted at 7.00 p.m. (hour 19) would have been carried northward in the evening for the fourth model day, south-west then north-west overnight, then north-eastward through the next day. By contrast, the trajectory which commenced an hour earlier moved initially south-west, then north-west overnight, and finally to the north-east.

The implication of this analysis is that there is potential for smoke to reach Perth not only from close sources, but also from large distances away. However, for photochemical smog to form when the source is distant, a low pressure trough must be present offshore. In these conditions, accurate trajectory forecasts are unlikely.

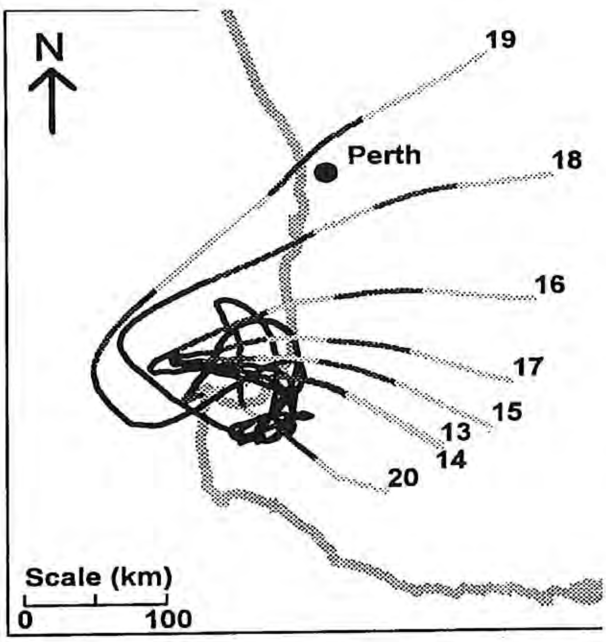

Figure 5. Trajectories calculated up to 6.00 p.m. on the fifth modelled day, for particles released in the south-west. Each trajectory is labelled with the hour of the previous day of its release. Contrasting shades show the final four three-hour periods on each.

DISCUSSION

The additional effect of bushfire smoke, in contributing to episodes of photochemical smog, introduces a complication to the management of both smoke and smog on the Perth metropolitan area. There are a number of factors to consider, including the following:

Seasonal Weather Factors For normal sea breeze strengths and directions, smoke from south-western sources passes the Perth region overnight. To pass the Perth metropolitan area during the day time, the path of the smoke must be extended by some form of recirculation, or the winds carrying the smoke must be significantly lighter. Both of these conditions normally require the presence of a low pressure trough along the west coast.

During summer, when such a trough is present, temperatures on the coast are generally above 35°C, higher than those considered by the Department of Conservation and Land Management to be ideal for controlled burns. In addition, private burning is prohibited through most of summer. For these reasons, such events should be rare in the height of summer.

But in the early spring period, conditions suitable for controlled burns can arise when temperatures are higher than normal. In these cases, careful consideration of possible smoke trajectories will be essential to minimize the chance of a photochemical smog event in Perth.

However, there is currently no formal requirement that private land-clearing burns be conducted with the same attention to weather constraints as those of the Department of Conservation and Land Management. The 22 October event occurred shortly before the commencement of summer-season fire restrictions. For the recurrence of such an event to be prevented, extra controls on the lighting of large fires may be required when a deep low pressure trough develops off the west coast.

Trough Occurrence and Forecasting The potential for events described here to produce photochemical smog requires the presence within the trough of a recirculating flow. While many coastal troughs form through a summer, most pass inland without forming such a flow pattern. Others cross the coast at a time of day when smog formation is prevented or limited by the lack of sunlight. The Bureau of Meteorology has long regarded the accurate prediction of movement of the trough as a high priority, and the potential effect of a trough passage in the crucial time range from about 6.00 a.m. to 3.00 p.m. provides a further reason for priority treatment.

Given the high variability of smoke trajectories, an accurate prediction of movement of smoke over Perth due to the passage of a trough is unlikely. Any control strategy based on weather predictions would therefore require inclusion of a wide margin of safety.

Future Trends Current vehicle emission controls are tighter on hydrocarbon than on nitrogen oxide emissions, so a long-term reduction in emissions of hydrocarbons from the vehicle fleet can be expected, but less so of nitrogen oxides.

The cause of the events described here was a large input of hydrocarbons to the urban atmosphere. Under conditions of surplus hydrocarbons, the principal controlling factor is the supply of nitrogen oxides. Given the lesser reduction of nitrogen oxide emissions, there appears little prospect of a reduction over time of the frequency of smoke-originated smog events.

CONCLUSIONS

The two events described here were the first major episodes of photochemical smog detected in three years of monitoring, to which a bushfire contribution could be ascribed. Nevertheless, both occurred due to a combination of smoke with a coastal low pressure trough, the occurrence of the latter being a normal part of Perth's summer weather pattern.

Measurements suggest that the smog developed due to a mixture of urban nitrogen oxide emissions with reactive organic compounds in the smoke. In one case, the mixing occurred offshore, in the other it occurred as the smoke passed over the Perth region.

Given the potential effect of the combination of bushfire smoke and the coastal trough on urban air quality, and the very specific circumstances involved, it should be possible to include its consideration within the smoke management program already operated by the Department of Conservation and Land Management. But additional controls may be required to ensure that events such as occurred in October, arising from smoke from private burning-off operations, do not recur.

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