POTENTIAL AIR QUALITY CONSEQUENCES OF ATMOSPHERIC CO_2-INDUCED GLOBAL WARMING IN PHILADELPHIA, PA

Jane Feng Powley
Department of Civil Engineering
University of Delaware
Newark, DE 19716

Guanri Tan
Department of Geography
University of Delaware
Newark, DE 19716

ABSTRACT: The question of the possible climatic effects of increased CO_2 is the largest international problem of this century. The objective of this study is to develop a quantitative method to link general circulation models and regional air quality models in order to determine the potential changes in trends and magnitudes of summer air pollutant concentration and the change in the number of polluted days under assumed scenarios of a doubled atmospheric carbon dioxide level in Philadelphia, PA.

Regional air quality models were first developed by applying an automatic air-mass-based synoptic and statistical methodology. The models then were validated by comparison with actual observations to decide their accuracy and reliability for "predicting" purposes. Finally, the climatic scenario generated for a doubled CO_2 level using a General Circulation Model created by the Goddard Institute for Space Studies was applied to the regional air quality models.

The results show that, in the event of doubled CO_2, there is a general trend towards increased air pollution concentrations. There is also a strong tendency for an increased ratio of polluted days to total days. The increase in the number of heavily polluted days is especially significant. The level of summer sulfur dioxide concentrations is more sensitive to increased atmospheric CO_2 than is the level of ozone.

INTRODUCTION AND BACKGROUND

The question of the possible climatic effects of increased CO_2 is the largest international problem of this century. There exists now a consensus among numerous climatologists that atmospheric CO_2-induced global warming is likely to have significant effects on regional temperatures, precipitation patterns, cloud cover, wind speed and direction, and atmospheric water vapor. Because of the close relationship between weather elements and air pollution concentrations (Niemeyer, 1960; Mather, 1968; Altshuller, 1978; Muller and Jackson, 1985; Kalkstein and Corrigan, 1986; Davis, 1989; Powley, 1991a and b) it is reasonable to assume that significant changes in various weather elements that will accompany global climate change will affect future air pollution levels and episodes in the United States.

For example, Morris et al. (1989) investigated the effect of climate change on ozone concentrations in central California, and the midwestern and southwestern United States. The results demonstrated that temperature change alone could increase ozone levels over what they would have been without a climate change.

In a response to a congressional request (Smith and Tirpak ed., 1989), a U.S. Environmental Protection Agency report called for research on the "interactions of climate change and air quality," and for "the development of innovative approaches between the general circulation and air pollution modeling." The objective of this study is to develop a quantitative

method to link general circulation models and regional air quality models in order to determine the potential changes in trends and magnitudes of summer air pollutant concentration and the change in the number of polluted days under assumed scenarios of a doubled atmospheric carbon dioxide level in Philadelphia, PA.

METHODOLOGY

Philadelphia is a highly industrialized city with a population of 1.7 million. It is one of 56 nation-wide metropolitan areas that had at least 10 days with pollutant concentrations above EPA standards recommended by the President's Council on Environmental Quality (Ruffner and Bair, 1984). The weather data were collected from Philadelphia International Airport (Fig. 1), during the summer season from 1954-1988. The pollution monitor for sulfur dioxide is located at Northeast Philadelphia Airport and the monitor for ozone is at East Lycoming Avenue in the city.

The pollution data were recorded from 1972-1986. The 1:00 a.m., 7:00 a.m., 1:00 p.m. and 7:00 p.m. values of temperature, dew point, pressure, visibility, cloud cover, wind speed and wind direction were extracted from 1954-1988 and used as input for the synoptic categorization. Wind speed and direction were converted into southerly and westerly scaler velocities by sine-cosine transformation (NOAA/National Climate Data Center).

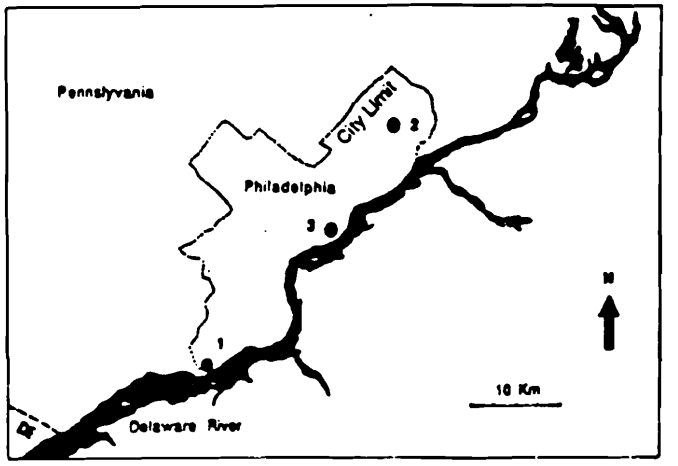
All pollution data are from SAROAD (Storage and Retrieval Aerometric Data) provided by U.S. EPD National Air Data Branch Monitoring and Data Analysis Division. Hourly readings were recorded and daily averages were calculated. The daily maxima were identified for each day. Among several pollution monitors in the city for each pollutant, the one that contains the longest and most complete pollution data record is chosen for the city and the pollutant.

There are basically two kinds of air pollutants under EPA regulations. They can be classified according to their emission sources: (1) Industry and household fuel-related and (2) transportation-related. Sulfur dioxide (SO_2) and total suspended particulates are industry and household fuel-related. The other four pollutants: nitrogen dioxide, nitrogen oxides, ozone and oxidants are transportation related, since they are emitted mainly from the internal combustion engine of automobiles.

SO_2 and ozone were chosen in this study to represent the two different types of air pollutants for the following reasons. First, the pollution data record for these two pollutants are typically the longest and the most complete. Second, the previous studies (Powley, 1991a and b) have shown that in terms of the weather/pollution relationship there is a strong link among all the pollutants. That is, a high concentration of one pollutant may very well indicate a possible high concentration of another. This is even more evident for the pollutants that emanate from the same source (either from industry and household fuel combustion or from transportation). Therefore, including only one pollutant from each of the two categories in this study seems reasonable to give a general assessment on the impact of global warming on air quality. This is also the most cost effective approach for a preliminary study.

Regional air quality models were first developed by applying an automatic air-mass-based synoptic and statistical methodology. The models then were validated by comparison with actual observations to decide their accuracy and reliability for "predicting" purposes. Finally,

the climatic scenario generated for a doubled CO_2 level using a General Circulation Model created by the Goddard Institute for Space Studies was applied to the regional air quality models. The results include the potential changes in mean values of various pollutant concentrations and changes in numbers of polluted and heavily polluted days under doubled CO_2 conditions.



1. Weather Station
2. Pollution Monitor for SO_2
3. Pollution Monitor for Ozone

FIGURE 1: Weather Station and Pollution Monitor Locations in Philadelphia, Pennsylvania.

RESULTS

Regional Weather-Air quality Models

Sulfur dioxide. The regression model developed to represent the relationship between averaged weather conditions and associated SO_2 levels is:

$$Sul = -0.286\, W_{7a} + 0.0188\, D_{1p} - 0.027\, C_{1p} + 0.00991 T_{7a}$$

where

Sul is cluster mean daily maximum sulfur dioxide concentration;
W_{7a} is cluster mean wind speed at 7:am;
D_{1p} is cluster mean dew point temperature at 1:00 p.m.;
C_{1p} is cluster mean cloud cover at 1:00 p.m.; and
T_{7a} is cluster mean temperature at 7:00 a.m.

The variance explained by the model is 96%. All the variables that entered into the model are

significant at the 1% level.

It is not hard to explain that daytime wind speed and cloud cover are important variables in accounting for SO_2 concentration and they are inversely proportional to the pollutant level. For emissions at a given source, the higher the wind speed, the greater the air volume can be provided to disperse the pollutants. Small cloud cover usually results from stable atmosphere and descending air flow. Under these conditions, the temperature decreases very little with height and the upward spread of pollutants are inhibited.

Dew point temperature and surface air temperature also have strong relationships with SO_2 concentrations. They are both directly proportional to SO_2 level. Warm and humid air are commonly the result of a tropical air mass intrusion with a dominant anticyclone to its south. This situation, as a matter of fact, is the synoptic condition warned of by Powley (1991a,b) for the summer season in Philadelphia: "the daily pollution concentration could be significantly higher than the normal level."

Ozone. The regional weather-air quality model developed for the relationship between ozone concentrations and related weather conditions is:

$$Ozo = 0.0195\ T_{1p} - 0.347\ W_{7a} - 0.0507\ C_{1p}$$

where

Ozo is cluster mean daily maximum ozone concentration;
T_{1p} is cluster mean temperature at 1:00 p.m.;
W_{7a} is cluster mean wind speed at 7:00 a.m.; and
C_{1p} is cluster mean cloud cover at 1:00 p.m.

The variance explained by the model is 77.9%. All the variables entered are significant at the 5% level.

It is interesting to observe that the weather variables that are significant to ozone concentrations are somewhat similar to those for SO_2 concentrations. It seems intuitively correct that higher wind speed would be in favor of any air pollutant dispersal regardless of their emission sources. The clear sky with little could cover is usually a result of a high pressure influence, promoting an atmospheric subsidence and poor ventilation for virtually all air pollutants. Temperature is important in accounting for pollution level for both SO_2 and ozone. But the early afternoon temperature is more important to ozone than that in the morning. This could be a reflection of the fact that warmer conditions in the afternoon are better indication of abundant solar radiation which is really crucial for ozone formation while early morning high temperature may or may not lead to sunny skies in the afternoon. The dew point temperature was selected into the SO_2 model but not ozone model.

Evaluating and Validating the Models

The regional weather-air quality models were evaluated by the following procedures.

The result from the Analysis of Variance on sulfur dioxide model shows that the model is significant at more than 0.001 level because the calculated F value, 1754.00 is much greater than the critical value for the F distribution with 4 and 13 degrees of freedom at the 0.001 significance level which is 5.23. This means that there is less than 0.1% probability that the

model is created by chance. The R-squared, adjusted for the degrees of freedom, defines the percentage of the variance that has been accounted for by the model. In case of the weather-SO_2 model, the adjusted R^2 is 96%, which is very high.

Final evaluation involved checking the residuals. There is no systematic variability found and the variances are moderately equal. The correlation coefficient between N-scores and residuals is 0.995, which indicates a good normal distribution. However, there is a certain degree of colinearity, and some of variance inflation factors (VIF) are greater than 5.

The result from Analysis of Variance for Ozone model shows that the calculated value of F is 20.97, which is greater than 5.56, the critical value for F distribution with 3 and 14 degrees of freedom at 0.01 significant level.

R^2, adjusted for the degree of freedom, for the weather- ozone model is 77.9 which is lower than that of weather-SO_2 equation, but still fairly good considering only 3 weather elements are used as predictors. Checking on residuals revealed that the assumptions upon which the linear regression model is based are reasonable. This means that the residuals are normally distributed with equal variances and statistically uncorrelated.

In order to validate the procedure or to check if those weather-air quality models are reasonable for prediction purposes, a three-year data recorded at the pollution monitors were compared to the computed values by the models. Standard correlation (r) and the index of agreement (d) (Willmott, 1985) values between the two sets of the data were calculated to determine if the estimates correspond to the observed values.

TABLE 1. Computed SO_2 Concentrations as Compared with Observed Values in Philadelphia Summer Season (1983-1985)

Cluster Name	Pollution Observed	Mean Computed	Frequency
1	-0.446	-0.389	23
2	-0.687	-0.617	12
3	-0.568	-0.901	3
4	0.268	0.266	55
5	0.676	0.694	26
6	0.399	0.201	14
7	0.285	0.120	10
8	-0.650	-0.436	21
9	1.297	0.068	5
10	2.794	0.842	1
11	-0.589	0.119	5
12	-0.850	-0.558	4
13	0.237	0.343	37
14	-0.382	-0.474	49
Standard Correlation*		r = 0.957	
Index of Agreement*		d = 0.978	

*All data used were weighted by their frequencies.

Table 1 shows the computed cluster mean SO_2 concentrations as compared with the

observed values from 1983 to 1985. The computed mean SO_2 concentration for each cluster generally demonstrated a good agreement with those from observations except for some very low frequency clusters such as cluster 3, 9, 10, 11 and 12. When those cluster mean values were weighted by their frequencies, the standard correlation between the observed and computed SO_2 concentrations yields a value of 0.957. The index of agreement suggested by Willmott et al. (1985) is 0.978. These two statistics suggest that use of the model to predict the cluster mean concentrations gives more than satisfactory results.

A similar study was done to validate the weather-ozone model in the Philadelphia summer season. The results are given in Table 2. The computed cluster mean ozone concentrations agree reasonably with those from the observations although the comparisons are not as good as those in the case of SO_2. Nevertheless, the standard correlation is 0.871 and the index of agreement is 0.926 which indicate a fairly good probability of acceptable predictions by the model.

TABLE 2. Computed Ozone Concentrations as Compared with Observed Values in Philadelphia Summer Season (1983-1985)

Cluster Name	Pollution Observed	Mean Computed	Frequency
1	-0.726	-0.570	24
2	-0.783	-1.401	12
3	-1.185	-2.960	3
4	0.124	0.095	57
5	0.913	0.563	27
6	-0.126	0.151	14
7	0.043	0.115	10
8	-0.569	-0.029	21
9	0.231	-1.248	5
10	-0.219	-1.762	1
11	-0.277	-0.391	5
12	-0.362	-0.316	4
13	0.687	0.811	38
14	-0.230	-0.249	52
Standard Correlation*		r = 0.871	
Index of Agreement*		d = 0.926	

*All data used were weighted by their frequencies.

Assessment of the Change in Air Quality Under Assumed Scenarios of Doubled Atmospheric CO_2 Concentration

By feeding the "future weather data" predicted by the GCM for a 2 • CO_2 condition into the synoptic categorization, 20 synoptic clusters were generated independently from the historical data. The mean values of the weather variables from those "future weather clusters" were then substituted into the pollution models. The result would be the "future mean pollution concentrations" for each "future cluster," provided that the amount of emission of pollutants remains the same in the future.

It is important to note that although the regression equations have been validated by three-year observed data, they represent the relationships in the condition of present climate. Since climate in doubled CO_2 condition has never occurred in the earth, the "prediction" being

made with these equations is in the sense of extrapolation. The extrapolation of an empirical equation contains inevitable uncertainties. It is preferable that the "predicted" values have more qualitative significance instead of quantitative ones.

Table 3 gives the changes in weighted mean SO_2 concentration and total frequencies of pollution related clusters from current to doubled CO_2 condition. It appears that the weighted mean SO_2 concentrations change by an insignificant amount (from 0.686 to 0.6089 for polluted clusters[1] and from 1.698 to 1.5138 for heavily[2] polluted clusters) compared to the change in the total frequencies for the polluted clusters (from 10.6 to 4.0), and especially to the increase in total frequency for the heavily polluted clusters (from 0.4 to 53.2). When the grand weighted mean and grand total frequency were calculated for all polluted as well as heavily polluted clusters, the results yield values of 101% increase in weighted mean (from 0.7228 to 1.4505) and 420% increase in total frequency (from 11.0 to 57.2).

TABLE 3. Changes in Weighted Mean SO_2 Concentrations and Frequencies of Pollution-Related Clusters from Current to Doubled CO_2 Condition

		Current	2 • CO_2
All Polluted Clusters	Weighted Mean (SD)	0.6860	0.6089
	Total Freq. (%)	10.6	4.0
All Heavily Polluted Clusters	Weighted Mean (SD)	1.6980	1.5138
	Total Freq. (%)	0.4	53.2
All Polluted and Heavily Polluted Clusters	Weighted Mean (SD)	0.7228	1.4505
	Total Freq. (%)	11.0	57.2

In case of ozone, the results were summarized in Table 4. Adding the increases for polluted as well as heavily polluted clusters together, the change in weighted mean ozone concentration is +22% (from 0.7615 to 0.9851) and that in grand total frequency is +99% (from 22.8 to 45.3). Considering the changes in the same terms for SO_2 of +101% and +420%, the increase in the weighted mean for ozone is only about 1/5 of that for SO_2 and the increase in total frequency for ozone is about 1/4 of that for SO_2. This can be explained by the following fact:

In a study on the threshold of weather elements for high pollutant concentration for the Philadelphia summer season (Powley, 1991), it was found that it takes a sunnier weather condition with less cloud cover to promote high level of ozone concentration that it does for SO_2. Therefore, there are some weather clusters that have reached the thresholds for high SO_2 concentrations. Nevertheless, they have still not quite met the thresholds for ozone.

[1]defined as the clusters with mean pollution level between 0.5-1.0 standard deviation.

[2]defined as the clusters with mean pollution level greater than 1.0 standard deviation.

TABLE 4. Changes in Weighted Mean Ozone Concentrations and Frequencies of Pollution-Related Clusters from Current to Doubled CO_2 Condition

		Current	2 • CO_2
All Polluted Clusters	Weighted Mean (SD)	0.562	0.826
	Total Freq. (%)	12.6	18.1
All Heavily Polluted Clusters	Weighted Mean (SD)	1.008	1.0909
	Total Freq. (%)	10.2	27.2
All Polluted and Heavily Polluted Clusters	Weighted Mean (SD)	0.7615	0.9851
	Total Freq. (%)	22.8	45.3

Generally speaking, CO_2-induced global warming encourages occurrences of warmer, more stable, and sunnier synoptic patterns with light winds. Those types of weather are generally associated with high pollution concentration.

CONCLUSIONS

First, the regional synoptic-air quality models developed in this study appears to be reasonable for climate-air pollution studies. The total variance explained by the weather-SO_2 model is 96% and that by the ozone model is 77.9%. Both models are significant at more than 0.01 level. The validation of the models revealed that predicted cluster mean pollution concentrations at least reasonably agree with those from the observations. The index of agreement is more than 0.926 which indicates a good probability of acceptable predictions by the models.

Second, the results show that the most important weather elements in terms of air pollution concentrations in the Philadelphia summer season are daytime temperature, wind speed and sky cover. The temperature is directly proportional to concentrations of both pollutants. The other two elements are inversely related to pollution levels. Therefore, under the condition of CO_2-induced global warming, there is a general trend towards increased air pollution concentrations. The weighted mean pollution concentrations for all the pollution-related clusters might increase 22% for ozone and 101% for SO_2 from the current to doubled CO_2 conditions estimated by the models.

The third conclusion is that there seems a tendency for an increased ratio of the number of pollution-related days from the current to doubled CO_2 conditions. This tendency is especially strong for the number of heavily polluted days.

Finally, it seems true that the level of summer SO_2 concentrations is more sensitive to increased atmospheric CO_2 than is the level of ozone. The increase in weighted mean pollution concentrations as well as the frequency of pollution-related clusters for SO_2 under doubled CO_2 condition is about 3 times more than that for ozone.

POTENTIAL AIR QUALITY CONSEQUENCES

It should be noted that the assessment made from this study is subject to some uncertainties caused by the limitations of the GCM and the unknown changes in pollution emissions, technology and scientific advances. In addition, the regional air quality models, or the synoptic-air pollution models are an empirical-statistical models, which means that the models are not deterministic. The models do not "explain" the physical-chemical mechanisms but merely describe the climate-pollution relationship numerically. Unfortunately, the models can not handle the cause-effect and feedbacks. However, due to the extremely complex atmospheric mechanisms which still are not known in sufficient detail to permit deterministic modeling, the synoptic technique has been used in recent years and proven informative. A suggestion for future study would be toward overcoming those limitations and bringing those models closer to serving predictive purposes with better precision.

REFERENCES

Altshuller, A.P. (1978), "Association of Oxidant Episodes with Warm Stagnating Anticyclones," Journal of the Air Pollution Control Association, Vol. 28, pp. 152-155.

Davis, R.E. (1989), "The Development of a Spatial Synoptic Climatological Index for Environmental Analysis," Ph.D. Dissertation, Department of Geography, University of Delaware, Newark, Delaware.

Jackson, A.L. (1984), A Synoptic Evaluation of Climate on Atmospheric Pollen Concentration, M.S. Thesis, Department of Geography, University of Delaware, Newark, Delaware.

Kalkstein, L.S. and Corrigan, P. (1986), "A Synoptic Climatological Approach for Environmental Analysis: Assessment of Sulfur Dioxide Concentrations," Annals of the Association of American Geographers, Vol. 76, pp. 381-395.

Mather, J.R. (1968), "Meteorology and air Pollution in the Delaware Valley," Publications in Climatology, Vol. 21, No. 1, pp. 1-136.

Morris, R.E., et al. (1989), "Sensitivity of a Regional Oxidant Model to Variations in Climate Parameters," in The Potential Effects of Global Climate Change on the United States, Report to Congress, Smith and Tirpak, eds., Appendix Vol. F.

Muller, R.A. and A.L. Jackson (1985), "Estimates of Air Quality Potential at Shreveport, Louisiana," Journal of Climate and Applied Meteorology, Vol. 24, No. 4, pp. 293-301.

Niemeyer, L.E. (1960), "Forecasting Air Pollution Potential", Monthly Weather Review, Vol. 88, pp. 88-96.

Powley, J.F. (1991a), "The Impact of Climate upon Variation in Air Pollution Using a Synoptic Climatological Approach," Ph.D. Dissertation, Department of Geography, University of Delaware, Newark, Delaware.

Powley, J.F. (1991b), "A Synoptic Climatological Approach for Assessment of Summer Air Pollution Concentration in Philadelphia, PA.," in Air Pollution Environmental Issues and Health Effects, S.K. Majumdar et al., eds., Penn. Acad. Sci., 1991.

Ruffner, J.A. and F.E. Bair (1984), The Weather Almanac. Gale Research Company. Book tower. Detroit, Michigan 48226.

Smith, J.B. and Tirpak D., ed. (1989), The Potential Effects of Global Climate Change on the United States, Report to Congress, US EPA-230-05-89-050.

Willmott, C.J., et al., (1985), "Statistics for the Evaluation and Comparison of Models," Journal of Geophysical Research, 90(C5), 8995-9005.