1.6 A TECHNIQUE FOR FORECASTING ENHANCED OZONE DAYS IN A COMPLEX SUB-TROPICAL COASTAL URBAN ENVIRONMENT

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1. INTRODUCTION

The meteorological conditions associated with enhanced ozone concentrations in Sydney, Australia are complex and not fully understood (Hyde et al., 1995). Concentrations of ozone often exceed Australian air quality goals in Sydney during summer. Australia has national ambient air quality standards, the National Environment Protection Measure for Air Quality (the Air NEPM) (NEPC, 1998). The Air NEPM standards for ozone are 100 ppb for a 1-hour average concentration and 80 ppb for a 4-hour average, with one exceedance allowed per year. The New South Wales (NSW) state regulatory body the Department of Environment and Conservation (DEC) currently uses a qualitative approach to forecasting the next day's pollution levels for Sydney and there remain gaps in the current knowledge of synoptic processes associated with enhanced ozone episodes. The study described here provides an objective, quantitative method to isolate and predict enhanced ozone days.

We assess the accuracy of an objective synoptic climatology of ozone episodes in Sydney in isolating and predicting enhanced ozone episodes. The climatology was generated using multivariate statistical techniques, including principal component analysis and a two-stage cluster analysis that classified days into meteorologically homogenous synoptic categories. Surface and upper air meteorological data for the warm months (Oct-Mar) over a ten-year period (1992-2001) were used as input to the statistical analyses.

The synoptic climatological technique discussed in this study is commonly used in many cities worldwide to determine the meteorological conditions behind tropospheric ozone episodes (e.g. Cheng et al., 1992: Cheng, 2001: Eder et al., 1994: Greene et al., 1999), but predictive skill is rarely analysed in any rigorous or quantitative way. One exception is described by Cheng et al. (1992), who used these methods to study ozone and tsp concentrations during summer months in Philadelphia over a 17-year period. They evaluated predictive ability by calculating daily mean pollution levels within each of the synoptic categories, and the percentage of the 50 most polluted days over the 17-year period that occurred in each category. The study found that only 24% of the 50 most polluted days occurred in the highest ozone synoptic category. A similar approach has been applied to ozone in Birmingham, Alabama by Eder et al. (1994), where both surface and upper air variables were used as input to the statistical analyses. They found 33.2% of days experiencing ozone concentrations greater than 80 ppb fell within the synoptic category associated with the highest ozone concentrations.

A previous analysis of synoptic-scale processes associated with high pollution events in Sydney (Hart et al., 2004) found that summertime ozone events are associated with an anticyclone centred over the northern Tasman Sea combined with a light west-north-westerly gradient wind.

2. SYNOPTIC CLIMATOLOGY

The synoptic climatology identified eleven synoptic categories in Sydney during the warm season; ozone concentrations associated with each were investigated. One synoptic category was associated with the majority of days exceeding current air quality goals. Days occurring in this category had an anticyclone centred in the Tasman Sea ridging back across the continent into northern New South Wales (NSW) and southern Queensland (Qld.) (Figure 1) that produced light west-north-westerly gradient winds, warm temperatures at the surface and aloft, reduced mixing heights, very little cloud cover and a north easterly sea breeze in Sydney. These days had a mean daily maximum 1-hour average ozone concentration of 86 ppb, while the days in the remaining ten synoptic situations had an average of 41 ppb. Furthermore, 91.2% of all days that exceeded the Australian Air NEPM for daily maximum 1-hour average ozone fell within this one category.

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Table 1 presents a breakdown of the ozone concentrations experienced for days falling within this high pollution category. The daily maximum 1-hour average ozone concentration has been grouped into four classes: (1) Low pollution days – days less than 60 ppb, (2) Medium pollution days – days between 60 and 80 ppb, (3) High pollution days – days between 80 and 100 ppb (80 ppb is the NSW DEC's long-term goal for 1-hour average ozone concentrations), and (4) Very High days - days which exceed the current Australian Air NEPM for 1-hour average ozone of 100 ppb.

During the ten-year study period, over 90% of days that exceeded the current air quality goal (Very High ozone days) occurred in the high pollution category and were associated with the synoptic category described above. Thus, the Tasman Sea anticyclone synoptic weather conditions are singled out by the synoptic climatological technique as a necessary condition for the formation of the majority of enhanced ozone days in Sydney. However, 49% of days within this synoptic category actually experienced Low or Medium ozone concentrations, indicating that while the conditions described by this synoptic situation are necessary for enhanced ozone formation, they are not always sufficient. The following analyses examine the additional conditions required to produce enhanced concentrations of ozone in Sydney.

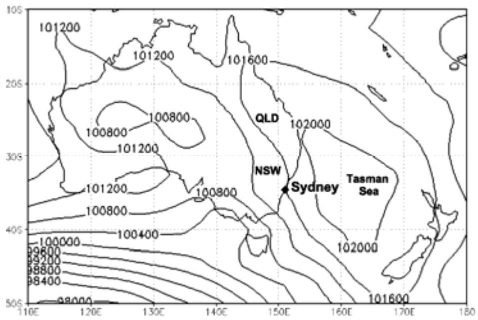

Figure 1 - Synoptic chart representative of mean meteorological conditions during a Tasman Sea anticyclone. Solid lines represent mean sea level pressure in Pascals. The chart was produced using NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics

2.1 Additional conditions required to produced enhanced concentrations of ozone

The meteorological variables used in the synoptic classification have been investigated for Low, Medium, High and Very High ozone concentration days within this synoptic category, in order to determine possible differences in the meteorological conditions experienced for each of these ozone classes. A discussion of the meteorological variables used in the production of the synoptic climatology and the rationale behind this particular configuration is presented elsewhere Hart et al., 2005. Table 2 presents the mean and standard deviation for each of the meteorological variables within each ozone class, while Figure 1 shows a representative mean sea level pressure (MSLP) chart for this synoptic situation.

The following analyses use multivariate statistical techniques to differentiate Tasman Sea anticyclone days of varying ozone concentration.

2.1.1Analysis of variance (ANOVA)

To determine the significance of the meteorological variables listed in Table 2, a one-way ANOVA was undertaken for each of these meteorological variables. Results indicate that the different ozone classes are most clearly differentiated by afternoon surface temperature, and upper-level morning and afternoon air temperature and wind variables. The mixing height at midday also differs significantly between ozone classes. Surface variables (excluding afternoon temperature) do not differ across the various ozone concentration classes, nor does the mixing height at 3pm.

On the basis of the results presented in Table 2, days with an anticyclone in the Tasman Sea associated with High and Very High ozone concentrations are characterised by warmer, dryer air aloft, a large afternoon coastal-inland (~60 km) urban temperature difference (5.9°C on Very High ozone days), lighter westerly gradient winds and reduced mixing at midday. The combination of shallow mixing depths before and after the sea breeze and high temperatures at both the coast and inland locations inhibits the dispersion of photochemical smog precursors, providing a favourable environment for the formation of ozone.

On the other hand, Table 2 shows that days with Low concentrations across the Sydney basin but a similar synoptic situation had a significantly higher mixing height at midday, cooler moister air and much stronger west-north-westerly winds at 850 hPa.

Total number of days in category	200
Mean daily ozone concentration (ppb) for category	86
Number Low pollution days (%)	42 (15%)
Number Medium pollution days (%)	63 (34%)
Number of High pollution days (%)	43 (23%)
Number of Very High days (%)	52 (28%)
Percentage of Very High days during 10-year period falling in category	91.2%

Table 1 - Mean ozone concentration for days associated with an anticyclone in the Tasman Sea. The number and percentage of Low, Medium, High and Very High pollution days are presented.

Meteorological Variables			Tasman Sea anticyclone								ANOVA	
			Low		Medium		High		Very High			
			O3 < 60 ppb		60 ppb ≤ O3 < 80 ppb		80 ppb ≤ O3 < 100 ppb		O3 ≥ 100 ppb		f stat	p value
			Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev		
6:00 AM	Surface	Temperature (°C)	21.0	*1.9*	20.8	*1.7*	21.0	*1.9*	21.5	*1.4*	1.77	0.15
6:00 AM	Surface	Dew point (°C)	18.3	*2.1*	18.2	*1.9*	18.0	*2.5*	18.9	*1.9*	1.79	0.15
6:00 AM	Surface	u wind (m/s)	-0.3	*1.3*	0.1	*1.4*	0.4	*1.2*	0.0	*1.6*	1.31	0.27
6:00 AM	Surface	v wind (m/s)	-1.0	*2.3*	-0.9	*2.1*	-1.0	*2.3*	-1.1	*2.3*	0.10	0.96
6:00 AM	Surface	MSLP (hPa)	1013	*5*	1012	*5*	1012	*5*	1013	*4*	1.12	0.34
6:00 AM	Surface	total cloud cover (oktas)	3.3	*2.8*	3.7	*2.8*	2.8	*2.5*	3.6	*2.8*	1.10	0.35
6:00 AM	Upper Air	**850 hPa temperature (°C) (~1500 m)**	**15.4**	***2.2***	**17.6**	***2.3***	**17.9**	***2.7***	**19.7**	***1.9***	**22.14**	**0.00***
6:00 AM	Upper Air	**850 hPa dew point temperature (°C)**	**6.1**	***5.7***	**5.1**	***5.4***	**6.0**	***5.0***	**2.5**	***7.3***	**3.70**	**0.01**
12:00 PM	Upper Air	**Mixing Height (m)**	**945**	***425***	**693**	***374***	**660**	***390***	**568**	***285***	**6.35**	**0.00**
3:00 PM	Surface	**Temperature (°C)**	**28.0**	***1.2***	**28.9**	***2.2***	**29.7**	***2.2***	**28.9**	***2.3***	**3.52**	**0.02**
3:00 PM	Surface	Dew point (°C)	18.4	*2.3*	18.2	*2.3*	18.1	*2.8*	18.2	*2.4*	0.10	0.96
3:00 PM	Surface	u wind (m/s)	-4.6	*2.0*	-4.7	*1.7*	-4.8	*1.5*	-4.9	*1.5*	0.29	0.83
3:00 PM	Surface	v wind (m/s)	-5.2	*3.3*	-4.5	*4.6*	-3.6	*4.3*	-3.9	*4.3*	0.97	0.41
3:00 PM	Surface	MSLP (hPa)	1010	*6*	1009	*5*	1009	*5*	1011	*4*	2.46	0.06
3:00 PM	Surface	total cloud cover (oktas)	3.3	*2.5*	3.0	*2.1*	2.9	*2.3*	2.7	*2.1*	0.51	0.68
3:00 PM	Surface	**Inland - Coastal temperature (°C)**	**3.8**	***2.8***	**4.0**	***3.4***	**3.9**	***2.6***	**5.9**	***2.6***	**4.69**	**0.00**
3:00 PM	Upper Air	Mixing height (m)	399	*337*	324	*308*	295	*314*	303	*168*	0.84	0.47
3:00 PM	Upper Air	**850 hPa temperature (°C)**	**18.2**	***2.1***	**19.2**	***2.3***	**19.8**	***2.2***	**21.1**	***2.0***	**12.81**	**0.00**
3:00 PM	Upper Air	**850 hPa dew point temperature (°C)**	**6.0**	***4.7***	**6.8**	***4.1***	**6.6**	***4.3***	**3.9**	***5.6***	**4.24**	**0.01**
3:00 PM	Upper Air	**850 hPa u wind (m/s)**	**6.8**	***4.4***	**5.6**	***3.8***	**5.5**	***3.7***	**2.8**	***3.3***	**8.96**	**0.00**
3:00 PM	Upper Air	**850 hPa v wind (m/s)**	**-2.4**	***4.1***	**-1.9**	***4.8***	**-0.3**	***4.1***	**0.0**	***3.6***	**3.42**	**0.02**
3:00 PM	Upper Air	**975 hPa temperature (°C) (within sea breeze)**	**24.1**	***2.3***	**25.5**	***2.8***	**26.5**	***3.2***	**25.9**	***3.4***	**3.66**	**0.01**
3:00 PM	Upper Air	**925 hPa temperature (°C) (above sea breeze)**	**22.3**	***2.2***	**24.2**	***2.8***	**25.2**	***2.6***	**25.5**	***2.9***	**9.29**	**0.00**

* Bold fonts highlight statistically significant F ratios at 0.05 level

Table 2 - Meteorological conditions associated with Low, Medium, High and Very High pollution days and results of a one-way ANOVA analysis investigating the difference between meteorological values for the pollution classes. Meteorological variables with F ratios that are significantly different at the 0.05 level across different ozone classes are shown in bold.

Final Model Regression Results					
Variable	**Parameter Estimate**	**Standard Error**	**t value**	**Pr > |t|**	**Tolerance**
Intercept	1.8828	1.61647	1.16	0.25	.
Inland - Coastal temperature	0.11646	0.05343	2.18	0.03	0.81
6am 850 hPa temperature	0.23746	0.08162	2.91	0.00	0.48
3 pm 850 hPa dew point temperature	-0.07333	0.03279	-2.24	0.03	0.91
3 pm 850 hPa *u* wind	-0.16594	0.03638	-4.56	<.0001	0.86
3 pm 850 hPa *v* wind	0.13143	0.03976	3.31	0.00	0.84
3pm 925 hPa temperature	0.14768	0.06907	2.14	0.03	0.53

All variables left in the model are significant at the 0.05 level.

Table 3 - Final stepwise model regression results

2.1.1Multiple Stepwise Regression

To quantify the relative importance of the meteorological variables identified by the Analysis of Variance as relevant to ozone episodes, and to produce a predictive model for ozone concentrations in Sydney, a multiple stepwise regression analysis was performed on daily maximum ozone concentrations using the significant meteorological variables in Table 2 as independent variables. Of the nine independent meteorological variables, the final model comprises six of these: 6am 850 hPa temperature, 3 pm 850 hPa u wind, 3 pm 850 hPa dew point temperature, 3 pm 850 hPa v wind, 3pm 925 hPa temperature and the inland - coastal temperature difference. The final regression model results are presented in Table 3.

3. DISCUSSION AND CONCLUSIONS

This paper has assessed the results of an objective synoptic climatology of ozone episodes in Sydney, particularly with respect to its ability to predict enhanced ozone days. The analysis investigated the differences between days with similar synoptic situations but different concentrations of ozone. The synoptic climatology technique accurately isolated enhanced ozone days, with over 90% of days exceeding the current air quality goals for Sydney falling within one synoptic category. However, used on its own as a forecast tool it would over-predict high ozone levels on about 50% of occasions, i.e. about one in every two days with the right synoptic conditions for enhanced ozone would actually experience Low or Medium ozone concentrations.

A two-pronged approach has been presented here for forecasting enhanced ozone days for a large city in a complex humid subtropical coastal setting. A synoptic climatological analysis of historical weather data in Sydney indicates that over 90% of all enhanced ozone days occur when an anticyclone in the Tasman Sea produces warm to hot west-north-westerly winds in Sydney. A subsequent step-wise regression analysis was able to isolate those days more likely to experience enhanced ozone concentrations.

Enhanced ozone days were associated with the following conditions: warm temperatures at the coast at both 6am and 12pm; low mixing heights at midday and within the sea breeze at 3pm; a large coastal-inland temperature difference; and warm dry light westerly winds at 850 hPa. On the other hand, days with Low to Medium concentrations of ozone had a significantly higher mixing height at 12pm; lower coastal inland temperature difference; cooler, moister air at 850 hPa with much stronger west-north-westerly winds. Therefore, because of increased vertical mixing and dispersion during the day these conditions are not favourable for the production of enhanced concentrations of ozone.

The current study highlights the sensitivity of ozone concentrations in Sydney to a range of meteorological conditions. It is anticipated that these results will assist the NSW air quality regulatory agencies to improve the accuracy of their forecasting of ozone episodes. The two-pronged approach described here can be easily tailored to individual regions and their particular synoptic situations, and can be applied to other urban contexts to more accurately forecast ozone and other pollutants of concern.

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