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Air Quality Impact of the Energy Shortage

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ABSTRACT

A statistical analysis assesses the effects of the energy shortage of 1973–74 on ambient air quality in Metropolitan Boston. Standard multivariate regression techniques were used to investigate relationships between measured pollutant levels, meteorological parameters and regulatory controls. The observed long-term decline in ambient sulfur dioxide and total suspended particulate levels from 1970 through 1974 cannot be attributed principally to changes in regional meteorological conditions. Rather, regulatory controls on the sulfur and ash content of fuels burned in the region are implicated. No statistically significant rise in pollutant levels occurred coincident with variances granted on clean-air regulations because of the energy shortage. This was due to simultaneous fuel conservation efforts and the fact that the energy shortage caused shortages of all grades of fuel.

1. Problem background

Demand for energy in the United States has increased at an average annual rate of 4.3% in recent years, while per capita demand has grown at a corresponding rate of 3.5% (U. S. Environmental Protection Agency, 1974). Both rates are significantly higher than long-term historical averages. The bulk of this increased demand for energy has been met by increased use of fossil fuels. At the same time, oil production by domestic sources and our traditional foreign suppliers (Canada and Venezuela) has decreased, forcing an increased reliance on oil imports from the Middle East. Foreign oil imports accounted for 36.9% of the oil consumed in the United States in 1974 (U. S. Bureau of Mines, 1974). Our increased dependence on foreign suppliers placed us in an extremely vulnerable position in October 1973, when the politically motivated Middle East oil embargo began. The embargo drastically restricted oil imports throughout the winter of 1973–74, leading to severe supply problems in many sections of the country during the critical winter heating period. These problems were most acute in the Northeast, where oil is the principal fuel used for heating, industrial processes and electrical power generation. This situation has come to be known as the "energy crisis" or "energy shortage" of 1973–74.

Prior to the oil embargo, as part of State Implementation Plans (SIP) to attain National Ambient Air Quality Standards for sulfur dioxide (SO_2) and total suspended particulates (TSP), several states adopted regulations limiting the sulfur and ash content of fuels burned in their jurisdictions. During the winter of 1973–74, the U. S. Environmental Protection Agency (EPA) granted many temporary variances on clean-air regulations due to restricted supplies of low-sulfur oil, allowing users to burn high-sulfur oil and coal. While such changes were expected to increase emissions of SO_2 and particulates, concurrent conservation efforts by consumers were expected to decrease fuel consumption and, therefore, emission of these pollutants. Thus, the impact on ambient SO_2 and TSP levels of the fuel changes necessitated by the energy shortage is not easily predicted. Variations in meteorological conditions between the winter of 1973–74 and earlier years further complicates resolution of the question of the impact on ambient air quality of the energy shortage. An analysis of the impact of the 1973–74 energy shortage on ambient SO_2 and TSP concentrations was therefore performed on a case study basis for a major urban area, the Metropolitan Boston Air Quality Control Region (AQCR). Three principal tasks were performed in this study: an air quality data analysis, a regulatory and emissions analysis and a diffusion modeling analysis. Presented herein are the statistical results of the air quality data analysis. The remaining tasks are discussed in Siegel *et al.* (1975).

TABLE 1. A summary of regulations adopted to control the sulfur and ash content of fuels burned in the Metropolitan Boston Air Quality Control Region (AQCR).

Effective date of adoption	Regulations in effect in Metropolitan Boston AQCR
1 July 1970	Ban on all open burning. Ash content of fossil fuels limited to 9% by dry weight
1 October 1970	Residual oil sulfur content limited to 2.2% and to 1.0% in core.* Distillate oil sulfur content limited to 0.3%.
1 October 1971	Residual oil sulfur content limited to 1.0% and 0.5% in core.* Coal sulfur content limited to 0.7% and 0.37% in core.*
1 June 1972	Ban on residual oil use at facilities with rated boiler capacities of 8.79×10^5 J s^{-1} (3 million BTU h^{-1}) or less. Ban on solid fuel use at hand-fired facilities with rated boiler capacities in excess of 4.4×10^4 J s^{-1} (150 thousand BTU h^{-1}).

* The core area consists of the central 13 cities and towns within the dark perimeter shown in Fig. 1.

2. Objectives

The objective of our statistical analysis was to interpret trends (or changes in trends) in measured SO_2 and TSP levels during the period January 1970–March 1974.[1] The principal focus of the analysis was to test statistically the relation between trends in regional air quality levels and 1) clean-air regulations implemented during the early 1970's and 2) variances granted on these regulations during the winter of 1973–74 because of the energy shortage. The effects of meteorological conditions on the air quality measurements were also evaluated. Our approach included use of standard multivariate regression techniques to investigate these relationships.

3. Regulations and variances

The Commonwealth of Massachusetts has adopted a number of regulations effecting fuel burning and process emission sources designed to control SO_2 and particulate emissions. Table 1 presents a summary of the regulations relevant to this study. The 1 July 1970, regulations caused the conversion of many wood- and coal-fired boilers to oil, increasing the region's dependence on oil. The 1 October 1970 and 1 October 1971 regulations effected a two-stage reduction in the sulfur content of fossil fuels burned. The 1 June 1972 regulation limited residual oil use to large boilers.

During the winter of 1973–74, when shortages of low-sulfur oil appeared imminent, many variances were granted on these regulations by the EPA to fuel users in the AQCR from 1 December 1973 to 15 May 1974. These variances were of four types:

(a) A blanket relaxation of the sulfur in fuel limitation for distillate oil from 0.3% to 0.5%.
(b) 300–400 individual variances relaxing residual oil sulfur content limitations from 0.5% and 1.0% to up to 2.2%.
(c) Conversion of units 1–3 of the Salem Harbor Power Plant from oil to coal of up to 2.5% sulfur and 15.6% ash content.
(d) Use of 2.6% sulfur residual oil by some sources with a rated heat capacity greater than 7.33×10^7 J s^{-1} (250 million BTU h^{-1}).

The sharp rise in energy costs brought on by petroleum price increases and dwindling fuel supplies is one of the most visible impacts of the energy shortage. It is interesting to note that the energy shortage is responsible for a recent relaxation in the Massachusetts clean air regulations. Effective 1 July 1975 (until 1 July 1977), electric generating facilities in the core area (see Table 1) with a rated boiler capacity of 7.33×10^8 J s^{-1} (2.5 billion BTU h^{-1}) or greater are allowed to burn 1.0% sulfur residual oil. Facilities outside the core with a rated boiler capacity of 2.93×10^7 J s^{-1} (100 million BTU h^{-1}) or greater are allowed to burn 2.2% residual oil.

4. Air quality measurements

Monthly average SO_2 and TSP concentrations measured in the Metropolitan Boston AQCR between January 1970 and June 1973 were obtained through the EPA SAROAD (Storage and Retrieval of Aerometric Data) air quality data file.[2] Supplementary air quality measurements for the period July 1973 to June 1974 were obtained from the Commonwealth of Massachusetts Bureau of Air Quality Control. The data base formed from these sources contained several substantive data gaps, thereby providing an inadequate analysis base at several monitoring sites. To insure a meaningful analysis, a data subset, consisting of air quality monitoring sites at which sufficient valid measurements were taken, was compiled by excluding, in general, any site that had more than two consecutive months of missing data. The results of this selection process are shown in Table 2 and indicate that SO_2 data from 13 sites and TSP data from seven sites were sufficient for statistical analysis from January 1971 to June 1974. For the more extended period beginning in January 1970, three sites had sufficient SO_2 data and one site sufficient TSP data. The geographical locations of the selected air quality monitoring sites are shown in Fig. 1, with the exception

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[1] Air quality measurements were not made on a regular basis in Metropolitan Boston prior to January 1970.

[2] Computer printouts of these data can be obtained from the National Air Data Branch, Environmental Protection Agency, Research Triangle Park, N. C. 27711.

of the Maynard site, which is located approximately 20 km west of the Waltham site.

The measured air quality data for Metropolitan Boston are summarized in Figs. 2 and 3, which present composite annual average SO_2 and TSP concentrations for the region. Data from sites inside/outside the urban core are shown separately in these figures. Figs. 2 and 3 indicate that regional SO_2 levels fell consistently from 1970 through 1974, with the steepest decline occurring prior to 1972. Ambient TSP levels also exhibit a general downward trend similar to that of SO_2 levels, but not as pronounced or consistent.

5. Meteorology

The first step in our analysis was to investigate the possibility that recent changes in average meteorological conditions in metropolitan Boston were responsible for the decline in SO_2 and TSP pollutant levels described above. Monthly heating degree-day and mean wind speed data were obtained for Boston for the period January 1970 through December 1974 from *Local Climatological Data* summaries. These data are based on measurements taken by the National Weather Service at Boston's Logan International Airport. A summary of the annual average values is shown in Table 3. The Logan Airport station and most of the air quality monitoring sites shown in Fig. 1 are situated in the Atlantic coastal plain. Five suburban air quality monitoring sites (Woburn, Waltham, Maynard, Needham and Norwood), however, are located inland from the coast. Although meteorological observations have been taken in the past (unofficially) at some suburban locations, a complete set of data for the time period of interest was not available from these sites, so the Boston Logan data were used throughout the analysis.

Degree-days are a measure of local fuel burning activities and emissions; mean wind speed is a measure of the dilution capability of the atmosphere. An examination of the degree-day statistics in Table 3 reveals no long-term trend in meteorological conditions over the time period of analysis toward lower annual degree-day totals (i.e., warmer winters). In fact, degree-day totals for four of the first five years of this decade are above normal. Table 3 also shows no long-term trend toward higher mean wind speeds over the time period of analysis. Consequently, the observed long-term changes in ambient SO_2 and TSP levels shown in Figs. 1 and 2 cannot be attributed principally to corresponding changes in these meteorological parameters.

TABLE 2. Metropolitan Boston air quality monitoring sites recording sufficient data for statistical analysis in the indicated time periods.

Site location	Data series name	Urban core sites	Time span of data
Government Ctr., Boston	SO2A	√	1970–74
Kenmore Sq., Boston	SO2B, TSP1	√	1970–74
South Bay, Boston	SO2C	√	1971–74
Central Sq., East Boston	SO2D	√	1970–74
Greenough St., Brookline	SO2E, TSP2		1971–74
Village St., Marblehead	SO2F		1971–74
U. S. Army Site, Maynard	SO2G, TSP3		1971–74
Main St., Medford	SO2H		1971–74
Dedham St., Needham	SO2I, TSP4		1971–74
Nahatan St., Norwood	SO2J, TSP5		1971–74
Hancock St., Quincy	SO2K, TSP6		1971–74
Beaver St., Waltham	SO2L, TSP7		1971–74
Montvale Ave., Woburn	SO2M		1971–74

TABLE 3. Annual average heating degree-day and mean wind speed data for Boston, Mass.

Calendar year	Degree-days	Wind speed (m s^{-1})
1970	5832	10.9
1971	5738	11.8
1972	5912	11.4
1973	5139	10.9
1974	5898	12.3
30-year average (1941–70)	5621	12.7

6. Statistical methods

The next step in our analysis involved an investigation of the clean air regulations implemented in Boston since 1970 and the variances granted on these regulations because of the energy shortage. Standard multiple linear regression techniques were used to test the effects of regulations and of the energy shortage

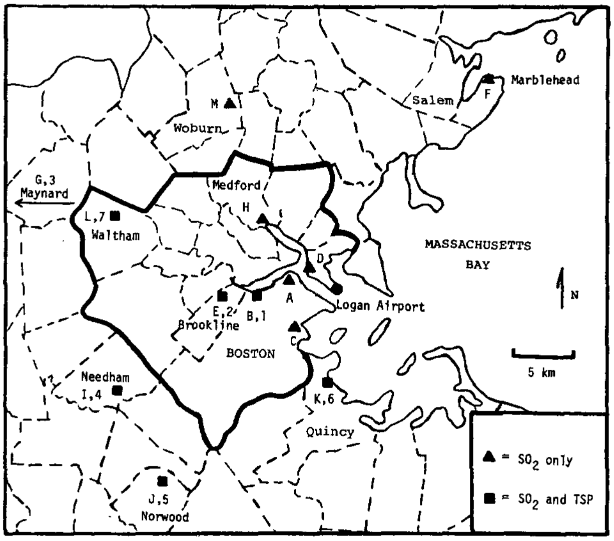

FIG. 1. Metropolitan Boston air quality monitoring sites with sufficient data for statistical analysis.

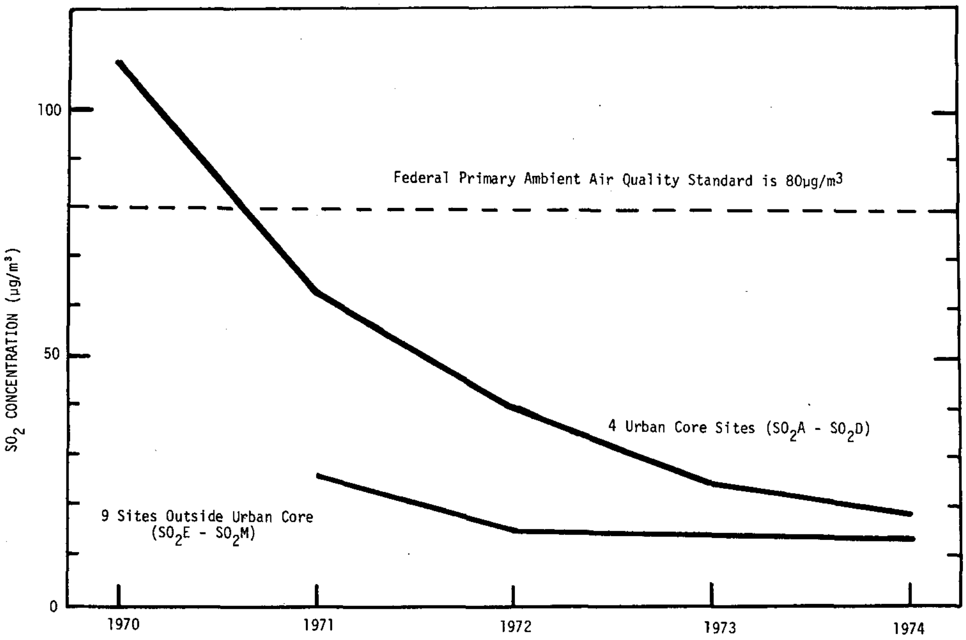

FIG. 2. Composite annual average SO_2 concentrations in Metropolitan Boston.

on Boston's air quality. The independent variables selected for the regression analysis represented meteorological conditions, regulatory controls and seasonal variations. Meteorological independent variables were monthly heating degree-days and a measure of air stagnation, the reciprocal of monthly mean wind speed. The latter is generally considered to be proportional to ambient pollutant levels, and wind speed is used in the reciprocal form in most air quality diffusion models. Indicator variables (Draper and Smith, 1968) were used to quantify the effects of the four significant regulatory dates (listed in Table 1) and the mean effective date of variances granted of 1 December 1973. These variables were defined as 0 before the associated effective date and 1 otherwise. Twelve indicator variables quantifying the effect of

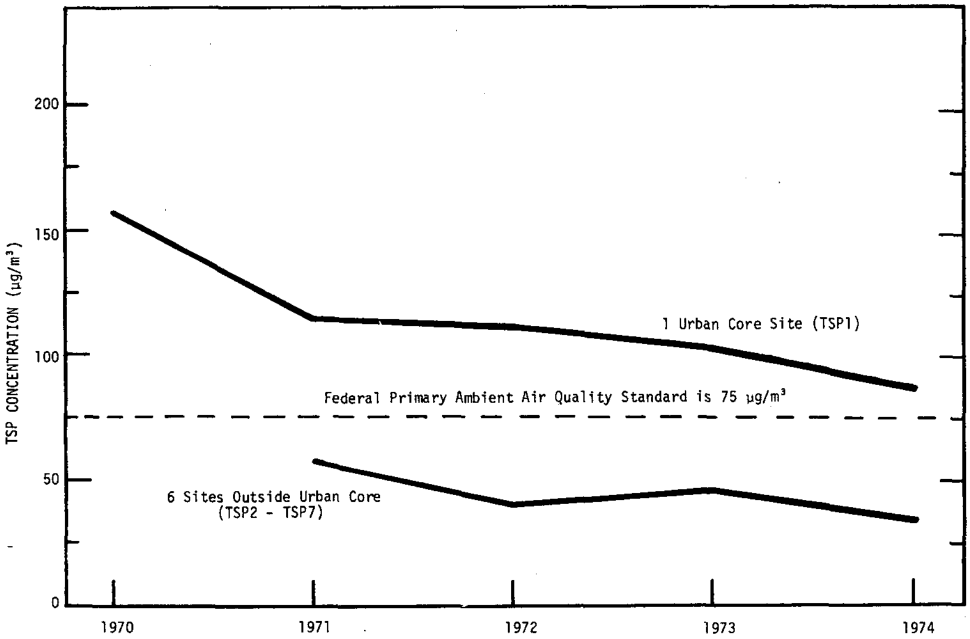

FIG. 3. Composite annual average TSP concentrations in Metropolitan Boston.

TABLE 4. Simple correlation coefficients† between ambient SO_2 and TSP levels and various other variables at several air quality monitoring sites in Metropolitan Boston

Dependent variables SO_2 & TSP Monitoring sites	Independent variables						
			Regulations				
	Reciprocal wind speed	Degree-days	7/70	10/70	10/71	6/72	Variance 12/73
SO2A, Boston	−0.41	0.47	−0.54	−0.49	−0.51	−0.41	−0.18
B, Boston	−0.43	0.54	−0.64	−0.56	−0.60	−0.59	−0.29
C, Boston	−0.38	0.42	*	*	−0.51	−0.44	−0.26
D, E. Boston	−0.34	0.36	−0.49	−0.44	−0.56	−0.59	−0.29
E, Brookline	−0.40	0.46	*	*	−0.39	−0.34	−0.13
F, Marblehead	−0.26	0.16	*	*	−0.27	−0.36	−0.02
G, Maynard	−0.28	0.25	*	*	−0.43	−0.19	−0.18
H, Medford	−0.30	0.35	*	*	−0.36	−0.43	−0.06
I, Needham	−0.40	0.47	*	*	−0.23	−0.26	0.01
J, Norwood	−0.56	0.68	*	*	−0.29	−0.20	0.05
K, Quincy	−0.45	0.61	*	*	−0.05	−0.07	−0.15
L, Waltham	−0.30	0.46	*	*	−0.22	−0.33	0.05
M, Woburn	−0.36	0.34	*	*	−0.28	−0.18	0.10
TSP1, Boston	−0.29	0.50	−0.72	−0.55	−0.40	−0.50	−0.26
2, Brookline	0.07	−0.07	*	*	−0.45	−0.30	−0.14
3, Maynard	0.29	−0.19	*	*	−0.30	−0.04	−0.26
4, Needham	0.48	−0.36	*	*	−0.59	−0.48	−0.43
5, Norwood	−0.06	0.15	*	*	−0.04	−0.07	−0.13
6, Quincy	−0.08	0.23	*	*	−0.57	−0.45	−0.22
7, Waltham	0.66	−0.56	*	*	−0.42	−0.08	−0.40

† An absolute value ⩾0.31 corresponds to the five percent significance level.
* No data available.

seasonal (*viz.*, monthly) variations were used in the regression analysis. Each monthly variable was defined as 1 on its associated month and 0 otherwise.

The dependent variables used in the regression analysis consisted of either the measured ambient SO_2 and TSP levels or the natural logarithms of these quantities. The results obtained by analyzing the data and the logarithms of the data were virtually identical. Only those results associated with analysis of the original data are presented here. The regression analysis was applied separately to each of the 20 data time series identified in Table 2.

We employed first a stepwise procedure that selected the most significant variables from the total set of those defined. Then, complete multiple regressions were performed in which all independent variables, regardless of significance, were included in the regression. The stepwise procedure consisted of adding one variable at each step and computing the residual sum of squares. The variable selected from the list of unused variables was the one that, when added to the equation of the previous step, provided the greatest reduction in the residual sum of squares. That is, the variable that provided the most additional information about the dependent variable Y was chosen. Thus, at some step in the procedure, a variable that was highly correlated with Y may not have been chosen in favor of one that had a lower correlation with Y. This occurred if the highly correlated variable simply duplicated information provided by a previous chosen variable. We found that this "masking" occurred between several independent variables in the current study.

A standard F-ratio test was used at each step of the multiple regression procedure to determine whether the reduction in the residual sum of squares due to each added variable was statistically significant. The critical F value used was 3.0, i.e., an independent variable was added into the regression if its F-ratio equaled or exceeded 3.0.

a. Zero-order correlations

The zero-order (i.e., simple) correlations between the dependent variables and the various independent variables are shown in Table 4 for the SO_2 and TSP data. The sign of the correlation coefficients indicates whether these variables are positively or negatively correlated. An absolute value ⩾0.31 for these simple correlation coefficients corresponds to the 5% significance level, i.e., there is at least a 95% chance that a correlation is not zero. The cutoff value of 0.31 is conservative in that it is based on the smallest sample size of all the time series analyzed.

From Table 4, it can be seen that the regulation and variance variables are consistently negatively correlated with ambient SO_2 and TSP levels. Statistical significance is attained most often for the regulations effective in July and October 1970 and October 1971. The correct interpretation of these negative correlations is that the average SO_2 and TSP levels after the effective date of a regulation or variance are

TABLE 5. Statistically significant regulatory and variance variables in the stepwise regression analysis of ambient SO_2 and TSP levels.†

	Regulatory and variance variables				
Monitoring sites	Jul. 1970	Oct. 1970	Oct. 1971	Jun. 1972	Dec. 1973
SO2A, Boston	−		−		−
B, Boston	−	−	−		−
C, Boston	*	*	−		−
D, E. Boston	−		−	−	−
E, Brookline	*	*	−		
F, Marblehead	*	*	−	−	
G, Maynard	*	*	−		
H, Medford	*	*		−	
I, Needham	*	*	−		
J, Norwood	*	*	−		
K, Quincy	*	*			−
L, Waltham	*	*	−		
M, Woburn	*	*	−		
TSP1, Boston	−			−	−
2, Brookline	*	*	−		
3, Maynard	*	*	−	+	−
4, Needham	*	*	−		
5, Norwood	*	*			
6, Quincy	*	*	−		
7, Waltham	*	*	−	+	

† At 10% significance level, + denotes an increase, − denotes a decrease, and a blank denotes no change in measured levels.

* No data available.

statistically significantly lower than the average values before this date. Statistical significance for the variance variable, however, is attained in only two of the data series.

b. *Partial correlation structure*

In order to investigate the possibility that statistically significant downward changes in SO_2 and TSP levels coincident with the effective dates of fuel use regulations and variances are due principally to changes in meteorological conditions, we computed the partial correlations of SO_2 and TSP levels with the regulatory and variance variables, removing the linear relationship with either degree-days or the reciprocal of wind speed. We found the resultant patterns of partial correlations to be, in general, the same as those shown in Table 4. Thus, statistically significant decreases in average SO_2 and TSP levels are associated with the effective dates of regulations and variances even after meteorological conditions have been taken into account.

The results in Table 4 show that degree-days are significantly positively correlated with SO_2 levels at most monitoring stations. That is, both quantities vary seasonally, with winter maxima and summer minima. From the meteorological observations, we found a strong correlation (-0.743) between heating degree-days and the reciprocal of mean wind speed for Boston, reflecting the climatological relationship between these quantities. A result of this interdependence is that partial correlations of SO_2 levels with the reciprocal of wind speed, removing the linear relationship with degree-days, are all close to zero. In other words, the previously discussed masking situation is occurring where, if degree-days are already present in the regression, they dominate the correlations, and the addition of wind speed as a variable adds little or no information about the SO_2 levels. Thus, the apparent negative correlation between SO_2 levels and the reciprocal of wind speed in Table 4 is due principally to the strong correlation climatologically between wind speed and degree-days. The same situation is observed for the TSP1 series, representing the one urban core site where TSP measurements were analyzed. Of the remaining TSP series, only the TSP4 and TSP7 series (see Table 3) have significant correlations with both wind speed and degree-days. At these sites, outside the urban core, wind speed is the more important of the two variables, and the correlation of its reciprocal with TSP levels is positive, i.e., both quantities vary seasonally, with maxima in the summer and minima in the winter months. The partial correlations of TSP levels with degree-days at these two sites, removing the linear relationship with wind speed, are all close to zero, emphasizing the dominant effect of wind speed on TSP levels at nonurban sites.

c. *Stepwise regressions*

We applied stepwise multiple linear regression analysis to each of the 20 data time series. A summary of those regulatory and variance variables which proved to be significant is shown in Table 5. Here a + sign indicates a significant increase, and a − sign indicates a significant decrease in ambient SO_2 and TSP levels after the associated regulation or variance date. The results in Table 5 indicate that the July 1970 and October 1971 regulations are associated with a significant decrease in SO_2 and TSP levels in practically all of the data series.

In addition, no statistically significant rise in SO_2 and TSP concentrations occurred at any of the sites coincident with variances granted because of the energy shortage during the winter of 1973–74. In fact,

TABLE 6. Most important variables and events in stepwise regression analysis.

SO_2	TSP	
(Entire region)	(Urban core)	(Nonurban)
Heating degree-days 1 October 1971 regulations	Heating degree-days 1 July 1970 regulations	Reciprocal mean wind speed 1 October 1971 regulations

a statistically significant decrease in levels of these pollutants during this winter occurred in seven of the 20 data series, commencing in December 1973.

Table 6 summarizes the variables and events in the stepwise regression which we found made the greatest total contribution toward explaining variations in regional SO_2 and TSP levels between 1970 and 1974. These quantities are listed in the order of their ability to explain these variations. In the instances where heating degree-days and the reciprocal of mean wind speed were the most significant variables in the multiple linear regression, we found them to be directly proportional to measured pollutant concentrations. These proportionality results are consistent with the relationships normally assumed between pollutant concentrations, emissions and wind speed in most air quality diffusion models.

d. Complete regressions

In addition to the stepwise procedure, we performed complete multiple linear regressions on all 20 data series. Here all independent variables were included in the regression rather than only those that passed the F-ratio test for significance. The signs of the regression coefficients for the regulatory and variance variables, regardless of significance, are summarized from the complete regressions in Table 7. The sign of a regression coefficient gives an unbiased estimate of the direction of change in the pollutant time series due to the independent variable involved. Note again that not all of these changes are statistically significant. A sign test (Dixon and Massey, 1969) at the 5% level of significance applied to the data in Table 7 indicates statistically significant decreases in SO_2 and TSP levels occurred regionally after the October 1971 and December 1973 dates. This analysis takes the effects of all other variables into account before assessing the relationship with the regulatory or variance variables. These results are important in that they represent a combined analysis for all sites.

TABLE 7. Signs of regression coefficients in complete regression analysis.†

	Regulatory and variance variables				
Monitoring sites	Jul. 1970	Oct. 1970	Oct. 1971	Jun. 1972	Dec. 1973
SO2A, Boston	−	−	−	+	−
B, Boston	−	−	−	−	−
C, Boston	*	*	−	+	−
D, E. Boston	−	−	−	−	+
E, Brookline	*	*	−	+	−
F, Marblehead	*	*	−	−	+
G, Maynard	*	*	−	+	−
H, Medford	*	*	−	−	+
I, Needham	*	*	−	+	−
J, Norwood	*	*	−	+	−
K, Quincy	*	*	−	+	−
L, Waltham	*	*	−	−	−
M, Woburn	*	*	−	+	−
TSP1, Boston	−	−	+	−	−
2, Brookline	*	*	−	+	−
3, Maynard	*	*	−	+	−
4, Needham	*	*	−	−	−
5, Norwood	*	*	−	+	−
6, Quincy	*	*	−	−	−
7, Waltham	*	*	−	+	−

† At 10 percent significance level, + denotes an increase, − denotes a decrease and a blank denotes no change in measured levels.

* No data available.

7. Conclusions

The principal finding of our analyses is that no statistically significant rise in regional SO_2 and TSP concentrations occurred coincident with variances granted because of the energy shortage during the winter of 1973–74. In fact, the results of the complete regressions indicate statistically significant decreases in these pollutant levels occurred regionally, starting in December 1973. The implication of this finding is that some other mechanism, most probably fuel conservation efforts by consumers, overrode the effects of any increase in SO_2 and TSP emissions due to the variances on clean-air regulations. This hypothesis is confirmed by a survey subsequently performed of major fuel users and distributors in Metropolitan Boston in which we found that the energy shortage caused shortages of all grades of oil, not just the low-sulfur oils, and that full advantage was therefore never taken of most variances.

Other results are that major SIP fuel use regulations effective of 1 July 1970 and 1 October 1971 are associated with statistically significant decreases in regional SO_2 and TSP levels. This is explained by the fact that both of these regulations were responsible for the conversion of many large fuel utilization facilities to fuels with lower sulfur and ash contents.

In addition, relationships between meteorological and pollutant variables revealed by the stepwise regression analysis indicate that 1) fuel burning emissions dominate SO_2 concentrations throughout the Metropolitan Boston AQCR, 2) TSP concentrations in the urban core are also dominated by fuel burning sources, but 3) TSP levels at nonurban sites are dominated by emission sources other than fuel burning facilities, most probably local particulate sources, road dust and pollen.

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