Source Emissions and the Vertically Integrated Mass Flux of Sulfur Dioxide Across the New York City Area[1]

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ABSTRACT

Sulfur dioxide concentrations (in ambient air), obtained from helicopter soundings and traverses, together with wind data from pibals, were used in a kinematic box model to determine hourly average three-dimensional fluxes of SO_2 for the New York City area. Continuous dry-bulb temperature and pressure height records were obtained concurrently and utilized in the analysis and interpretation of the flux data.

The SO_2 fluxes were compared to degree-day-dependent emissions from residential, industrial and utility sources. Results indicate that the vertical structure of the fluxes is related to diurnal variations of the temperature lapse rates. Furthermore, the emission rates determined from the measurement of flux in 13 tests agree with those derived from the New York City sulfur dioxide emission inventory within limits which have been considered acceptable for use in air pollution modeling.

1. Introduction

A numerical physical model for describing diffusion and transport of pollutants requires two essential types of input: 1) the prevailing wind velocity vector and turbulence characteristics, and 2) source emission inventory. Models for dispersion can be formulated to predict the diurnal and hourly ground-level concentration, provided these parameters can be made available on the time and space scale required.

Turner (1964), in an investigation of diffusion from multiple urban sources, indicated a need for detailed information concerning the temporal variation of the source emission on an hourly basis. Simon (1964) estimated the diurnal and seasonal emission patterns in New York by calculating the SO_2 flux through a ground-based monitoring station. A detailed annual source emission inventory for the New York metropolitan area was prepared by Simon *et al.* (1965). The seasonal fuel usage in New York City was obtained from an analysis of detailed fuel consumption records at large apartment complexes, as well as the monthly delivery records of a large number of dwellings of various sizes. As a sequel to this work, Simon designed a program to investigate the diurnal and day-to-day variation of SO_2 sources in the New York City area. The diurnal SO_2 emission rates for residential sources during the period 1964–68 were determined by recording on-off patterns of boilers in a number of "typical" apartment houses. The daily temperature-dependent emission rates were determined by correlating the total on-time of boilers during each day with its degree-day value. The findings were similar to those of Turner (1968) who investigated the diurnal and day-to-day variations of fuel usage from space heating using utility records in St. Louis, Mo. Based on the data obtained from the New York study, diurnal and daily SO_2 emissions from residential sources could be calculated for the entire metropolitan area. Emission rates were found to vary linearly with temperature change.

This paper describes a method of validating these empirical estimates of emission rates by comparing them to measurements of the vertically integrated SO_2 flux using a mass conservation approach. In this study, fluxes of SO_2 are calculated from SO_2 concentration measurements taken by an instrumented helicopter and by wind measurements obtained from pibal and low-level radiosonde observations. A kinematic box model based on mass conservation is used to demonstrate a mass balance of SO_2 and to verify the hourly emission rates.

[1] Part of the research presented in this paper was done while the authors were at the Department of Meteorology and Oceanography, New York University.

2. The SO_2 flux model

For a bounded volume in space, the time rate of change of SO_2 within that volume can be written as

$$\frac{\partial C}{\partial t}=\mathbf{V}\cdot\nabla C+S, \tag{1}$$

where S is the sink or source per unit volume, C the concentration of SO_2 expressed as a mixing ratio, and $\mathbf{V}$ the three-dimensional velocity vector.

In this experiment we have assumed that no significant natural SO_2 sources exist. Furthermore, we have assumed that no SO_2 formation occurred as a result of chemical reaction, desorption, or any physical process.

In recent studies of SO_2 decay in the atmosphere, the major sink of SO_2 has been attributed to catalytic conversion of the gas to a sulfate upon adsorption on ambient aerosols. Gatrelle (1960) indicated, on the basis of atmospheric studies in ambient air, that an exponential decay of SO_2 with a half-life of 4–6 hr may be postulated. This decay was attributable to chemical reactions involving SO_2, physical adsorption of surfaces, and removal from ambient air by atmospheric processes. Recently, Weber (1970) used ratios of CO_2 and SO_2 concentrations measured at stack and ground levels in Frankfurt am Main to derive SO_2 decay rates. His results were found to be in good agreement with those of Gatrelle.

On the basis of these findings we are assuming that the source or sink term S has a zero value. Since the air quality observations used in our study were made within time intervals $\leqslant 1$ hr and spanning distances up to 10 km, we can assume that the sink term may be neglected.

If we now integrate Eq. (1) using a coordinate system which is fixed with respect to the earth's surface, assume the steady-state condition and employ the divergence theorem, the conservation statement becomes

$$\int\int_{\sigma} C\mathbf{V}\cdot\mathbf{n}\,d\sigma=0, \tag{2}$$

where σ denotes the closed surface bounding a volume, and $\mathbf{n}$ the unit vector directed outward to the surface.

The upper and lower surfaces of our region are assumed to be horizontal. We designate the vertical surface area as A_v and the upper and lower surfaces as A_h. With this convention, we may write Eq. (2) in the form

$$\int_{A_v}(C\mathbf{V}_h\cdot\mathbf{n})d\sigma+\int_{A_h}(Cw)_z d\sigma-\int_{A_h}(Cw)_{z_0}d\sigma, \tag{3}$$

where w is the vertical velocity component.

We have further assumed that: 1) diffusion in the upwind direction is small, 2) the height of the upper horizontal area where the SO_2 concentration approaches zero is denoted by z, 3) the height of the lowest boundary z_0 is 25 m, and 4) $\mathbf{V}_h$ is the two-dimensional horizontal velocity vector.

On the basis of assumption 2) the flux at the top of the layer is zero and the second term of Eq. (3) is by definition zero. Thus, Eq. (3) can be written as

$$\int_{A_v}(C\mathbf{V}_h\cdot\mathbf{n})d\sigma\approx\int_{A_h}(Cw)_{z_0}d\sigma\equiv QA_h, \tag{4}$$

where the left-hand integral represents the horizontal flux through a vertical wall of area A_v, and Q is the upward flux produced by ground-based emissions. An integral formulation similar to this was employed by Fleagle *et al.* (1967) to calculate horizontal flux of water vapor for small areas of the Indian Ocean.

This model based on mass-balance considerations is the vehicle we have used to verify an SO_2 emission inventory in the New York City metropolitan area. Its proper application requires the use of detailed observations of the wind field and ambient SO_2 distribution.

3. Experimental procedure and data

Measurements of time and space variations in SO_2 concentration distributions used in this study were obtained by use of an instrumented helicopter. Its use has been discussed by Simon and Proudfit (1967).[2] They found that reliable crosswind measurements of concentration distributions in power plant plumes could be obtained by multi-level horizontal traverses of the aircraft. A second method, the vertical sounding, was also employed to determine the vertical variation of SO_2 in plumes or in the ambient atmosphere at a particular location. The SO_2 measurements were made by using a conductivity analyzer without compensation for variable CO_2 interference. However, it was deduced that variations in CO_2 interference generally would account for less that 5% error even at the low values of the vertically integrated flux.

In our experiments, the top of a sounding was considered to be the height at which SO_2 could no longer be detected. The time between consecutive SO_2 soundings rarely exceeded 12 min. In order to obtain a quasi-synoptic picture of the SO_2 distribution, the time interval between the first and last sounding for each test case was generally less than 1 hr.

Test cases were chosen in which vertical wind direction shear was small. To evaluate the flux integral of SO_2 [Eq. (4)], concentrations of SO_2 were obtained at a number of helicopter sounding locations (Fig. 1). These measurements were averaged over height inter-

[2] Simon, C., and E. Proudfit, 1967: Some observations of plume rise and plume concentration distributions over New York City. Paper presented at 60th Annual Meeting, Air Pollution Control Assoc.

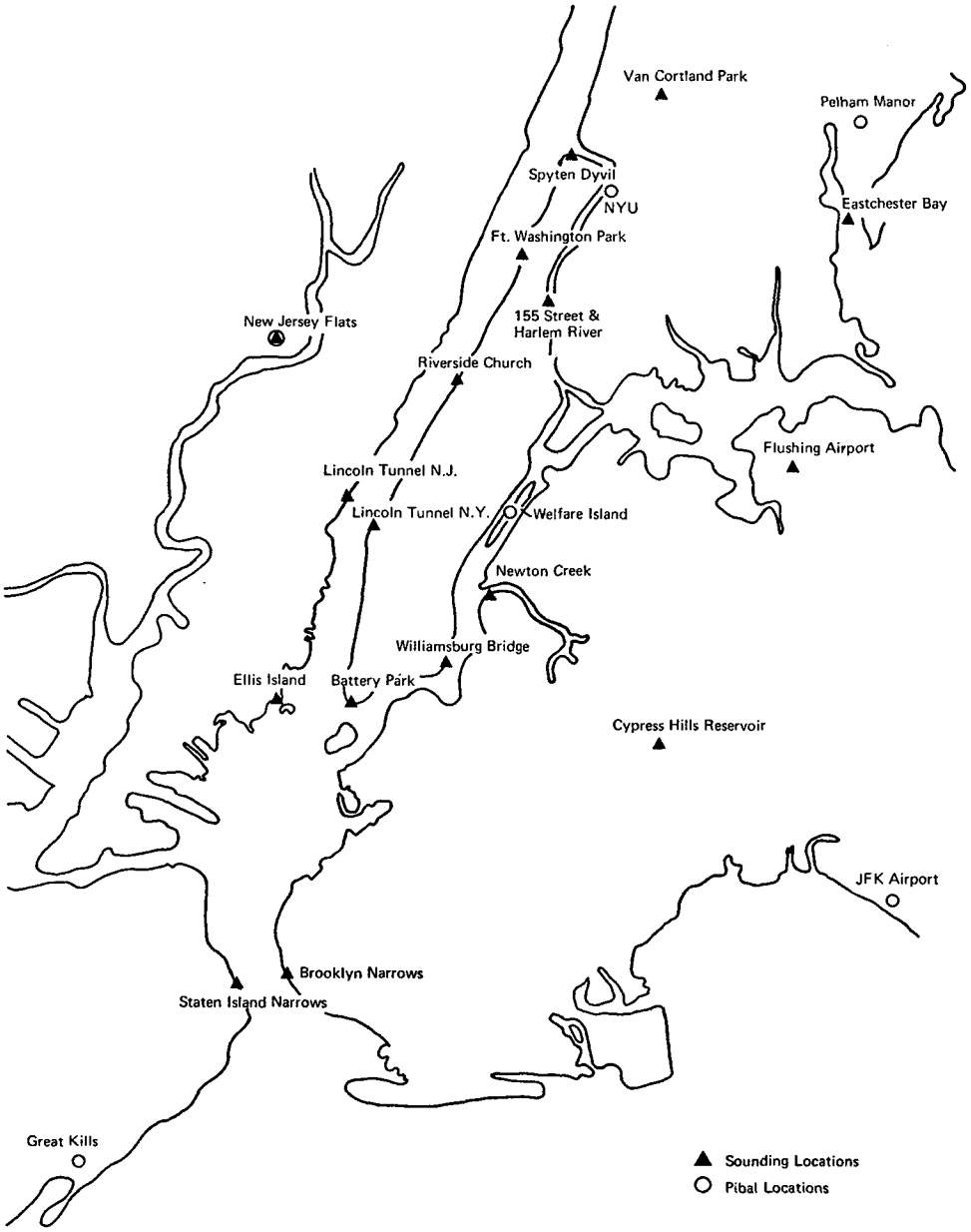

FIG. 1. The distribution of sounding and pibal locations in the New York City area used during the test cases.

vals of 50 m starting from local ground. (These intervals were centered at 25 m above local ground and at 50 m intervals above this level.) The horizontal distribution of SO_2 at each elevation was obtained by interpolation between these measurements. Vertical wind profiles for these tests were obtained by use of pilot balloon observations. For each observation two balloons were launched at each operating station (Fig. 1) every 2 hr. In addition, the surface wind field was obtained from data collected by a mesoscale anemometer network. The wind velocity was averaged over the same vertical interval as the concentration data. Starting from 25 m above the ground, streamflow and isotach analyses were made for every 50 m interval.

Vertical integration was accomplished by projecting the source areas onto each of the equally spaced horizontal computational levels. At each level, the SO_2 concentration and wind speed were horizontally averaged every 2 km along the upwind and downwind boundaries of the area.

The daily and hourly emission rates of the sources used to compute the right side of Eq. (4) were obtained from the annual SO_2 emissions inventory. These annual residential SO_2 emission rates per square mile for the

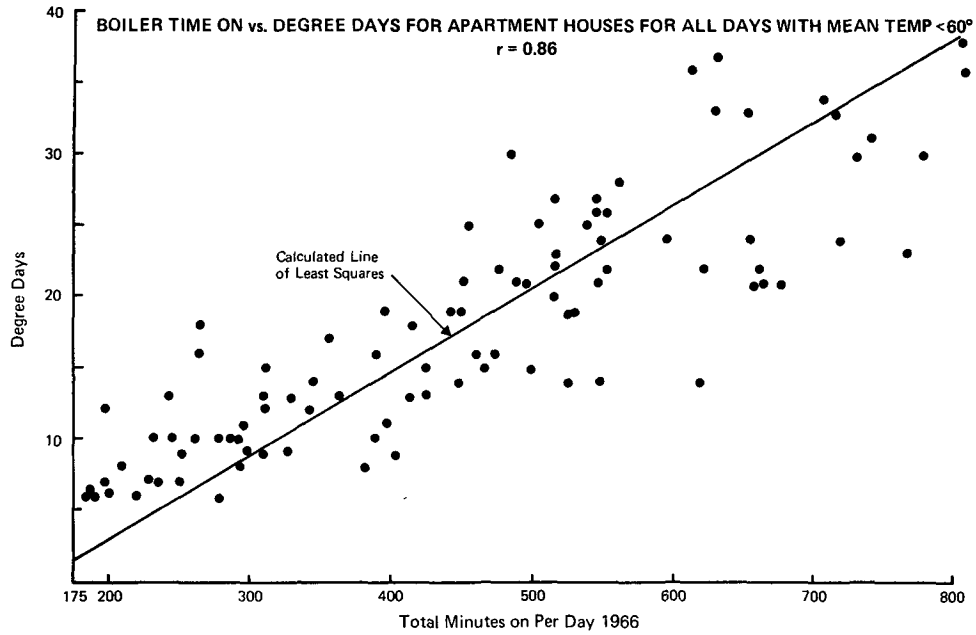

FIG. 2. Boiler operating time for apartment houses vs degree days as observed in New York City area for 1966.

New York City area have been reported by Davidson (1967).

Hourly power plant emissions for each test period were obtained from utilities. The manufacturing and industrial emissions were estimated from annual emissions data and spread uniformly throughout an 8-hr day, 5-day week and a 50-week year. Hospitals, schools and other institutions were treated as residential emitters.

The estimated residential emissions per square mile per year for those sources contained in the area chosen for flux calculations were totaled and multiplied by appropriate factors to give daily and hourly rates. The daily residential SO_2 emission rates for New York City have been determined by Simon *et al.* (1965). They found a reasonably good fit using a linear relationship between daily residential SO_2 emission rates and degree days, although some wind speed dependence was demonstrated. This relationship was given by

$$Q_d = \left(\frac{0.7TT}{4871} + \frac{0.3}{365}\right) Q_y, \tag{5}$$

where Q_d is the daily emission, Q_y the yearly emission, and TT the number of degree days.

The duration of hourly operation times for apartment house boilers using fuel oil was used to evaluate the hourly residential emission rates. The total boiler operating time for each day was correlated with the degree days for that day. Using a least-square fit, we have obtained a linear dependence between degree days and total operation time per day (Fig. 2); the correlation coefficient r is 0.86. This relationship is

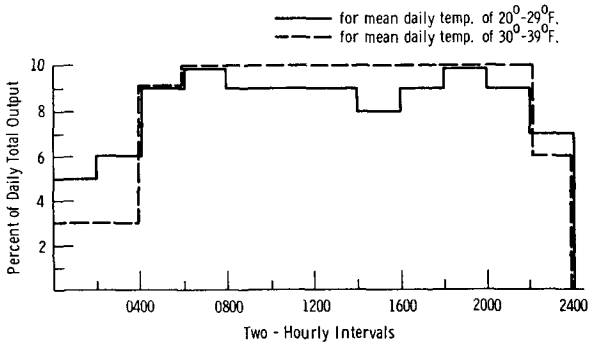

FIG. 3. Diurnal variation of the percentage of SO_2 output from an area source on a 2-hr basis as a function of mean daily temperature (20–39F).

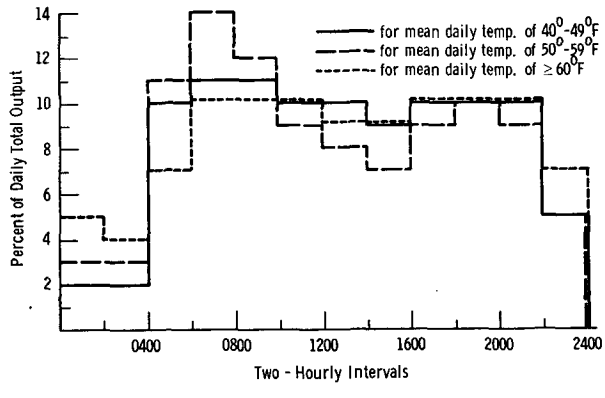

FIG. 4. Diurnal variation of the percentage of SO_2 output from an area source on a 2-hr basis as a function of mean daily temperature (40–65F).

given by

$$t=17.2TT+192.0, \quad (6)$$

where t is the total operation time of the boiler in minutes. Space heating boilers receive fuel oil at a preset constant rate when in operation. A knowledge of the "on-time" of a boiler and the sulfur content of the fuel is generally sufficient to describe the rate of SO_2 production. Using these data, daily emissions for 1966 based on degree days were found to closely follow Eq. (5). Hourly emission rates were found to be dependent on the mean daily temperature as shown in Figs. 3 and 4. These rates were used by Shieh (1969) in conjunction with a multiple-source diffusion model.

For the test cases described below, daily emission percentages were obtained by using Eq. (5) and the hourly emissions estimated from the diurnal curves. The industrial and utility emission rates were added to these modified residential rates permitting the computation of the right side of Eq. (4).

4. Presentation of results

There were 13 tests for which flux calculations were obtained. We will discuss in detail four of the most interesting tests.

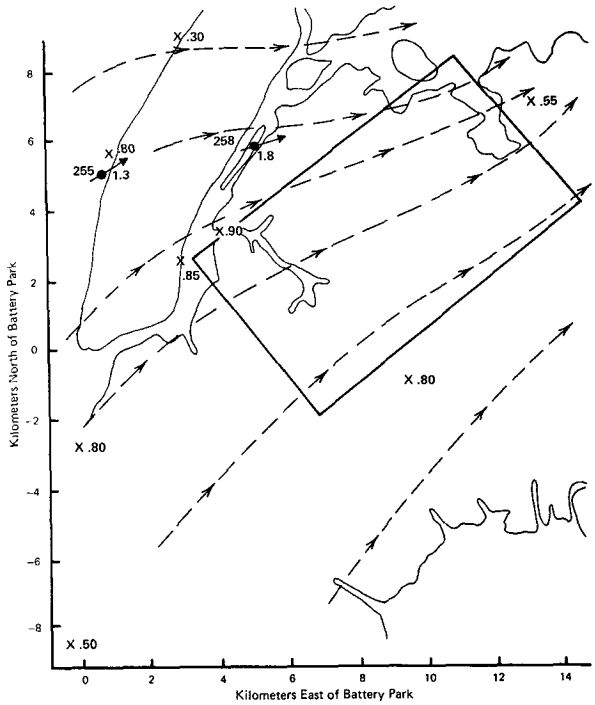

FIG. 5. Wind speed (m sec^{-1}) and direction (deg) as observed by the anemometer network and the 25 m averaged SO_2 concentration (ppm) on 3 May 1966 at 0540–0640 EST.

TABLE 1. Sulphur dioxide source emission and integrated net flux data (kg hr$^{-1}\times 10^4$) for the 13 tests.

Case	Test	Date	Time (EST)	Integrated net flux	Source emission data Residential	Utilities	Mfg.	Total	R^*
I	a	5/ 3/66	0540–0640	20.2	6.1 41%	6.7 44%	2.3 15%	15.1	74.7%
	b	5/ 3/66	0745–0845	36.6	15.7 45%	19.0 55%	>10² <1%	34.7	94.8%
	c	5/ 3/66	1745–1845	26.1	7.0 36%	12.6 64%	>10² <1%	19.6	75.0%
II	a	5/ 4/66	0600–0700	240.0	68.8 42%	90.0 54%	6.0 4%	164.8	68.6%
	b	5/ 4/66	0800–0900	219 3	62.6 39%	90.0 57%	6.0 4%	158.6	72.3%
III	a	5/ 5/66	0800–0900	98.1	20.8 32%	43.0 67.0%	0.2 <1%	64.0	65.2%
	b	5/ 5/66	1000–1100	108.6	15.1 20%	60.1 79%	0.6 1%	75.8	69.8%
IV	a	11/15/66	0600–0700	40.4	9.8 27%	25.4 71%	0.8 2%	36.0	89.1%
	b	11/15/66	1300–1400	129.7	37.8 39%	58.1 60%	1.6 1%	97.5	75.1%
V	a	11/16/66	0900–1000	262.3	119.9 46.0%	130.9 50%	10.1 4%	260.9	99.4%
VI	a	11/17/66	0700–0800	117.9	19.2 21%	69.3 77%	1.3 2%	89.8	76.1%
	b	11/17/66	0900–1000	110.8	26.4 27%	71.0 72%	1.8 1%	99.2	89.5%
	c	11/17/66	1200–1300	82.8	17.9 32%	35.9 64%	2.1 4%	55.9	67.5%

R^*=Total emission data/net flux.

a. 0540–0640 EST 3 May 1966

Fig. 5 shows the horizontal source area for which the SO_2 emission rates were compared to the vertically integrated SO_2. The test area was in Queens, oriented SSW–NNE approximately parallel to the streamflow lines as analyzed from the anemometer network. The wind speed range in the area was 1.3–1.8 m sec^{-1}.

The test area was composed of three major types of SO_2 emitters: residential dwellings, limited light manufacturing facilities, and utility plants. As can be seen in Table 1, which gives the source emission data and integrated flux data, the utility emissions were almost equal to those of the residential dwellings. Manufacturing and other industrial emissions comprised only 15% of the total emissions. This represents their high for all the tests.

The maximum SO_2 concentration observed at the 25 m level was in the Newton Creek area of Queens. Fig. 6a shows the vertical variation of the integrated flux along the upwind and downwind sides of the test area. The peak flux upwind and downwind was found to occur at 275 m and the flux decreased to zero at 425 m. The peak net flux was between 225 and 275 m.

In Fig. 6b, we note that the temperature soundings in the vicinity of the upwind vertical area at Cypress Hills, Queens, contained an isothermal layer from 125 to 225 m and an inversion layer from 225 to 325 m.

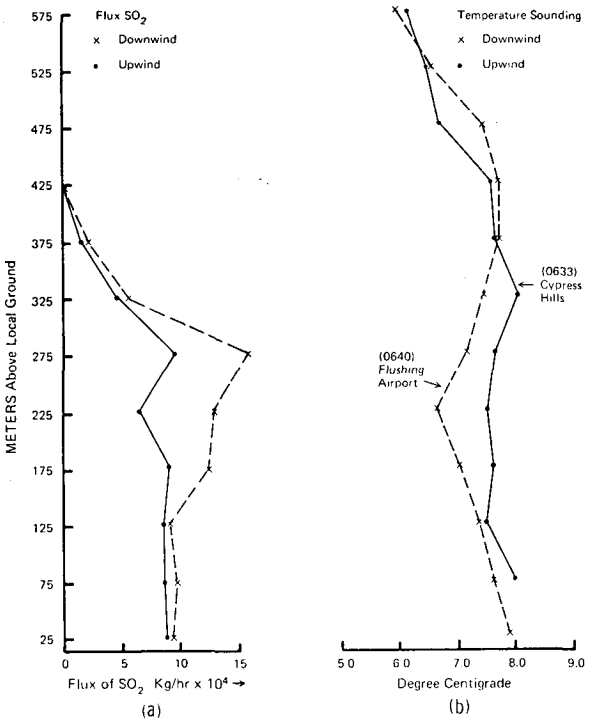

FIG. 6. Vertical variation of the horizontally integrated flux (kg hr^{-1}) of SO_2 upwind and downwind of the test area on 3 May 1966 at 0540–0640 EST (a), and representative temperature soundings in the upwind and downwind vicinity of the test area (b).

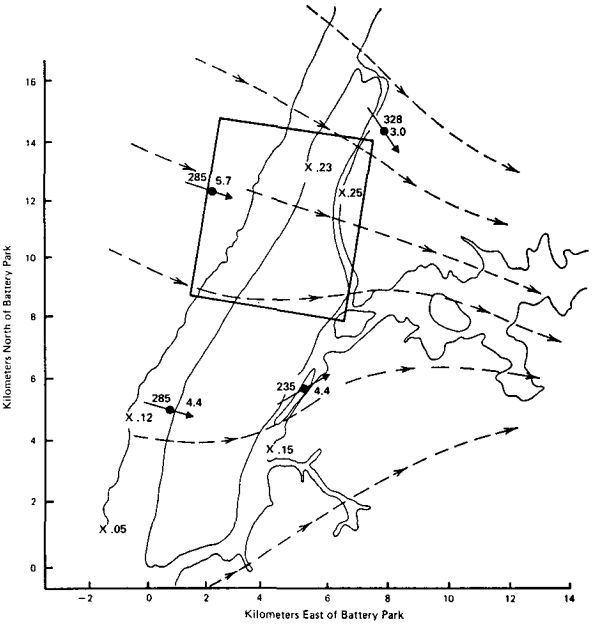

FIG. 7. Same as Fig. 5 except for 3 May 1966 at 1745–1845 EST.

Above 325 m a lapse condition prevailed. At a downwind station, Flushing Airport, the inversion layer extended from 225–375 m. The SO_2 was mainly confined below the base of the inversion, resulting in the occurrence of the peak flux and net flux between 225 and 275 m.

b. 1745–1845 EST 3 May 1966

The test was the only late afternoon experiment and was, therefore, of great interest. The wind direction (Fig. 7) had changed, shifting to NW and veering slightly with height. The test area covered 60% of the 0540–0640 test and included sources similar to those discussed in the previous example. The source emission data confirmed this observation. The residential and industrial emissions for this case were similar to those in the 0540–0640 test (see Table 1). However, the public utility emissions had almost doubled and this was reflected in the increase of the total emissions.

The wind speed in the area decreased slightly compared to the 0540–0640 test. The maximum SO_2 concentration at the 25 m level was at the same location as the 0745–0845 test (see Table 1), but decreased in magnitude from 0.55 to 0.25 ppm. This was reflected in Fig. 8a which shows the vertical variation of the calculated flux. Both the upwind and downwind fluxes increased to a maximum at 275 m and decreased to zero at 425 m. The net flux showed an unusually uniform distribution between 175 and 375 m.

The temperature sounding at Fort Washington Park on the west side of Manhattan (Fig. 8b) showed a temperature inversion between 125 and 225 m. An isothermal layer was present between 225 and 375 m.

The temperature sounding at the Harlem River and 155 Street on the east side of Manhattan showed one inversion layer between 125 and 225 m and an isothermal layer between 275 and 325 m. The major portion of the emissions were trapped between 125 and 375 m.

Again, one could interpret the flux below the inversion as due primarily to residential area sources. The net flux above the inversion could be a result of point sources which either were released above or punched through the relatively low-based inversion.

The temperature soundings taken during these tests gave some insight into the height variation of the local inversion across the urban area. In the 0745–0845 test, the urban sounding at 155th Street showed the inversion base to be 150 m higher than the rural sounding in the New Jersey Flats. This would suggest that the urban atmosphere was well mixed to a greater height over the central city than over the edges. This was also observed by Bornstein (1968). The greater height of the mixing depth resulted in the presence of SO_2 flux at greater heights over the central city. The vertical gradient of flux was therefore correspondingly reduced.

c. 0900–1000 EST 16 November 1968

As seen in Fig. 9, this is the only test case in which the prevailing wind direction was southeast. During this test a high pressure center was southeast of the city, causing SE flow over the metropolitan area. The 25 m SO_2 concentration maximum was on the west side of Manhattan at Fort Washington Park. The concentration was 0.55 ppm compared to a trace value found on the previous day. Similarly, the 25 m concentration at Battery Park showed an increase from 0.17 to 0.35 ppm. The wind speed range was 1.3–2.0 m sec^{-1}. This decrease in wind speed and the reversal of wind direction were in part responsible for the increase in the concentrations. The time of day was also a contributing factor.

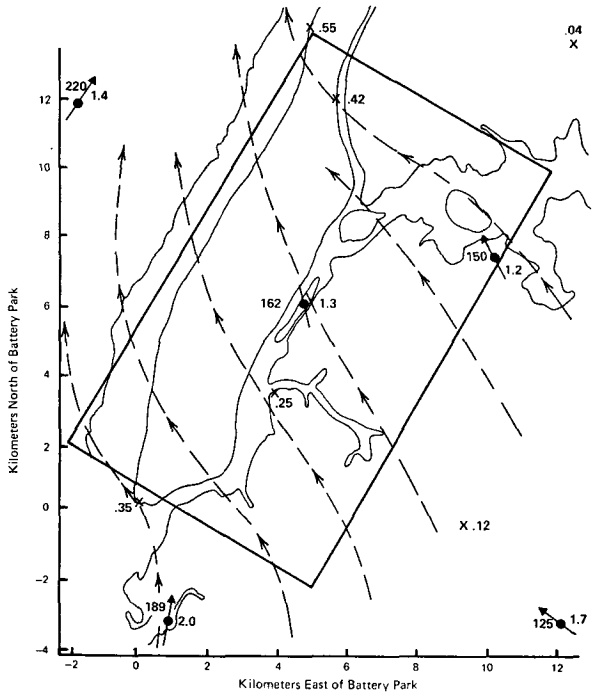

FIG. 9. Same as Fig. 5 except for 16 November 1966 at 0900–1000 EST.

Table 1 shows that the total emissions for the test represented the maximum for all test cases considered. This was primarily a consequence of the area source which included most of Manhattan, south Bronx, west Queens and southeast Brooklyn. These are areas of extremely high annual emissions.

The vertical variation of the net flux is shown in Fig. 10a. The unusually high elevations at which the maximum flux occurs seem to be due to high-rising plumes which exhibit rapid rates of vertical spread as they travel over Manhattan.

The temperature sounding at Eastchester Bay in the Bronx (Fig. 10b) was taken on the upwind edge of the area and showed an inversion layer between 325 and 475 m. This inversion was also present, but with reduced intensity, downwind at Fort Washington Park. The base of the inversion here was at 425 m. We note that the base of the urban inversion was at a greater elevation in the core of the city than in the outlying regions.

The upwind flux was uniformly distributed from 225–575 m. The low-level maxima were primarily due to area sources. A consequence of the prevailing SE

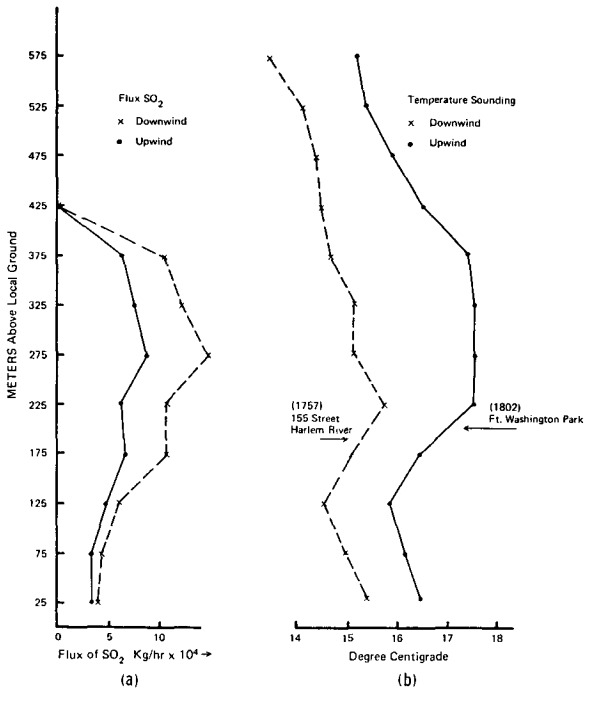

FIG. 8. Same as Fig. 6 except for 3 May 1966 at 1745–1845 EST.

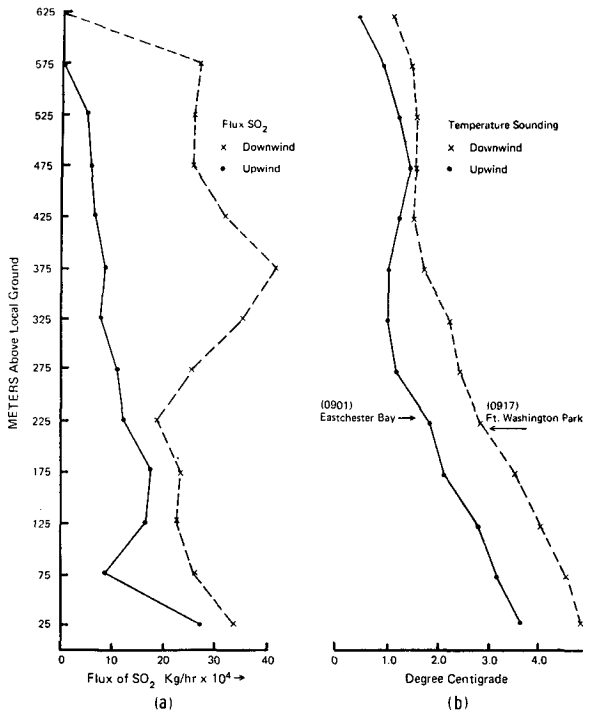

FIG. 10. Same as Fig. 6 except for 16 November 1966 at 0900–1000 EST.

winds blowing off Jamaica Bay was the absence of sources from this area capable of producing upper level plumes. However, in the downwind portion of this area, the flux maxima at 375 and 575 m were unusually high reflecting the concentrations found in plumes from point sources near the downwind wall. These had either failed or barely managed to penetrate the weak downwind inversion. As a result of this, a significant amount of SO_2 flux was present at the unusually high elevation of 575 m.

d. 0900–1000 EST 17 November 1966

On this day the high pressure center was located off the Atlantic Coast. The New York City area was under the influence of a SW flow at 25 m. A cold front moved in behind the high and dominated the area. Below the base of the inversion was a well-mixed atmospheric column. The wind direction remained essentially constant throughout the day and enabled a similar area source to be used for all the tests run during this case.

Fig. 11 shows the 25 m streamflow isopleths and the SO_2 concentration distribution 1 hr later. The prevailing wind was from the southwest and the speed in the source area varied between 2.2 and 4.5 m sec^{-1}. The 25 m SO_2 concentration peak remained at 0.80 ppm at 155th Street and Harlem River.

The emissions estimated this hour were comparable with those estimated for the preceding test. This was not unexpected since both tests occurred within an hour of each other and the source areas were nearly identical. In fact, the utility emissions (Table 1) decreased by 5%, residential emissions increased by 6%, and manufacturing emissions decreased by less than 1%.

Fig. 12a indicates that a rapid vertical decrease in the flux with height occurred at both upwind and downwind locations above the 325 m elevation. The distribution of net flux appeared to be uniform below down to 125 m.

The temperature sounding at the upwind station, Battery Park (Fig. 12b), showed the inversion layer extending from 425–575 m. The downwind station at 155th Street and Harlem River also indicated the inversion between 425–575 m. The uniform net flux distribution below 325 m was an outcome of the steep temperature gradient present from 25 to 325 m.

5. Discussion of results

For the 13 tests described in Table 1 the vertically integrated SO_2 flux was greater than the flux estimated from the emissions inventory.

Table 1 also shows that the mass balance of SO_2 has been verified by comparing calculated SO_2 flux to source emission data. The details of the source emissions indicate that the power plant emissions exceeded the residential emissions in all 13 tests. The manufacturing

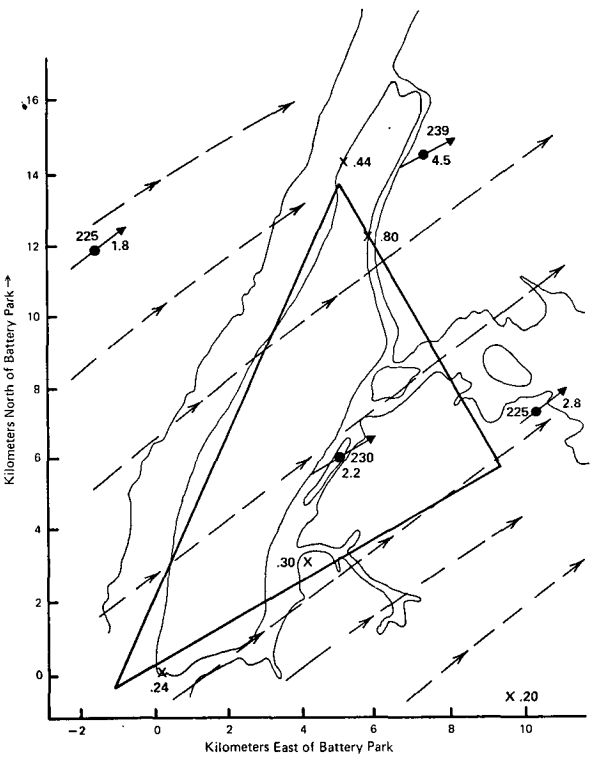

FIG. 11. Same as Fig. 5 except for 17 November 1966 at 0900–1000 EST.

emissions were never greater than 4% of the total emissions for any of the test hours.

The average value of the ratio of source emission flux to the vertically integrated flux was 0.74 for the May tests and 0.83 for the November tests. This would indicate that the source emission estimates were more responsive to the degree-days dependence in the colder November tests than in the warmer May tests. The average value for this ratio for all the tests was 0.78.

A portion of the inventory deficit might be attributed to an underestimate in actual emissions, judged to be the order of 5–10%. This was caused by personal errors in the compilation of the data. The remainder of the deficit is most likely due to the influx of SO_2 through the sides of the box under the influence of a non-uniform flow pattern in the crosswind direction.

The vertical stratification of the SO_2 flux was generally insensitive to small changes in the distribution of temperature and wind in the urban atmosphere below the level of the urban inversion. This appeared to be a direct consequence of the extent to which dynamic effects of the urban area affected the dispersion of pollutants. The base of the temperature inversion over New York City when present was always elevated. The depth of the urban mixing layer (defined by the elevation of the lowest urban temperature inversion) was a function of the sounding location and time of day. It was higher within the interior of the city than in the semi-rural areas. It was also a function of the time of day, that is, lowest in the early morning and increasing in height in the late morning. Its spatial and temporal variations affected the height distribution of the SO_2 flux since the peak flux usually occurred just below the base of the inversion. When no inversion was present, for example, SO_2 was found at greater heights over the urban center than over the outlying areas. The vertical flux gradient was correspondingly less in the urban center.

The relatively small vertical flux gradients found in the sub-inversion layer indicated, for short travel times, that diffusion rates in this urban area were extremely high and significantly greater than those found over rural areas. This anomaly was produced by the intensity of low-level turbulence found over cities as a consequence of their increased surface roughness and the general absence of high stability at low elevations.

The omission of SO_2 sinks resulting from chemical conversions and physical depletion appears to have relatively insignificant effects in this analysis. There probably is some permanent loss of material in the surface layer below the lower boundary of the flux box resulting of our selection of z_0 and the physical characteristics of the ground surfaces.

The steady-state assumption is technically valid only for long averaging time and strictly speaking should be used in conjunction with sink terms. Moreover, in an area which has such highly concentrated and intermittent point-source emissions as New York City, the steady-state assumption should be applied with care. In fact, higher resolution finite-differencing would be more appropriate in evaluating the flux integral, but this would require kinematic analysis of the wind and SO_2 fields on a finer grid basis. Such precision could not be achieved in this study since the frequency of observation was restricted because of the use of a single aircraft. In this application and particularly in areas with strong emission gradients, the use of multiple aircraft measurements would have been more appropriate. A commensurate increase in the density of the pibal network would have provided the basis for a more rigorous analysis.

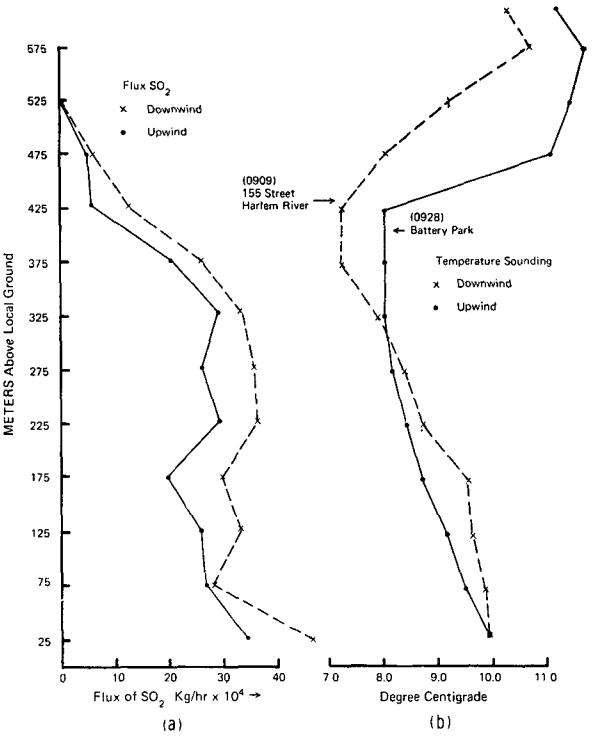

FIG. 12. Same as Fig. 6 except for 17 November 1966 at 0900–1000 EST.

6. Conclusions

The experiments carried out in this research have confirmed the hypothesis that a mass balance between SO_2 emissions and ambient SO_2 concentrations can be achieved by comparing the vertically integrated measured flux to the empirically derived mass emissions from a complex of sources.

The 13 test cases reported here demonstrate that a determination of vertical and horizontal fluxes of atmospheric pollutants can be used to provide a very useful and critical validation tool for multi-source diffusion models. Of particular importance is the implicit need for those engaged in modeling to include fluxes of

pollutants across the boundaries of their domains. It has been demonstrated, in the absence of a reliable or updated inventory, that flux observations obtained from multiple soundings and traverses can be used to determine the magnitude and distribution of surface and elevated emissions. When flux determinations have been made throughout the day, they can be used to determine diurnal variations in emissions. Flux considerations can be used to determine the height of the mixing layer and its diurnal variations. This type of analysis may, in turn, be used to obtain a measure of the diurnal growth of convection and dispersion for an urban area.

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