J5.6 POSSIBLE CLIMATE CHANGE IMPACTS ON OZONE IN THE GREAT LAKES REGION: SOME IMPLICATIONS FOR RESPIRATORY ILLNESS

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1. INTRODUCTION

A variety of weather phenomena in the Great Lakes region can affect human health. Additionally, health effects partly depend on previous exposure, physiological adaptation, genetic predisposition, age, and other health conditions. People who lack protection to extremely hot or cold weather may eventually suffer heat stress, dehydration, respiratory distress, heat stroke or cardiac malfunction. The impact of temperature extremes depends on various historical and socioeconomic factors (Martens 1998). Some heat waves may last for a few days or for weeks, but the difference can influence how people with previous exposure or social or physical conditions respond.

Additional weather-related health effects involve the air that we breathe. Recent epidemiologic studies have shown associations between certain atmospheric components at ground level and increased diagnoses of asthma, respiratory distress, and even cardiopulmonary function (Schwartz 1994; Moolgavkar et al. 1997; Sheppard et al. 1999). Because links to respiratory diseases often involve additional factors, the mechanisms for increased risk associated with atmospheric pollutants are still unclear. In the Great Lakes region, air pollution associated respiratory disease has not been well studied.

In addition to climatic and atmospheric variations, concern over possible health impacts of long-term climate change has recently received attention (McMichaels et al. 1996, Patz and Lindsay 1999). For example, several reports have considered how climate change not only may affect heat related deaths (Kalkstein 1993), but infectious diseases that may be transmitted by aerosol (Macfarlane 1977), by water (e.g. Pasqual et al. 2000), or by arthropod vectors (e.g. Epstein et al. 1998). Yet other studies have focused on how extreme events such as floods and blizzards, which have obvious affects on well-being, may occur with increasing frequency under some climate change scenarios (Zwiers and Kharin 1998). To date there have been no studies that have considered how forecasted climate change scenarios may impact air quality, and hence health.

The relationships between various atmospheric pollutants (e.g. ozone) and synoptic patterns have been explored using available climatological information (e.g. Comrie and Yarnal 1992), but this information has not been applied to existing output from General Circulation Models (GCMs). The use of such output for considering changes in air quality that may occur because of changes in synoptic patterns is feasible because GCMs now have sufficient horizontal resolution to capture synoptic patterns. While vertical resolution may still be unable to capture inversion layer/level development and diurnal cycles, studies have shown strong correlations, for example, between ozone levels and general air mass patterns. Thus, because nothing like this has been done before, it is useful to perform even the most rudimentary study to evaluate output from GCMs to determine potential changes in synoptic patterns that are conducive for high levels of ozone to develop, under the assumption that emission characteristics will not change appreciably, of which no account can be taken at the present time. The main objective of this study is to determine some basic relationships between ozone in southeastern lower Michigan and current synoptic patterns, and then to apply these relationships to existing GCM output.

2. CLIMATOLOGY OF OZONE IN MICHIGAN

Previous studies have investigated the dependence of tropospheric ozone concentrations on the synoptic-scale atmospheric circulation (e.g., Comrie and Yarnal 1992). A similar (synoptic climatology) approach for historical conditions was used here to examine ozone concentrations in southeastern lower Michigan for the current climate and to set the stage for examining potential future climate scenarios.

2.1 Ozone Data

Hourly ozone data were collected from ten air quality monitoring sites across southeastern lower Michigan (Fig. 1) for the months May through September, for the years 1986-95. The ten sites represent a cross-section of the urban, suburban, and rural characteristics of the region. The daily maximum 8-h average ozone concentration was calculated for each station. This method was chosen to reflect the U.S. Environmental Protection Agency's 80 parts per billion (ppb), 8-h standard for ozone (MDEQ, 1998). In order to determine a representative daily maximum 8-h average ozone concentration $[O_3]_{max}^{8av}$ for southeastern lower Michigan, the maximum 8-h averages from the ten sites were averaged. This averaging ensured that the ozone data used were not biased by using only a hydrocarbon-limited urban site or a NO_x-limited rural site. Correlation coefficients for the ozone concentrations measured at the ten stations compared to the mean were high, ranging from r = 0.85 to 0.92.

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2.2 Meteorological Data

Archived meteorological data for the May - September 1986-95 period were obtained from the NCEP/NCAR Reanalysis Project (Kalnay et al. 1996). These data have a resolution of 2.5° latitude x 2.5° longitude and were used to evaluate the daily synoptic-scale atmospheric conditions over southeastern lower Michigan. An objective method was used to categorize each day as one of nine synoptic circulation types (Table 1). The Reanalysis gridpoint located at 42.25N, 82.75W was used because it was closest to Detroit, Michigan. The sign of the 1000 hPa geostrophic relative vorticity and the surface geostrophic wind direction (NE, SE, SW, or NW) were used to classify each day as one of eight distinct synoptic regimes. An additional synoptic type (STH) was included for anticyclonic conditions exhibiting surface geostrophic wind speeds less than 2.5 m s^{-1}.

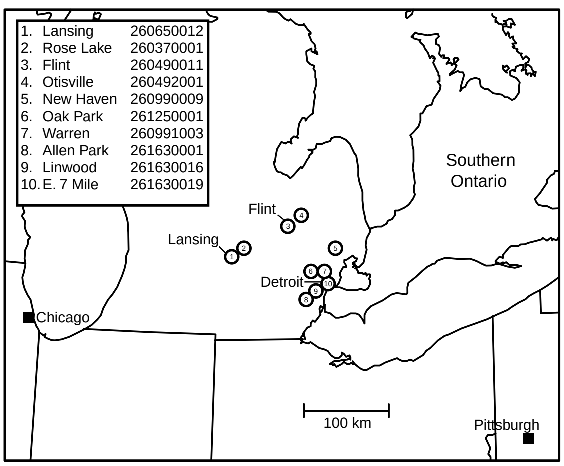

Fig. 1. Locations of ozone stations in southeastern Lower Michigan used in the study.

2.3 Synoptic Climatology of Ozone in Southeastern Lower Michigan

Figure 2 shows the summary of the May-September ozone climatology for southeastern lower Michigan for the period 1986-1995. For each of the nine synoptic types, the 1000 hPa geostrophic winds and geostrophic relative vorticity objectively describe the synoptic weather pattern. The use of geostrophic rather than actual wind speed and direction may lead to a slightly different categorization distribution, different frequencies of occurrence, and hence some discrepancies between our results and those from other similar studies. However, the use of geostrophic wind here allowed for fair (inter-model) comparison. The 1000-850 hPa thickness field is included in Fig. 2 to illustrate boundary layer temperature characteristics of the different synoptic patterns. The boundary layer temperature has been shown in many studies to be an important factor for ozone production. The correlation between 1000-850 hPa thickness and mean daily surface temperature in this study was r = 0.97.

SYNOPTIC TYPE	SFC FLOW	VORT
STH – Stagnant High	< 2.5 ms^{-1}	+
DHS – Departing High South	SW	+
ALN – Approaching Low North	SW	-
AHS – Approaching High South	NW	+
DLN – Departing Low North	NW	-
DHN – Departing High North	SE	+
ALS – Approaching Low South	SE	-
AHN – Approaching High North	NE	+
DLS – Departing Low South	NE	-

Table 1. Synoptic types classified by surface flow and relative vorticity.

Two synoptic patterns were associated with mean ozone concentrations in excess of 50 ppb. The STH synoptic type has a mean $[O_3]^{8av}_{max}$ value of 51.2 ppb and the DHS synoptic type has the highest mean $[O_3]^{8av}_{max}$ value of 55.3 ppb. Of the 42 exceedences in southeast Michigan from 1986-95, defined as those days with a $[O_3]^{8av}_{max}$ value of 80 ppb or greater, 43% occurred under the DHS synoptic type, while the STH synoptic type accounted for 17%. In contrast, Comrie and Yarnal (1992) found that excessively high ozone events were more likely under an STH type than a DHS type regime. Differences in the classification schemes may account for this discrepancy. Nevertheless, the propensity for a greater number of exceedences in southeastern lower Michigan under a DHS flow seems reasonable given a slow-moving synoptic pattern, where a persistent southwesterly flow under anticyclonic conditions would allow for significant ozone transport from the Chicago-Gary industrial area located 300 km to the southwest (Sillman et al. 1993). While the ALN synoptic type is associated with a much lower mean $[O_3]^{8av}_{max}$ value of 43.5 ppb, it accounts for 21% of all exceedences. Significant cloud cover and precipitation under strong cyclonic flow is likely responsible for the lower mean. However, considering the favorable southwesterly flow for warm advection and in-situ ozone production as well as ozone transport from Chicago, exceedences are likely to occur under the ALN pattern when less cloud cover permits greater solar insolation and further photochemical ozone production.

Together, the STH, DHS, and ALN synoptic types account for 81% of the exceedences over southeastern lower Michigan. These patterns support the high solar insolation to drive the photochemical reactions responsible for local ozone production; the high temperatures to accelerate chemical reactions; the high absolute humidity values for hydroxyl radical production that helps to initiate ozone formation; and the light-to-moderate surface winds that allow pollutants to accumulate in the boundary layer. In general, southwesterly anticyclonic flow (DHS type) is most conducive to these atmospheric conditions, and is

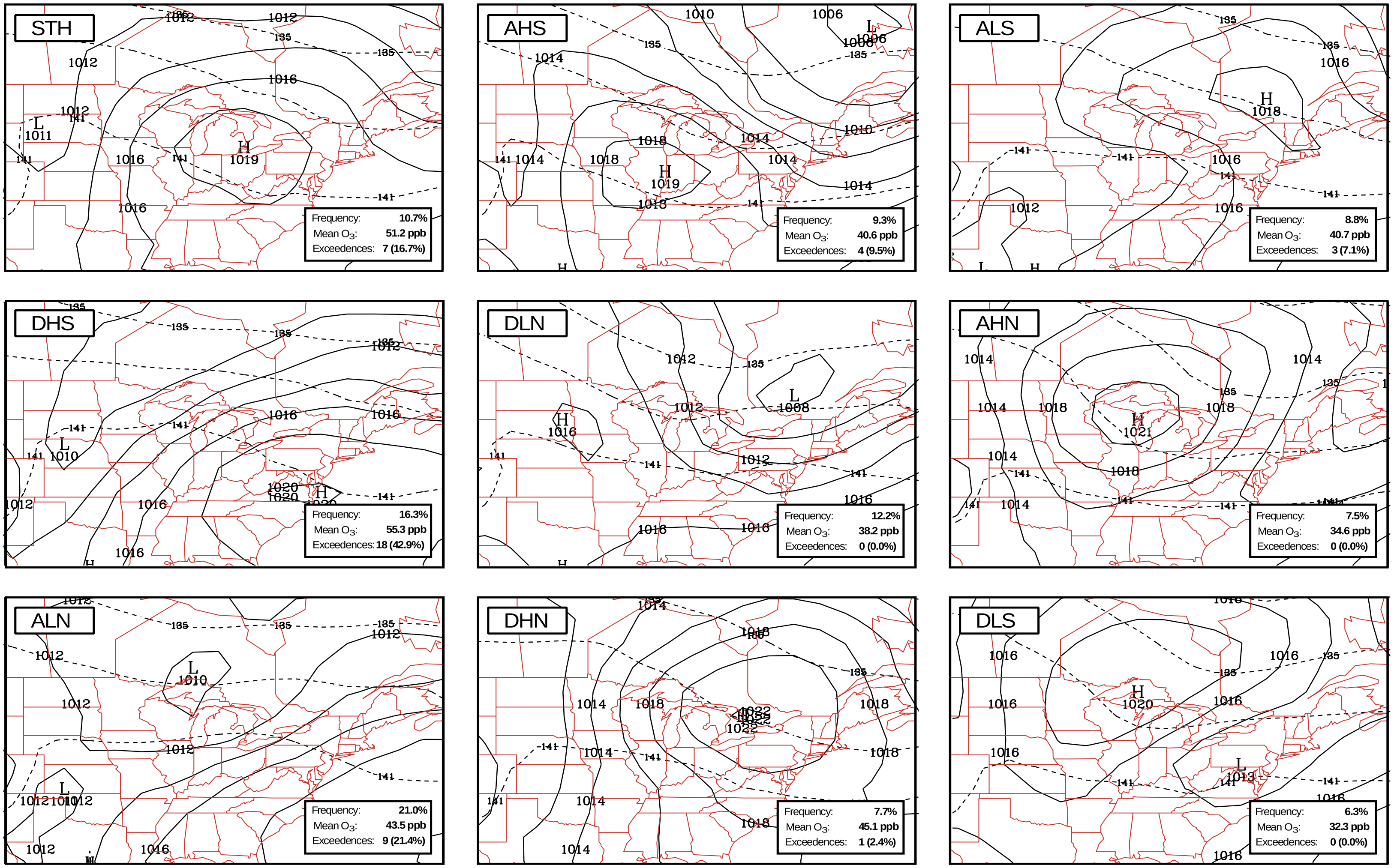

Fig. 2. Mean sea-level pressure (solid, contour interval 2 hPa) and 1000-850 hPa thickness (dashed, contour interval 3 dam) from NCEP/NCAR Reanalyses associated with each synoptic type. Frequency of synoptic type, mean 8 hr average maximum ozone, and number of exceedences (e.g., > 80 ppb) per type are indicated.

associated with the highest $[O_3]^{8av}_{max}$ values and number of exceedences. Flow from the north provides a supply of clean cool and dry continental air that is associated with low mean ozone. Only one northerly flow types (AHS), was responsible for any exceedences. The northwest anticyclonic flow associated with this type can transport relatively polluted air from the Milwaukee-Green Bay area, which led to 4 exceedences between 1986 and 1995. Generally, however, ozone exceedences in southeast Michigan are associated with southerly flow, with the DHS, ALN, and STH types being the most conducive.

2.4 Linear Regression Model

A statistical linear regression model for ozone was developed using meteorological variables available from the NCEP/NCAR Reanalysis Data. The motivation for developing such a model lies in its utility as a tool for predicting ozone concentrations under future climate scenarios. Davis and Speckman (1999) used linear regression as the foundation for successful short term (1 day) ozone prediction models for Louisville, Kentucky and Houston, Texas respectively. The present model uses a standard linear regression on 13 atmospheric variables with data from the May-September 1986-95 time period to develop an expression for predicting $[O_3]^{8av}_{max}$ values for a given day. The atmospheric variables were chosen subjectively - based on demonstrated significance from an ozone production standpoint in previous studies and based on availability of corresponding variables from daily GCM output for future climate scenarios. It is noted that relative humidity and cloud cover, which have been shown to be important from an ozone production standpoint, are not explicitly included in this model, although other variables that do correlate strongly with them, are. For example, a persistent (anticyclonic) southerly wind with high boundary layer temperatures in summer is almost always accompanied by high humidities and partial cloud cover.

The correlation between observed and hindcasted $[O_3]^{8av}_{max}$ values using the linear regression model with observed previous day ozone is r = 0.76. Considering the non-linear complexities of ozone chemistry, this result is acceptable and is comparable to that in Davis and Speckman 1999. The correlation is particularly impressive considering the simplicity of the model - only 13 independent variables are used. A slope correction was applied to the regression model in order to match approximately the number of predicted to actual exceedences.

This regression model was applied to simulate ozone concentrations using GCM output, where previous day ozone concentrations also have to be generated using the regression model. This constraint adds some additional uncertainty to the use of this model. The correlation between observed and hindcasted $[O_3]^{8av}_{max}$ values using the linear regression model with computed previous day ozone is r = 0.72. A plot of these model predicted ozone values versus observations (Fig. 3) still shows excellent agreement.

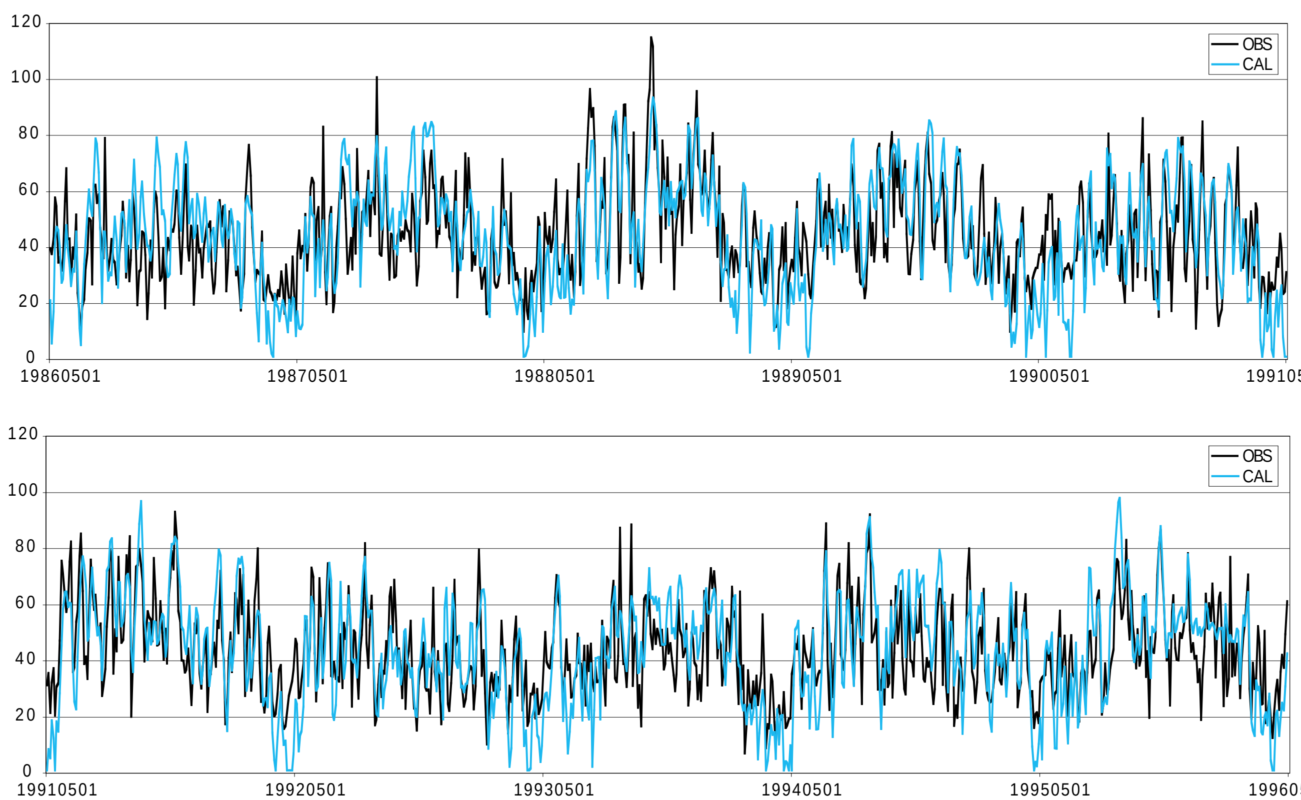

Fig. 3. Observed and calculated mean maximum 8 hr average ozone values over southeastern lower Michigan for the study period 19860501-19960501. Calculated values are generated using linear regression formula with simulated previous day ozone.

3. MODEL PROJECTIONS OF SYNOPTIC TYPES AND OZONE CONCENTRATIONS

Daily output from the Canadian Climate Model (CGCM1) and the Hadley Climate Model (HadCM2) were evaluated to determine how ozone concentrations may change by the end of this century. These two models were used for the Great Lakes Regional Climate Change Impacts Assessment (Sousounis et al. 2000). The CGCM1 output has a resolution of 3.75° latitude x 3.75° longitude. The HadCM2 output has a resolution of 2.50° latitude x 3.75° longitude. Before evaluating the impacts of climate change on ozone concentrations in southeastern lower Michigan using future climate GCM output, it is necessary to evaluate first the current climate model output in order to determine model biases and other model characteristics. The exercise allows a more informed analysis of future climate output and hence a better understanding of how and why predicted ozone conditions may differ from those at present.

3.1 Current GCM Scenarios and Ozone Concentrations

Output from CGCM1 was evaluated for the period May-September 1975-1994 and from HadCM2 for the period May-September 1960-1979. Figure 4a shows that two of the three most frequently observed synoptic types, DHS and ALN, are reproduced well by both models for the current climate. In general, CGCM1 correlates better with observations in terms of frequency of occurrence than does HadCM2 (r = 0.76 for CGCM1 vs. 0.57 for HadCM2) for all synoptic types combined. But, HadCM2 correlates better with observations than does CGCM1 in terms of frequency of the five most frequently observed categories: STH, DHS, ALN, AHS, and DLN (r = 0.81 for HadCM2 vs 0.51 for CGCM1). Both models exhibit too few STH days. CGCM1 exhibits too many DHS days and HadCM2 exhibits too many AHN days. Neither model simulates well the patterns with an easterly wind component. Stronger-than-observed southwesterlies in CGCM1 and stronger-than-observed northeasterlies in HadCM2 are the primary reasons for the reduced number of STH days and the different synoptic type distributions.

Figures 4b and c show the mean $[O_3]^{8av}_{max}$ values that were computed for each synoptic type in both models. The correlation between observed and model-calculated $[O_3]^{8av}_{max}$ values for the synoptic types is not as good in CGCM1 as it is in HadCM2 (r = 0.71 for CGCM1 vs 0.96 for HadCM2). The DHS synoptic type is the most ozone-significant type in both models. The very high number of exceedences for this synoptic type in CGCM1 stems from higher $[O_3]^{8av}_{max}$ values, greater synoptic variability, and higher frequency of occurrence. This type occurs nearly 70% more frequently than observed. All else equal, this feature alone accounts for ~60 of the 149 exceedences. The DHS type in HadCM2 compares very closely to the observed one in terms of frequency of occurrence and mean $[O_3]^{8av}_{max}$ value. Higher 1000-850 hPa thickness, lower stability, and more low-level anticyclonic vorticity than observed contribute to the slightly higher mean $[O_3]^{8av}_{max}$ value and the greater number of exceedences.

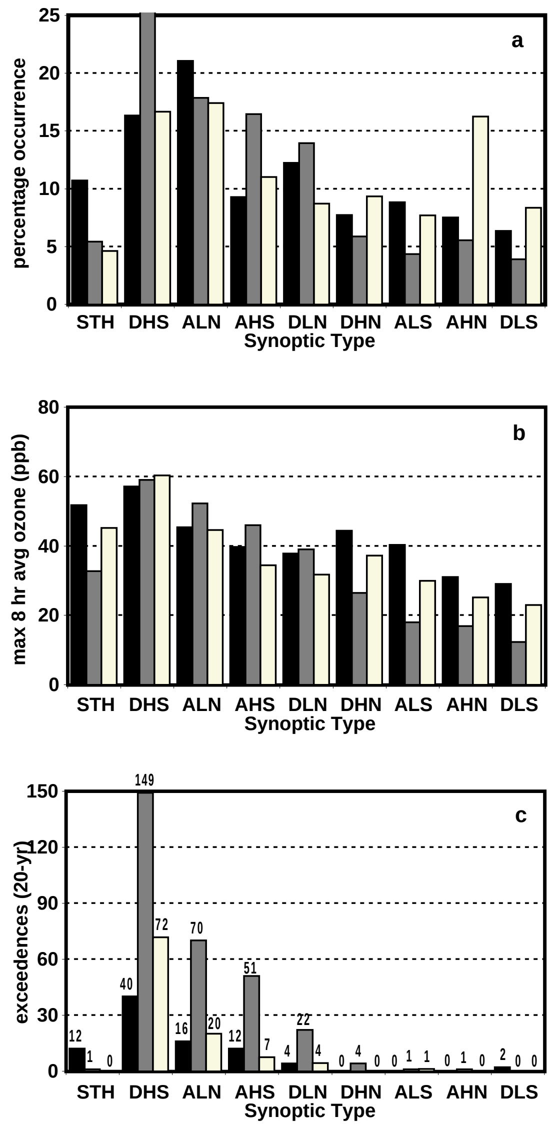

Fig. 4. Synoptic ozone results for current climate. a) Frequency of occurrence for the different synoptic types described in the text, b) Mean maximum 8 hr ozone concentrations (ppb), and c) number of exceedences based on a 20 yr period. NCEP/NCAR Reanalysis Data (black bars), Canadian Model (grey bars), and Hadley Model (white bars).

3.2 Future GCM Scenarios and Ozone Concentrations

Output from CGCM1 was evaluated for the period May-September 2080-2099 and from HadCM2 for the period May-September 2070-2089.

A comparison of future and present climate scenarios for CGCM1 shows few differences in the frequencies of occurrence of the synoptic types (Fig. 5a). However, changes in the characteristics of the types account for differences in ozone concentrations and exceedences within each synoptic category (Figs.

5b and c). Casual inspection reveals that mean $[O_3]^{8av}_{max}$ values decrease slightly for all of the westerly flow synoptic types except for the DHS type, while increasing for all of the easterly flow synoptic types and for the STH type. The mean $[O_3]^{8av}_{max}$ value for all types increases from 43.6 to 46.2 ppb. Despite this net increase the total number of exceedences decreases. Only the DHS synoptic type exhibits an insignificant increase of two exceedences.

The large decreases in the easterly flow categories appear to be a reflection of the increased east-west (synoptic) variability at 850 hPa associated with these categories (not shown). The increases in 1000-850 hPa thicknesses and decreases in 850 hPa westerly flow are primarily responsible for the increase in the mean $[O_3]^{8av}_{max}$ values in the STH and DHS types (Fig. 5). Despite an increase in the mean value, there is only an insignificant increase in the number of exceedences for the DHS type. A larger decrease in the number of exceedences in the ALN type is likely the result of a decrease in the mean $[O_3]^{8av}_{max}$ value in that type. The decrease occurs despite an increase in 1000-850 hPa thickness because of a very large increase in 850 hPa westerly flow.

The northwesterly flow synoptic types also exhibit significant decreases in $[O_3]^{8av}_{max}$ values and exceedences. These decreases are primarily the result of decreases in surface westerly flow and increases in 850 hPa westerly flow. The decreases occur despite considerable increases in 1000-850 hPa thicknesses. The easterly flow synoptic types all exhibit significant decreases in 850 hPa westerly flow and significant increases in 1000-850 thicknesses that both contribute to significant increases in $[O_3]^{8av}_{max}$ values, but still the number of exceedences drop to zero (the DLS synoptic type remains unchanged at 0 exceedences) for all of these synoptic types. These results suggest less variability in the flow. This is supported by the reduced strength of the meridional flow. It is likely that the exceedences that are generated in the CGCM1 current climate scenario occur during relatively strong southerly flow.

The differences in the HadCM2 synoptic types between the future and current climate scenarios are more significant (Fig. 6a). In general, an increase in the mean $[O_3]^{8av}_{max}$ value from 38.2 to 48.6 ppb is the result of increases in southerly flow and 1000-850 hPa thickness. Inspection of some of the changes in the frequencies of occurrence reveals that the HadCM2 future climate scenario consists of considerably more days with southerly (component) anticyclonic flow and considerably fewer days with northerly (component) anticyclonic flow. Also, the STH synoptic type exhibits an increase in the mean $[O_3]^{8av}_{max}$ value of less than 1 ppb but an increase of 2 exceedences (Figs. 6b and c). The small change in $[O_3]^{8av}_{max}$ occurs because changes in the different parameter values cancel their effects on ozone concentration. For example, increases to $[O_3]^{8av}_{max}$ from increases in 1000-850 hPa thickness are negated by those from increases in stability. Increases to $[O_3]^{8av}_{max}$ from increases in 850 hPa northerly flow are

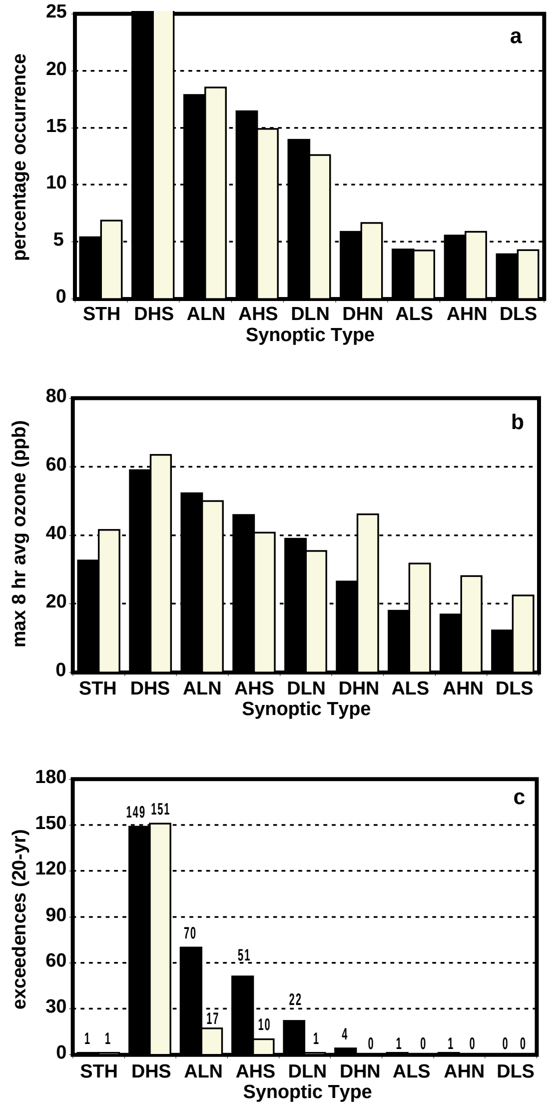

Fig. 5. Comparison of current (black bars) and future (white bars) climate results from CGCM1. a) Frequency of occurrence for the different synoptic types described in the text, b) Mean maximum 8 hr ozone concentrations (ppb), and c) number of exceedences based on a 20 yr period.

negated by those from increases in 850 hPa wind speed. The fact that the mean $[O_3]^{8av}_{max}$ value and the frequency of occurrence remain essentially unchanged and the number of exceedences increases implies that the future STH synoptic type is associated with slightly more synoptic variability.

Both southwesterly flow synoptic types exhibit large increases in mean $[O_3]^{8av}_{max}$ values and exceedences. The mean $[O_3]^{8av}_{max}$ value for the DHS synoptic type increases from 60.3 to 69.6 ppb and the exceedences increase from 72 to 193. The mean $[O_3]^{8av}_{max}$ value for the ALN synoptic type increases from 44.5 to 55.1 ppb and the exceedences increase from 20 to 57. The exceedences increase in both these synoptic types

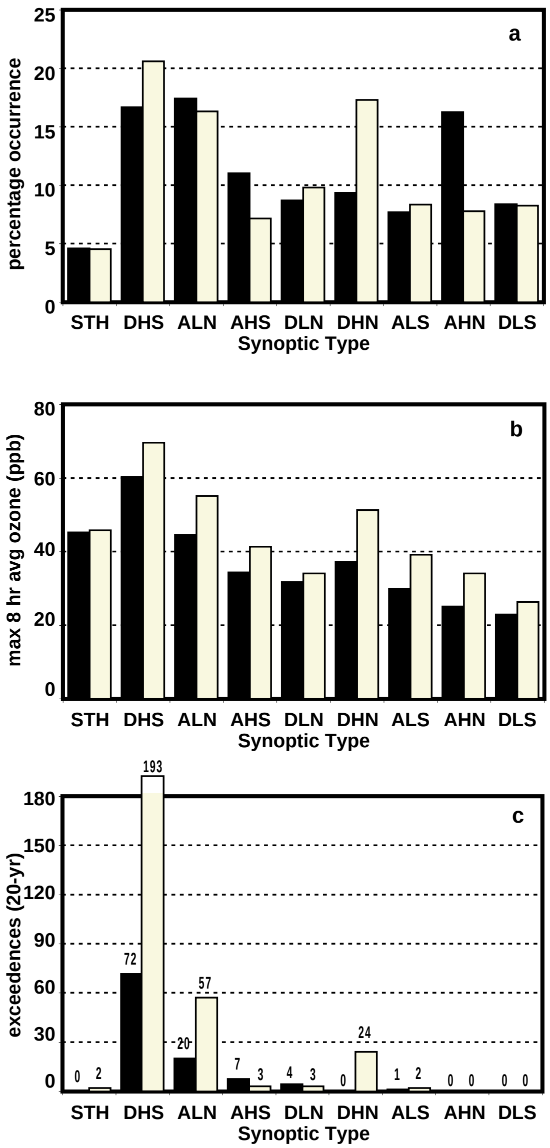

Fig. 6. Similar to Fig. 5 but for HadCM2.

because of increases in mean $[O_3]^{8av}_{max}$ values. Although 1000-850 hPa thicknesses increase, changes in the other parameter values occur to increase or decrease ozone concentrations as they do in the STH type, again implying increased variability for the future DHS and ALN synoptic types.

The northwesterly flow synoptic types exhibit relatively small increases in mean $[O_3]^{8av}_{max}$ values and small decreases in exceedences (as a result). In the AHS synoptic type, positive contributions from decreases in surface windspeed and increases in 1000-850 hPa thickness are canceled to some degree by decreases in anticyclonic vorticity and increases in 850 hPa windspeed.

The easterly flow synoptic types all exhibit very large increases in mean $[O_3]^{8av}_{max}$ values, primarily a result of very large decreases in the 850 hPa westerly wind component. The values are small enough so that these increases do not result in increases in exceedences, with the exception of the DHN type. For this type, the mean $[O_3]^{8av}_{max}$ value increases from 37.1 to 51.2 ppb and the frequency nearly doubles from 9.3 to 17.3%, accounting for the increases from 0 to 24 exceedences. The significant decrease in the frequency of occurrence for the AHN synoptic type is inconsequential given the fact that this type is not conducive to ozone formation anyway.

3.3 Ozone Concentrations and Large Scale Flow

Both models suggest that characteristics and/or frequencies of the various flow patterns may change so that mean ozone concentrations in summer increase. CGCM1 suggests that mean ozone values will increase slightly from their present values. However, owing to changes in large(r) scale flow patterns, these increases do not translate to increases in exceedences. Specifically, reduced synoptic variability (e.g., increased zonal flow) in the future climate scenario leads to more days with weaker southerly (and northerly) flow than in the current climate scenario even though the overall change reflects more southerly flow. The more quiescent flow pattern results in fewer instances where warm anticyclonic (moist) flow exists to the degree it needs in order to generate ozone concentrations in excess of 80 ppb. This is even more amazing given the fact that there are higher average values of ozone and that there are likely more consecutive days with high ozone so that the contribution from the previous day ozone is more significant. The more quiescent flow pattern in CGCM1 is likely related to the greater warming at polar latitudes in the northern hemisphere. This warming decreases the planetary scale baroclinicity and hence the amplitude of the planetary scale waves that are generated. HadCM2 suggests that mean ozone concentrations will increase more significantly. Additionally, because of an increase in the frequency of ozone significant patterns and because of slightly more synoptic variability, the number of exceedences may increase considerably from their current value.

4. POTENTIAL RESPIRATORY ILLNESS IMPACTS

If understanding how the climate will change by the end of this century is uncertain, and anticipating how ozone levels will change as a result is even more complicated, then projecting accurately how those ozone levels may affect respiratory illness in southeastern lower Michigan by the end of this century is extremely difficult. For example, In addition to ozone and other pollutants, temperature and relative humidity are important covariants that influence health outcome. Furthermore, warmer weather can enhance fungal spores and pollen, which in turn may increase allergic reactions, including those that involve the respiratory system. This uncertain association between climate and most health impacts makes forecasts of future risk very tenuous.

However, our results suggest that increased respiratory stress resulting from elevated ozone and possibly other atmospheric pollutants is likely. The result may be greater hospital admissions for respiratory disease (Moolgavkar et al. 1997, Sheppard et al. 1999) especially among the elderly (Schwartz 1994), and possibly an increase in daily mortality related to respiratory disease. Extrapolation such as this derives from studies of current short-term impacts during ozone exceedences, and the inference that more exceedences will lead to more acute respiratory assaults. The logic underlying this extrapolation assumes that an improved treatment for acute events will not override future population-level effects of the current association. Furthermore, analysis of confounding factors (e.g. unrecognized allergens, shifts in diet or other exposures, seasonality, other weather events) may reveal that atmospheric influences are less important if they act in synergy with these other causes.

Results of the current study underscore the need for understanding better the synoptic aspects of climate change, e.g., besides just temperature and precipitation. CGCM1, for example, suggests a warmer and drier future climate for the Great Lakes region than does HadCM2 (Sousounis et al. 2000). These changes, however, do not necessarily translate into an increased number of exceedences. It is clear from this study that the number of exceedences (as well as the mean ozone values) in the future will also depend strongly on the short-term synoptic variability that is superimposed on the mean climate state. It is clear from this study that additional analyses of future climate output from other state-of-the-art GCM simulations are needed. It is clear from this study that additional analyses of current synoptic weather conditions are needed to identify more precisely the relationships between respiratory disease incidence and atmospheric pollutants. Finally, it is clear that a better understanding of how emissions may change in the future is needed to understand more completely how climate change may affect air quality and respiratory illness.

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