URBAN VENTILATION AND PHOTOCHEMICAL SMOG IN MELBOURNE FOR A FUTURE CLIMATE SCENARIO

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1. ABSTRACT

Climate change may alter patterns of air pollution in urban environments, through changes to wind speeds, temperatures and other climate parameters. This project reviewed the relevant literature, then made use of CSIRO climate forecasts dynamically downscaled (Mk3 → CCAM → TAPM) to a 5 km grid over Melbourne, Australia, with the aim of discerning possible climate-related trends in air quality. Summer photochemical smog is examined using a statistical method for predicting urban ozone, based on projected climate parameters and several years of ground-based ozone measurements. General air quality over the autumn-winter period is considered by calculating airshed ventilation rate and vertical stability, which provide an indication of air pollution potential. Analyses were conducted using only a single IPCC scenario (A2) to obtain preliminary estimates of likely trends. Results indicate that climate change may cause some worsening of air quality in Melbourne over the next 50 years.

2. INTRODUCTION

Changes to climate are likely to affect many aspects of environmental quality, including the quality of urban air. This project attempts preliminary predictions of the effect of climate change on Melbourne's air quality, by estimating trends in:

- Ozone,
- Ventilation rate (mixing height X wind speed), and
- Pasquill vertical stability class.

To quantify the effect of climate on photochemical smog, urban ozone measurements from 1996-2005 were matched against parameters from a climate model, dynamically down scaled to a 5 km grid over the region of interest. Regression models were developed from this data, and then used to predict ozone metrics for 2021-2030 and 2051-2060.

Subsequent to this analysis, the meteorological results were further examined to look for trends in urban ventilation and Pasquill stability class in an attempt to assess the impact of climate change on the general potential for air pollution accumulation. Urban air pollution episodes in autumn and winter typically involve a low ventilation rate and stable conditions.

3. THEORY & LITERATURE

Climate change may affect air quality though a range of mechanisms. Jacob (2008) provides a recent review of the effects of climate change on air quality, finding that urban ozone is likely to worsen under a warmer climate, but particle concentrations may increase or decrease depending on locality.

The literature on climate change and air quality has been comprehensively reviewed, including a focus on implications for the Victorian region (Pearce, 2008; Walsh, 2008). Published studies indicate that climate change may affect background concentrations, emissions, photochemistry, dispersion and deposition, thus potentially having important effects on future air quality. A brief summary of the state of knowledge is provided below.

3.1 Tropospheric background concentrations

Although higher temperatures are expected to increase urban ozone, global-averaged ozone is expected to decrease. This is due to an increase in specific humidity, causing a greater production of OH and HO_2 radicals, which in clean background air (low NO_X) act to destroy ozone (Collins, 2003). This decrease in ozone is partly offset by a projected increase the stratosphere-troposphere exchange rate (Zeng & Pyle, 2003).

The actual background experienced regionally may be significantly different from the global average. Measured trends in background pollutants show regional variations; for example southern hemisphere background ozone has shown a clear upward trend between 1982 and 2003 (Galbally et al,, 2005), but northern hemisphere data do not consistently show a trend (Oltmans et al., 2006).

Climate change may also alter global average fine particle concentrations, but as yet there is no clear consensus on the sign of the change (Jacob, 2008). Likely influences include changes to wet deposition (which increases with rainfall), secondary particles (sulfate formation increases with temperature, whilst nitrate and organics shift towards the vapour phase in higher temperatures), and changes to dust and fire emissions.

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3.2 Emissions

The likely effects of climate change on pollutant emissions include:

- Increases in temperature-dependent biogenic emissions of ozone precursors from soil and vegetation (DEFRA, 2007);
- Increases in motor vehicle evaporative emissions, and various changes to tailpipe emissions (Cope et al., 2008);
- Changes to windblown dust, wildfire and planned burn emissions (Pearce, 2008), likely to increase across parts of Victoria;
- Increases in temperature-dependent fugitive emissions from industry, such as odours and volatile organics.

Additional effects may involve human responses:

- Increases in hot-weather related emissions (mode shift towards private transport and increased use of electric air conditioning);
- Decreases in cold-weather related emissions (direct emissions from wood and gas heating, and indirect emissions from electric heating).

Some of these effects can be quantified through established functions of temperature. Dust and fire emissions are much more complex to predict.

Further emission changes may also arise from climate change mitigation efforts, for example increases in the use of alternative fuels and industrial co-generation.

3.3 Photochemistry

Sunlight, in particular UV radiation, is the key driver of photochemical reactions in urban air, resulting in the formation of ozone and secondary particles (organic and inorganic). Projections by CSIRO (2007) indicate a possible increase in solar radiation across Southern Victoria by 2050.

Temperature is also a key driver of air pollution chemistry. For example, in urban air NO_2 exists in dynamic equilibrium with PAN (peroxyacetyl nitrate), with the balance shifting towards more NO_2 in higher temperatures. This in turn leads to more ozone formation (Finlayson-Pitts & Pitts, 1986):

$$NO_2 + h\nu \text{ (wavelength} \leq 430\text{ nm)} \rightarrow NO + O$$

$$O + O_2 + M \rightarrow O_3 + M \qquad \ldots(1)$$

Where M is an inert molecule such as N_2. This is the key mechanism by which a warmer climate is expected to increase urban ozone.

3.4 Dispersion

Three aspects of dispersion may be important to consider under a changed climate.

Firstly, horizontal dispersion needs to be examined, as typical pollution event days are associated with light recirculating winds.

Secondly, vertical dispersion needs to be characterized, including influences such as cloud cover (affecting radiation reaching the ground).

Thirdly, the persistence of blocked anticyclones (or alternatively, the frequency of cyclones) should be considered, as this affects the likelihood of multi-day stagnation events (Mickley et al. 2004).

As air pollutant events are often critically dependent on meso-scale winds (such as sea-breezes and katabatic flows) and the local mixing layer, simulations of local meteorology in the region of interest are essential.

3.5 Deposition

A key removal process for ozone is contact with vegetation, thus where vegetation cover and/or species mix change in response to an altered climate, so may the ozone sink (DEFRA, 2007). It has also been found that plant stomata close in response to increasing CO_2, reducing ozone deposition (Sitch et al, 2007).

Globally, increased moisture and rainfall is predicted to reduce fine particle concentrations through wet deposition (Jacob, 2008). However, reduced rainfall is expected in future decades across much of Victoria (CSIRO, 2007), leading potentially to increased urban fine particle concentrations.

4. CLIMATE MODELS

This project involved the use of three meteorological models. The CSIRO Mk III model provided global projections at 200km grid spacing, from 1950 to 2100 (CSIRO, 2002). The Cubic Conformal Atmospheric Model (McGregor & Dix, 2005) provided regional projections at 55 km grid spacing (centered on Australia), over the same time period. Finally, the CSIRO model TAPM v3.0.7 (Hurley, 2005), configured with 3 nested grids (45 km, 15 km and 5 km) was used to downscale results for Melbourne, for three decades (1996-2005, 2021-2030 and 2051-2060)[1].

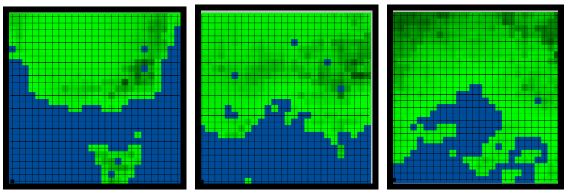

Figure 1: Nested TAPM grids (45, 15 and 5 km)

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[1] Due to technical difficulties with the interfacing of models, leap years were excluded from this study, reducing the available data to 7,8 and 7 years in the first, second and third decades respectively.

5. STATISTICAL OZONE MODEL

5.1 Method

Global climate projections are not constrained by daily weather observations. Therefore one cannot expect a useful regression between hourly or daily climate model outputs and hourly or daily pollutant measurements. However, seasonal and inter-annual effects should be effectively represented in the climate model[2]. A monthly scale was therefore chosen to represent both model output and ozone measurements.

Regression models were developed for ozone measurements from 1996-2005 at two coastal suburban locations (Pt. Cook and Brighton). Measurements were first converted into the following monthly metrics:

- Monthly maximum 1-hour average ozone
- Monthly maximum 4-hour average ozone
- Monthly average ozone
- Monthly # of hours > 30 ppb
- Monthly # of hours > 50 ppb

Input variables were derived from two grid points of the inner (5 km) TAPM grid, one over Port Phillip Bay ("BAY") and one over the inner eastern suburbs ("LAND"). Climate Variables (CV) used as input included monthly averages, minima and maxima of:

- T=Temperature at 1.5m height (deg C)
- RH=Relative Humidity at 1.5m height (%)
- ZMIX=Depth of Mixing Layer (m)
- Q =Total Solar Radiation (W/m^2)
- L* = Monin Obukhov Length Scale (m)
- w* = Deardorff Velocity Scale[3] (m/s)
- u* = Friction Velocity Scale (m/s)
- u_{8am} , v_{8am} = morning 10m wind vector (m/s)
- u_{5pm} , v_{5pm}= afternoon 10m wind vector (m/s)

Regression analyses were performed in Minitab v14, and included checks for

- interactions between variables;
- normality of residuals;
- serial correlation; and
- curvature of relationship.

Resulting models were of the form:

$$f(ozone\_metric) = \sum_i a_i CV_i + \varepsilon \qquad \text{... (2)}$$

Where f() is a transformation function chosen to best represent any nonlinearity in the data; and ε is a normal random error.

5.2 Results

Useful and meaningful correlations were obtained for a subset of the ozone metrics; in particular, the monthly maximum ozone values at Pt. Cook:

$$\mathrm{Log}_{10}(\mathrm{Max\_PtCook\_1hrO_3}) = 0.862 + 0.0457\mathrm{Min}(T_{BAY}) + 4.03\ \mathrm{Max}(Q_{LAND})/10^4 \qquad (r^2 = 0.782)$$

$$\mathrm{Log}_{10}(\mathrm{Max\_PtCook\_4hrO_3}) = 0.897 + 0.0445\mathrm{Min}(T_{BAY}) + 3.35\ \mathrm{Max}(Q_{LAND})/10^4 \qquad (r^2 = 0.748)$$

... (3)

The predictor variables in this case are monthly peak Total Solar Radiation (Land), and monthly minimum Temperature (Bay). These are both plausible factors leading to high ozone, as radiation is required for photochemical reactions, and minimum temperature is correlated with maximum temperature (in this case, the statistical analysis found minimum temperature to be a slightly better predictor variable).

Good correlations were also obtained for monthly maximum 1-hour and 4-hour ozone at Brighton (r^2 values of 0.791 and 0.777 respectively). The other metrics (monthly average ozone and counts of ozone hours > 30 ppb and > 50 ppb) were not consistently well correlated with climate variables.

Making use of the regressions obtained for monthly maximum ozone, and TAPM predictions for the decades 2021-2030 and 2051-2060, preliminary predictions of future monthly maximum ozone concentrations were obtained. This of course assumes that the established relationship continues to hold in future climates. These results were summarized into annual average values and warm-season average values (see Appendix). The results clearly indicate a likely upward trend in peak ozone concentrations at Pt. Cook, resulting from climate change. A similar upward trend was found when predictions were made at Brighton. (Note that these predictions involve the effect of climate change only, and do not consider any trends in emissions.)

5.3 Discussion

The above results are considered preliminary, as they have been obtained using only a single suite of nested models and a single IPCC scenario. Furthermore, to simplify the statistical modelling effort, only two grid points from the TAPM output were used for input.

During the time period over which the regression was undertaken (1996-2005), there may have been improvements in emissions; it is assumed that these trends are not correlated with any trends in climate variables. Finally the use of a monthly temporal scale makes it difficult to relate these results to more traditional studies of ozone and weather variables, which typically focus on individual days, involving such factors as light recirculating winds and temperature. A more advanced approach, that could potentially provide daily ozone predictions, would be to employ "analogue" statistical downscaling methods (e.g. Zorita & Von Storch, 1999).

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[2] In this study, measured pollutant concentrations were modelled using *predicted* meteorological variables; an alternative would be to use *measured* meteorological data. The former approach was preferred to ensure consistency in the input data for future predictions.

[3] Also known as the Convective Velocity Scale.

6. POLLUTANT DISPERSION METRICS

6.1 Method

Ozone and fine particles are the two major pollutants of concern in Melbourne. Modelling fine particle concentrations by regression is more difficult than for ozone (Wise & Comrie, 2005) because of the many and varied sources of particles, and because some sources are strongly episodic and not easily related to meteorology (e.g. bushfires and prescribed burns).

To assess the likely impact of climate change on fine particle (and other pollutant) accumulation in Melbourne, two surrogate meteorological metrics were examined:

- Ventilation Rate
- Pasquill stability classes (A-F).

Ventilation Rate was computed using the method of Cope et al. (2008), as a simple scalar product of wind speed (10m height) and mixing layer depth.

Pasquill stability classes were taken directly from the TAPM model, which uses a calculation based on Pasquill (1974), using wind speeds, sensible heat flux and solar radiation as input data. These classes broadly describe the stability of the atmosphere:

Stability Class	**Description**
A	Highly unstable
B	Unstable
C	Slightly unstable
D	Neutral
E	Stable
F	Very stable

Table 1: Pasquill Stability Classes

A subset of the inner grid points were selected for post processing, focusing mainly on the inner and more populated areas, but also including two points in Port Phillip Bay (Figure 2).

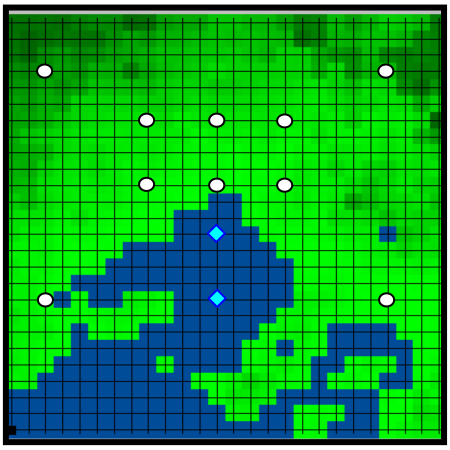

Figure 2: Selected grid points for calculation of dispersion metrics

6.2 Results

Calculations were undertaken for each hour of the simulation, but are summarized here only for the autumn and winter months (March-August inclusive), since this period is of most interest in terms of fine particle pollution in Melbourne.

Table 2 shows the decade-averaged ventilation rates predicted by TAPM. Statistical analysis of daily average ventilation rate found a small but significant downward trend was present at all of the grid points examined, with most of the reduction occurring after 2030. A stronger trend is apparent over the land surface.

	Average Ventilation Rate, autumn and winter months **(m^2/s)**		
Decade	**1996-2005**	**2021-2030**	**2051-2060**
Avg. of 10 Land Points	1544	1583	1315
Avg. of 2 Bay Points	1500	1511	1400

Table 2: Predicted Ventilation Rates

Table 3 shows the results of assigning each hour of the simulation period to a stability class, and determining the fraction of hours falling into each of the six Pasquill classes. Results are presented as an average over the 10 land points shown in Figure 2. (Results for the bay points are not presented as all TAPM results were class D for these points.)

	Stability Class Frequencies – average of 10 land points, autumn and winter months		
Decade	**1996-2005**	**2021-2030**	**2051-2060**
A	1.2%	1.1%	1.3%
B	5.5%	5.2%	6.0%
C	12.3%	12.0%	12.9%
D	53.6%	55.3%	51.9%
E	19.1%	18.6%	18.8%
F	8.2%	7.9%	9.1%

Table 3: Stability Class Projections

The data show essentially no trends.

6.3 Discussion

In terms of ventilation of the airshed during autumn and winter, the results in Table 2 indicate a potential worsening through lower ventilation rates after 2030. Further analysis indicates that both mixing height and wind speeds contribute to the projected trend.

For *particle* pollution, the situation is more complex than this, with particle concentrations being nonlinearly dependent on wind speed (at higher wind speeds, wind blown dust becomes important; at lower wind speeds, pollutants accumulate). This effect is also dependent on particle *size*; it is possible that reduced urban ventilation in future may result in lower *coarse* particle concentrations but more frequent *fine* particle episodes.

Ventilation rate is one of many factors that may influence future particle concentrations. Higher overnight minimum temperatures may act to reduce winter particle levels, through reductions in the use of wood combustion for home heating. Other factors may act to increase particle concentrations. Reduced rainfall is expected in the Melbourne region, leading to less wet deposition and therefore longer atmospheric residence times for particles.

Furthermore, drying of soil and reduced vegetation cover from reduced rainfall is likely to cause higher windblown dust emissions, and drying of vegetation is expected to increase the risk of bushfires and consequently the prescribed burning effort. During times of drought, dust and fire emissions can be the dominant sources of air pollution experienced in Melbourne (Walsh & Monahan, 2003).

Changes in patterns of urban air recirculation have not been addressed here, as the ventilation metric was based on a simple scalar average. To assess possible changes in this effect, meso-scale simulations of pollutant transport will be required.

No attempt was made to examine trends in multi-day stagnation events (typically involving blocked anticyclones). A study of synoptic scale changes is beyond the scope of the present work; for a review see Pearce (2008). Significant shifts are occurring in the southern hemisphere circulation (Cai and Cowan, 2007), these will need to be carefully considered in future studies.

At present there is insufficient data to quantify all of these effects; thus the prediction of how climate change will affect particle concentrations remains a significant research task.

7. CONCLUSIONS

This preliminary study has found a possible worsening of peak ozone concentrations during photochemical smog events in Melbourne, as a result of predicted climate change. The numerical predictions in this study carry substantial uncertainty, resulting from the use of only a single model suite and global warming scenario.

An attempt to examine trends in meteorological surrogates for general air quality found a shift towards lower ventilation rates for Melbourne, with most of the change occurring after 2030. No significant changes were found in vertical stability.

Correlating measured ozone with climate variables has proven useful, as ozone is produced from well-understood pre-cursor compounds (NOx and Volatile Organics, mainly from motor vehicles) which show only gradual changes with time.

Applying this method to the prediction of particle concentrations is more complex, as there are many more pollutant sources involved, and historical measured data may be strongly influenced by bushfires, prescribed burns and dust storms, which cannot be linked to climate variables in a simple way.
The pollutant dispersion metrics computed in this study have provided only limited insight into future particle concentrations. A critical determining factor is future rainfall and consequent changes to vegetation coverage, dust emissions and fire frequency. Predicting these parameters for future decades remains a substantial challenge.

Future research effort will be directed towards the use of synoptic scale studies, statistical downscaling techniques and grid-based airshed models of dispersion and photochemistry. Nested grid airshed models, such as those used by Cope et al. (2008), will be deployed with ensembles spanning multiple models and scenarios. This will allow a far more detailed examination of the likely effects of climate change on air quality, and should provide greater insight into the uncertainties involved.

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9. APPENDIX

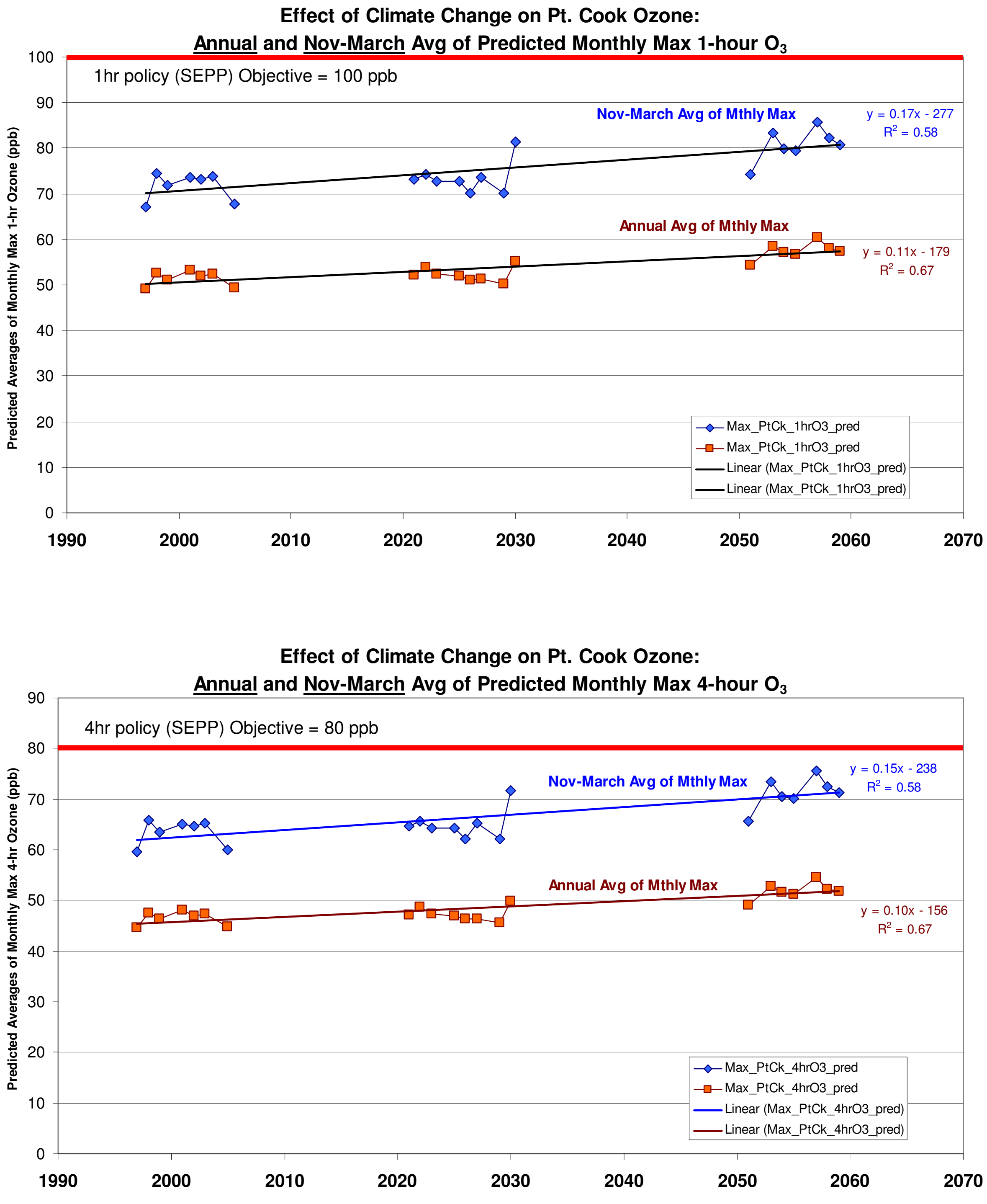

Figure 3: Effect of climate change on Melbourne ozone