Effects of Frictionally Retarded Sea Breeze and Synoptic Frontal Passages on Sulfur Dioxide Concentrations in New York City

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ABSTRACT

Temporal changes in the spatial distribution of sulfur dioxide concentrations in New York City resulting from the passage of sea breeze and synoptic fronts were studied using data from the New York University/New York City Urban Air Pollution Data Set. Results show that upwind portions of New York City experience decreasing concentrations with the passage of sea breeze fronts, while downwind portions experience increasing concentrations. Synoptic fronts produce increasing concentrations in the less urbanized areas to the east and west of Manhattan and decreasing concentrations in Manhattan. The one synoptic front which moved extremely slowly showed extreme frictional retardation and produced the opposite effects on the concentration field.

1. Introduction

Synoptic fronts were found by Loose and Bornstein (1977) to be significantly retarded as they moved over New York City (NYC) due to its increased surface roughness. When a stationary cold front oscillated over NYC, Nudelman and Frizzola (1974) found pollutant concentrations increased due to the advection of polluted air back and forth over the city.

The inland passage of sea breeze fronts is usually accompanied by a wind shift, temperature decrease and increase in dew point. These characteristics were noted by Edinger (1959, 1963) in Los Angeles, by Fosberg and Schroeder (1966) in San Francisco, by Johnson and O’Brien (1973) on the rural Oregon coast, and by Simpson et al. (1976) on the coast of England.

Similar observational studies were carried out in the urban New York City area by Frizzola and Fisher (1963) who showed that when the prevailing large-scale synoptic flow reinforced the sea breeze, it began early and penetrated quickly. However, if the gradient flow opposed the sea breeze, it began later in the day, and as it moved inland, took on the characteristics of a cold front. Opposing gradient flows with speeds > 10 m s⁻¹ were found sufficient to inhibit inland penetration of sea breeze fronts.

Sea and lake breeze effects on pollutant concentrations have received significant attention in recent years, with an up to date summary of pollutant transport and diffusion in coastal environments presented by Lyons (1978). Sea breeze circulation cells were found by Hewson and Olsson (1967) to recirculate air pollutants back over their sources, as polluted air first carried inland and upward by the near surface sea breeze flow is then carried out to sea in the return flow layer aloft. The subsequent sinking of this air leads to its again being caught up in the near surface sea breeze flow. This phenomenon was described in a general manner by Hewson and Olsson (1967), while a detailed case study of the phenomenon, using tetron derived trajectories, was provided by Lyons and Olsson (1972, 1973). A similar effect was found in the San Fernando convergence zone (formed by opposing sea breezes) by Edinger and Helvey (1961).

The present research uses data from the New York University/New York City Urban Air Pollution Project to investigate temporal and spatial distributions of sulfur dioxide resulting from passages of sea breeze and synoptic fronts. Preliminary results from this study have presented by Bornstein, Fontana, and Thompson (1978, 1979) and Thompson and Bornstein (1979).

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tardation of sea breeze fronts (Fontana and Bornstein 1981).

Data collected from most of the sites were previously averaged over one hour periods, centered on the hour, except for data from airports, military bases and coast guard stations, which were standard hourly airways observations. Hourly average wind speed and direction data were plotted at 1 h intervals and mesoscale streamline and isothach analyses performed. After frontal positions were determined, isopleth analyses of frontal passage time and speed of frontal movement were performed by either Loose and Bornstein (1977) or Fontana and Bornstein (1981).

Sulfur dioxide concentration data were also collected during the original project at 33 fixed sites (Fig. 2). These data also have been used in previous studies of meteorological factors affecting sulfur dioxide concentration, the effect of greenbelts on sulfur dioxide concentration across Manhattan, plume rise, and as input data for a Gaussian puff air pollution model.

Eight of these sites were instrumented with electroconductivity devices manufactured by the Davis Company and maintained by NYU Project members. Calibration of these instruments included compensation for interference by atmospheric carbon dioxide. Eleven other stations also used Davis instruments, but they were operated by either NYC or the Consolidated Edison Company, while 14 NYC stations used West-Gaede wet chemistry devices. The present study utilized the hourly averaged data, centered on the half hour. When these data were not available, values were obtained by interpolating data previously plotted on mesoscale maps at 2 h intervals.

To demonstrate the effects of frontal passages on sulfur dioxide concentrations, the following procedure was carried out for each of the six frontal cases: 1) determination of the time of frontal passage at each sulfur dioxide monitoring site by interpolation of the hourly positions given in the isochrone analysis; 2) construction of a transection consisting of a family of curves showing the change in concentration after frontal passage for successively longer intervals at 1 h time steps at stations along a line through the center of the city in the direction of frontal movement (i.e., normal to the isochrones); 3) visual determination of the time interval from the transection for which the change in concentration was generally maximized; 4) an isopleth analysis of the change in concentration ($\Delta S_T$) at all stations after the frontal passage over the selected time interval; 5) the same isopleth analysis over the identical time interval on a nearby day ($\Delta S_N$) having a persistent wind direction, preferably similar to that observed

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2. Analysis

The New York University/New York City (NYU/NYC) Urban Air Pollution Dynamics Project described by Davidson (1967) and Bornstein et al. (1977a,b) studied the polluted urban boundary layer in the NYC area. Data were collected during 11 test periods, during which four synoptic and two sea breeze frontal passages occurred.

Wind data were collected by a mesoscale anemometer network consisting of 97 sites located in a rectangular area centered on the west side of midtown Manhattan (Fig. 1). Data from the network have been used in previous studies of mesoscale perturbations on synoptic-scale flows, mesoscale trajectories (Druyan, 1968), urban-rural velocity differences (Bornstein and Johnson, 1977), frictional retardation of synoptic fronts (Loose and Bornstein, 1977), the vertical structure of sea breeze fronts (Bornstein and Anderson 1981), and frictional re-

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prior to frontal passage on the test day; and 6) an isopleth analysis of the change in concentration at all stations due to frontal passage ($\Delta S$) by subtraction of the diurnal variation over the selected time interval on the non-frontal day ($\Delta S_n$) from the observed total change in concentration on the frontal day ($\Delta S_f$).

3. Results

For each of the six cases, some or all of the following are summarized: surface flow, sulfur dioxide concentrations and change in sulfur dioxide concentrations due to frontal passage. All times appearing in the paper are local standard.

a. 8 March 1966 (sea breeze event)

Mesoscale analyses of the surface winds on 8 March in and around New York City showed a persistent flow from the north, varying only from NNE to NNW. Speeds varied between 5 and 8 m s$^{-1}$ occasionally reaching 10 m s$^{-1}$ with maximum speeds generally over Manhattan Island. Surface winds over the city on the 9th were northerly until 1000 (all times EST), but speeds were generally less than 3 m s$^{-1}$ as the center of the surface high came closer to the area.

A sea breeze front came onshore at 1100 and passed JFK Airport at 1300 (Fig. 3), bringing southerly winds at 5 m s$^{-1}$. The front showed the effects of frictional retardation by 1600 when it entered Manhattan and a distortion developed along it (Fig. 4). This effect lasted until 1900 when the front broke through the city.

Sulfur dioxide concentrations during the morning of 8 March reflected the effects of the strong persistent northerly winds as concentrations were low (4–24 ppm)$^6$ and there was more than one maxima. Concentrations at 1230 were even lower (~4 to 20

$^6$ Parts per hundred million.
pphm), but a general increase began in the afternoon which lasted into the late evening.

Concentrations continued to increase after midnight, such that during the morning on the 9th values were higher (8–48 pphm) as shown in Fig. 2. At 1230, the lowest concentration for the day again occurred at all stations and by 1430 the concentration field reflected the change in wind direction associated with advection and the onshore movement of the sea breeze front. In the late afternoon and evening values again increased, but with maximum values considerably displaced to the NW (with respect to their prefrontal positions).

The initial effect of the sea breeze front of 9 March on sulfur dioxide concentrations in NYC was a reduction in values at sites in the southern part of the city as clean air was advected into the city behind the front. For example, the frontal passage at John F. Kennedy Airport (JFK) on the southern shore of Long Island in the NYC borough of Brooklyn at about 1230 was associated with a significant decrease in sulfur dioxide concentrations (Fig. 5).

Concentrations in the air behind the front increased with inland movement as pollutants were emitted into the marine air. Thus when it passed La Guardia Airport (LGA), on the northern shore of Long Island in the NYC borough of Queens, at 1730 concentrations increased significantly (Fig. 6). The concentration shown at 1730 was obtained by extrapolation of the 1630 value as observations were not available for 1730.

The transection for 9 March (Fig. 7) shows that the 3 h period was most appropriate for constructing the \( \Delta S_T \) map for this day (Fig. 8) because after this period additional changes are small. This map shows that locations in the southeastern part of the city experienced decreased concentrations after frontal passage, while sites in the northwestern part of the city experienced increased concentrations when the front passed those locations.

The \( \Delta S_T \) values were adjusted by an amount equal to the change in concentration experienced at each site during the corresponding 3 h period on the 8th, i.e., the \( \Delta S_N \) values (Fig. 9). The adjustment was
made in order to correct for the expected diurnal variation during a similar non-sea breeze period and values were smaller than the $\Delta S_T$ values at almost all sites on this day.

The distribution of $\Delta S$ values resulting from the correction (Fig. 10) thus shows the same general pattern as in the uncorrected $\Delta S_T$ values. This distribution is due to emissions into the marine air as it passed over the city in combination with the effects of frictional retardation exerted by Manhattan on frontal movement. When the front stalled over the southern part of Manhattan (Fig. 3) the air became increasingly polluted, and thus concentrations increased over the northern part of Manhattan when it finally did pass over those sites. On the other hand, since the front moved rapidly through the area southwest of Manhattan, the air behind it was relatively clean and concentrations decreased after it passed.

The daily variation of concentration at LGA was similar on both the 8th and 9th until the front passed at 1730 on the latter day (Fig. 6). This is true as the wind direction before this hour on both days was very similar, and because small differences in wind direction will not greatly affect concentrations in this area since few point sources are located north of the site.

The daily variation of concentration at JFK was also similar on both days (Fig. 5) until 1030, after which time concentrations on the 9th rose dramatically until the sea breeze front passed 2 h later; they rose only slightly on the 8th during the same period. The large rise on the 9th was due to a shift in the direction of the wind (from NNE at 1000 EST to NW at 1100 EST) which placed JFK downwind of 11 power plants and approximately 36 smaller point sources. There are no major sources to the NNE of JFK. The wind on the 8th also was NNE at 1000, but on this day it shifted to the north (rather than to NW) at 1100, placing JFK downwind of only one power plant and approximately five smaller point sources.

Frictional retardation is not responsible for the distribution of positive and negative $\Delta S$ values, as this pattern results from the passage of the sea
breeze front. However, retardation is responsible for increasing the magnitude of the positive values and the tightness of the gradient of the $\Delta S$ isopleths at the exact location where the isochrones (Fig. 3) have the smallest spacing.

b. 7 May 1966 (sea breeze event)

Sulfure dioxide concentrations during the May case were generally lower than those during the previously discussed March case due to the expected seasonal temperature dependence of sulfur dioxide emissions. On 4 May, the non-sea breeze day, concentrations were low at midnight and in midafternoon, with multiple maxima located near the East River. For most of the day on the 7th, a northwesterly gradient flow produced a tighter concentration gradient in the northwest part of the city than in the southeast. Maximum concentrations during this period (until 1630) were again generally centered over the East River, but by 1730 the pattern had become similar to that on the other sea breeze day. The first of the two minimum concentrations over the city on this day was the expected diurnal minimum at 1330, while the second at 1630 occurred when the sea breeze front finally passed over the city.

At 3 h period was again used to construct the current $\Delta S_T$ map. As in the March case, locations in the SE part of the city experienced decreased concentrations after the frontal passage, while sites in the NW part of the city experienced increased concentrations after the front passed these locations. These changes were generally smaller than those on the previous sea breeze day due to the lower sulfur dioxide concentrations during this test period.

Concentration data from 4 May were used to construct the $\Delta S_N$ distribution. The positioning of positive and negative values, as well as their magnitudes, was relatively similar to that on the previous (non-sea breeze) day. Note that in this case, $\Delta S_N$ values were comparable to $\Delta S_T$ values, a situation which was not true in the previous case.
However, adjustment of the $\Delta S_T$ values by the $\Delta S_N$ corrections still resulted in a $\Delta S$ distribution (Fig. 11) with the same general pattern as that of the $\Delta S_T$ map. While the May $\Delta S$ values also are much lower than those in March, the general distribution of positive and negative values for both sea breeze cases is fairly similar. Also, the position of the largest gradient of the $\Delta S$ isopleths again corresponds to the location of the greatest packing of the isochrones. However, the zero-change line is displaced several miles to the south in the present case.

c. 3 May 1966 (synoptic event)

Hourly surface mesoscale wind analyses from 3 May showed two frontal passages. In the early morning hours, before the first passage, winds were light and westerly. The front was weak and oscillated over the city between 0200–0700. After it dissipated at 0800, the winds were south to southwest at 5–8 m s$^{-1}$.

As the second (interesting) front approached the city at 1800, the winds were southerly at 8–11 m s$^{-1}$. Frictional retardation produced minor distortions in frontal shape over the city and reduced its speed up to 50%. The front moved out of the area by 2200, leaving northerly winds at 3–5 m s$^{-1}$. Winds on the comparative non-frontal day (4 May) were discussed in Section 3b.

Sulfur dioxide concentrations on the 3rd increased dramatically to a maximum of 67 ppm at 0530, probably due to the oscillation of the first front, an effect previously reported by Nudelman and Frizzola.
(1974). Concentrations began to decrease at 1030, as they had during this period on the already discussed two sea breeze days, so that by 1730 the maximum was only 20 ppb.

By 1930 the maximum values shifted to the south as the front advanced. Maxima at 2030 were elongated with N-S axes, and by 0030 a single maximum of only 10 ppb was over Welfare Island. Concentration patterns on the non-frontal day (4 May) were also previously discussed in Section 3b.

The transection for the 3 May concentrations indicated a 4 h period for computing $\Delta S_T$ values. Results showed large decreases in concentration centered over mid-Manhattan, with small increases to the NE and SW.

The decreasing concentrations resulted when polluted urban air was replaced with clean air as the front passed through the area. The increasing concentrations were probably due to the transport of polluted air from the urban region by the complex three-dimensional flow field associated with non-uniformly retarded fronts.

Magnitudes and distribution of the 4 h adjustment $\Delta S_N$ values for the current case were similar to the corresponding 3 h $\Delta S_N$ values for this day which were used in the previous case. As the current 4 h $\Delta S_N$ values are very much smaller than the current $\Delta S_T$ values, the resulting $\Delta S$ distribution (Fig. 12) is quite similar to the original $\Delta S_T$ map. As in the previous two cases, the maximum gradient of both the $\Delta S$ isopleths and the isochrones coincide due to the effects of the minimum frontal speed.

![Fig. 9. Distribution of $\Delta S_N$ values (pphm) for 8 March 1966.](image-url)
d. 6 May 1966 (synoptic event)

Sulfur dioxide patterns for 5 May showed maxima oriented NE to SW, with minimum concentrations at 0030 and 1730. Prefrontal maxima on the 6th were higher than those during the corresponding time period on the previous day. Maxima were oriented N-S due to the southerly pre-frontal flow and the northerly post-frontal winds. Values generally fell after the passage.

A 3 h period was again used for the $\Delta S_T$ computation for 6 May. Although values are smaller than in the previous case, negative values are still found over most of Manhattan.

Although the $\Delta S_N$ values for the present case are larger than both the $\Delta S_N$ values of the previous case and the current $\Delta S_T$ values, the current $\Delta S$ map (Fig. 13) is similar to that of the previous case, i.e., a strong region of falling concentrations over Manhattan surrounded by smaller increases. This result is obtained as the $\Delta S_N$ values over Manhattan are more negative than the corresponding $\Delta S_T$ values.

e. 16 October 1965 (synoptic event)

Sulfur dioxide concentrations on 14 October, the non-frontal day, increased in the hours near sunrise to a maximum value of 51 ppm at 0730. Values decreased during the remainder of the day, such that the maximum value at midnight was 13 ppm. Concentrations on the 16th, the frontal day, were much lower than those on the 14th until 1330, the end of the test period.

A 4 h period was used for the $\Delta S_T$ computation for 16 October. As in the previous two cases, nega-
tive values were again found over Manhattan and Brooklyn, while positive values were found over Queens. However, no consistent pattern was apparent over the Bronx and New Jersey for all three cases. Also, the magnitudes of the current $\Delta S_T$ values were the smallest for the three cases.

The $\Delta S_X$ values for 14 October were all positive, consistent with the time of frontal passage (i.e., 0300) relative to the time of the normally expected maximum of urban sulfur dioxide. When these values are subtracted from the generally negative $\Delta S_T$ distribution, resulting $\Delta S$ values are all negative (Fig. 14). However, the current $\Delta S$ pattern is not really dissimilar to those of the previous two cases as the largest magnitudes are still found over Manhattan. In addition, the smallest magnitudes are near zero and are located in the regions where small positive values were found in the previous two cases.

**f. 11 March 1966 (synoptic event)**

The front was unusually slow moving, i.e., first appearing in the study area at 0100 and not leaving the area until 1200. It traveled at a speed of 4 m s$^{-1}$ upwind of the city, was frictionally decelerated to a speed of $<$1 m s$^{-1}$ over Manhattan Island, and was accelerated to a speed of 5 m s$^{-1}$ by the urban heat island over Queens. These effects produced a very large distortion in frontal shape around the central part of the city (Fig. 15). In fact, it is possible that the front never really passed the center of the city but dissipated and reformed to the south.
Sulfur dioxide patterns on 10 March showed a persistent elongated maximum over Manhattan Island which slowly retreated to the NE during the day due to the southerly flow. Minimum concentrations for the day were observed at 1230.

On 11 March concentration patterns over Manhattan until 1430 were similar to those of the previous day, the magnitudes were not. At 0300 the concentration maximum was 32 pphm, and values increased slowly until 0630. As the front “wrapped around” Manhattan from 0700 to 0800, concentrations rose dramatically to 64 pphm. As the front reformed to the south, values began to drop.

A 4 h period was used to construct the $\Delta S_T$ map, which showed negative values over almost the entire area. The largest magnitudes were found at the Brooklyn-Queens boundary and over the Bronx. As compared to those of the three previous synoptic cases, the present $\Delta S_T$ chart had a smaller area of positive values and larger magnitudes, the latter due to the expected seasonal variation of sulfur dioxide emissions.

It is interesting that the zero isopleth, which encloses the small positive area, corresponds closely to the 0800 isochrone (the one in Fig. 15 with the largest distortion). This implies that a plume of polluted air is being “squeezed” out of the Manhattan area by the distorted front.

The corresponding $\Delta S_N$ distribution showed almost all large negative values, consistent with the time of frontal passage (i.e., 0800) relative to the time of the normally expected morning maximum.

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Fig. 12. Distribution of $\Delta S$ values (pphm) for 3 May 1966.
of urban sulfur dioxide. When the $\Delta S_N$ values are subtracted from the corresponding $\Delta S_T$ values, the resulting $\Delta S$ pattern (Fig. 16) shows an area of large positive values over Manhattan surrounded by regions of smaller negative values. This pattern is the reverse of those from the previous three synoptic frontal cases. It supports the contention that the front never passed over Manhattan, and thus the idea that there was no transport of polluted air out of Manhattan as in the three previous cases.

4. Conclusion

The present study utilized wind and sulfur dioxide concentration data from the New York University/ New York City Urban Air Pollution Project to investigate temporal and spatial distributions of sulfur dioxide resulting from passages of sea breeze and synoptic fronts. Results show different patterns of behavior associated with sea breeze fronts synoptic fronts, and synoptic fronts with extreme frictional retardation, i.e., slow-moving fronts.

A sea breeze frontal passage resulted in decreasing pollutant concentrations in the upwind portions of the city (nearer to the coast) and increasing concentrations in the downwind portions of the city in the two cases studied. This is due to the advection of clean air which, as it travels over the city, becomes polluted and arrives in downwind areas with relatively high concentrations. Sea breeze fronts move through the city when pollutant levels are
decreasing on a diurnal basis so that, when diurnal
effects are removed, downwind increases are aug-
mented and upwind decreases are made less ap-
parent.

In the New York City area, frictional retardation
of the front over the roughest (central) part of the
city acts to further increase concentrations in down-
wind areas. The downwind regions include Man-
hattan and the Bronx, which contain some of the
most depressed areas of the city, e.g., Harlem and
the South Bronx, respectively. Thus, there is a
meteorological component to the concept of the
"long hot summer", as the more affluent sections
of the city, e.g., Queens, experience cool clean air
with the early passage of the sea breeze front. How-
ever, due to the frictional retardation of the sea
breeze fronts, people in Harlem and the South Bronx
experience warm polluted air when the sea breeze
fronts pass over these sections later in the day.

Synoptic cold frontal passages caused decreasing
pollutant concentrations in Manhattan and increas-
ing values to the east and west in the three cases
studied. Reduction in concentration is due to re-
placement of polluted air by continental polar air
behind the front. The increase is probably due to
transport of polluted air from regions of highest con-
centration (i.e., Manhattan) to surrounding regions
by the complex three-dimensional flow associated
with frictionally retarded fronts.

One possible conceptual model of this situation
envision near-surface confluence into the urban
area as the front moves forward more rapidly on
either side of the city than it does over the urban center. This creates upward vertical motion over the city, which transports polluted air vertically. The circulation cells are completed with the subsequent sinking of the polluted air on both sides of the urban area.

In the one case of an extremely slow moving front, it "wrapped around" the central portion of the city and probably dissipated and reformed to the south. This prevented polluted air over Manhattan from being transported to surrounding areas and then being replaced by clean air behind the front. This resulted in increasing concentrations over Manhattan and decreasing concentrations in the surrounding areas, the reverse of the pattern found with the other three synoptic frontal passages.

An observational study by Slade (1962) on dispersion in coastal areas around Chesapeake Bay was utilized by van der Hoven (1967) in an analytical model of sea breeze fumigation. This phenomenon is analogous to classical air pollution fumigation, except that the former lasts somewhat longer (several hours to a day) than classical fumigation which results from the breakup of nocturnal radiation inversions. Sea breeze fumigation reduces air quality under conditions that would seem conducive to good ventilation, i.e., the advection of clean marine air into coastal areas. However, changes in atmospheric stability resulting from air mass modification as the marine air travels inland produce the fumigation episode. The ideas of van der Hoven were applied to complex coastal terrain by Collins (1971). No evidence of fumigation was found in the data used in the present study, because it generally occurs on a spatial scale too small to be resolved by the present SO2 network.

Findings of the present study, with respect to concentration changes associated with cold and sea breeze frontal passages, should be valid for any large urban or large coastal urban area, respectively. In fact, increased pollutant concentrations were
found at inland locations in Boston after sea breeze frontal passes (Barbato, 1978).

Recommendations for future research include the need for development of four-dimensional numerical models of the concentration fields associated with frictionally retarded synoptic and sea breeze fronts. Such a model will be developed under a grant recently received by the first author of this paper from the Electric Power Research Institute.

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