CONCENTRATION PROFILES OF ACIDIC AND BASIC AIR POLLUTANTS AROUND AN INDUSTRIAL PARK OF TAIWAN

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Abstract. The results of spatial and temporal distribution of acidic and basic air pollutants in ambient air around Hsinchu Science-Based Industrial Park (SBIP), Taiwan during August 2000 to October 2001 are presented. The sampling was performed on 13 different sites around the SBIP for 12 hrs each every month, and a total of 195 samples were collected. The effect of geographical and meteorological conditions, and production volume of the SBIP on the variation of pollutant's concentration was investigated. The spatial distribution shows that comparatively higher concentration of pollutants was found on the sites, which are either low in altitude such as the WS (west-southern) part of SBIP, in the downwind location or close to the factories. In case the wind velocity was low, i.e. below 2 m s^{-1}, the concentration of pollutant tended to increase and became uniformly distributed around the science park. The temporal distribution shows a decrease in ambient concentration of pollutants from February to June 2001, mainly due to the decline in the production volume of the SBIP in this period. During the whole period of investigation, the concentration of most of the species (except HF) was found to be lower than the factory-surrounding air quality standard of Taiwan, but in some cases it was higher than the AALG.

Keywords: air pollutants, inorganic acids and base, industrial park, spatial distribution, temporal distribution, meteorological and geographical effect

1. Introduction

Air pollution monitoring studies around an industrial area are important for developing emission control strategies, determining applicability of permitting and control programs, ascertaining the effects of sources and appropriate mitigation strategies, and a number of other related applications by the governments, local agencies, consultants and industries. Neves (1996) has reviewed the air quality at Camacari petrochemical complex area situated at Bahia, Brazil and brought to light the environmental problems of the industrial park and its area of influence. Gargava and Aggarwal (1996) have discussed the impact of industrial activities on the air environment in a coastal region of India, as a case study. Bizjak *et al.* (1996) have studied the air quality of surroundings of the Salnit industrial plant, Anhovo, Slovenia and concluded that the concentration of airborne inorganic fibers was reduced due to the partial replacement of asbestos with alternative materials.

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Gytarsky *et al.* (1995) studied the effect of industrial pollution on subarctic forest in Russia.

Many companies such as semiconductors, electronics and electrical peripherals etc., which are situated at the SBIP, use inorganic acidic (i.e. HF, HCl, HNO_3, H_2SO_4, H_3PO_4, etc.) and basic (NH_4OH) chemicals extensively in their manufacturing processes. The presence of these chemicals in the ambient environment may cause detrimental effects on the respiratory system. Spengler *et al.* (1990) has reviewed extensively the health effects, health evidence, concentration ranges, and epidemiological studies of acidic aerosols. This study is to investigate the level of acidic and basic air pollutants in the ambient air of the SBIP. The gases: HCl, HF, HNO_3, HNO_2, SO_2 and NH_3, and fine particulate species (aerodynamic diameter <2.5 μm): Cl^-, F^-, NO_3^-, NO_2^-, SO_4^{2-} and NH_4^+ were monitored at 13 different sites of the SBIP for 12 hrs each every month during August 2000 to October 2001, employing a previously developed personal porous metal denuder sampler (Tsai *et al.*, 2001). The spatial and temporal variation in concentration levels and the effect of geographical and meteorological conditions, and the production volume of the SBIP on it were studied and documented. The monitoring data were compared with the factory-surrounding air quality standard of Taiwan (Taiwan EPA, 1999) and Ambient Air Level Goal (AALG) (Calabrese and Kenyon, 1991). In addition, the pattern of the sampling data was compared with data calculated using the Industrial Source Complex Short Term3 (ISCST3) simulation model.

2. Material and Methods

2.1. THE SITE

The Hsinchu Science-Based Industrial Park was mainly developed after 1980. Now as of December 2001, a total of 312 hi-tech companies, which includes: integrated circuits (123), computer and peripherals (51), telecommunications (57), optoelectronics (51), precision machinery (11) and biotechnology (19) are operating in this park. Many of these companies, mainly integrated circuits related, use inorganic acids in their cleaning or etching processes, and an annual consumption of HCl, HF, HNO_3, H_2SO_4, H_3PO_4 and mixed acids (concentrated acids) of the semiconductor industry is reported to be about 1288, 2121, 427, 7135, 1125 and 1368 thousand liters respectively, in the year 2001. Companies use wet scrubbers to control the emission of these inorganic pollutants.

The city of Hsinchu, situated nearby to the northwest coast of Taiwan, covers an area of about 100 km^2. The population of the city is about 0.35 million (as of December 2001). The city is mainly known for the Science-Based Industrial Park (SBIP), which is located at the southern side of the city lying between 2739000 to 2743000 m latitude and 247000 to 252000 m longitudes (Figures 1 and 2). The northern side of the park surrounded by the urban area, i.e. residential colonies,

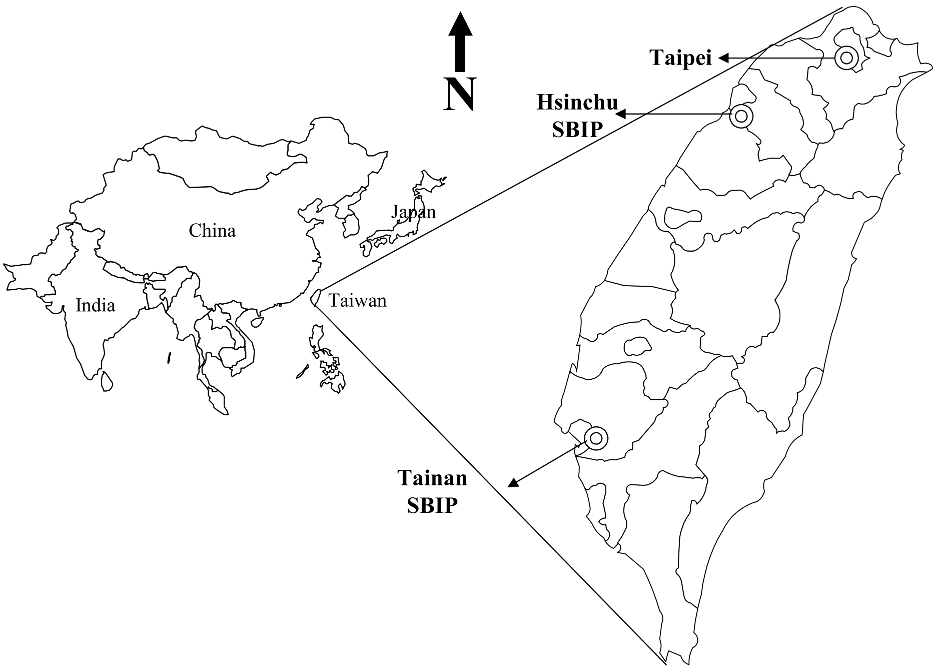


Figure 1. Location of the SBIP in Taiwan.

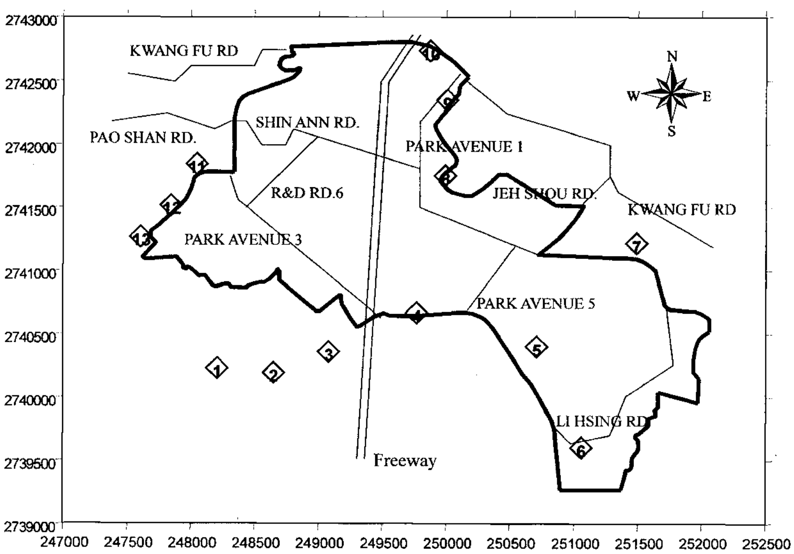


Figure 2. Sampling sites in the SBIP.

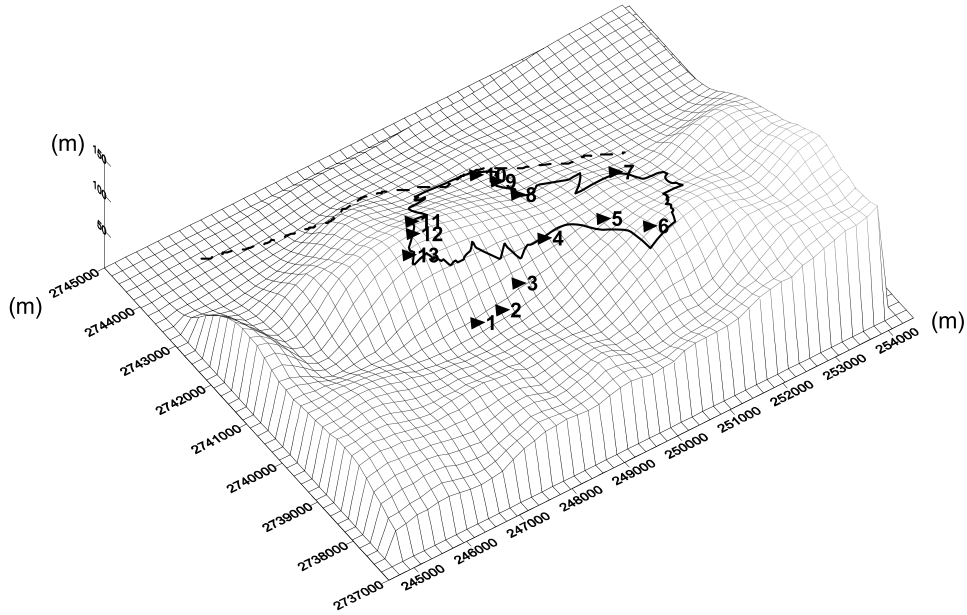


Figure 3. Altitude of the SBIP (UTM system).

commercial complexes and universities campuses, whereas the southern side of the park is mainly rural, agriculture farm, etc. The ambient aerosol samples were collected from 13 different sites (S1–S13) of the SBIP. The height of the SBIP from the sea level is about 50–120 m and is extended over an area of about 605 hectares. Altitude of each of the site of the SBIP is pictorially represented in Figure 3, where sites S1–S3 are shown to be lower in altitude than other sites and in the downwind direction of the prevailing NE (north-easterly) wind from September to April in Taiwan.

2.2. Sampling

Sampling was based on a previously developed porous metal denuder (Tsai *et al.*, 2001) containing a 1-stage impactor with 2.5-μm cutoff aerodynamic diameter, D_{P50}, to remove coarse particles, two porous metal discs (diameter: 4.7 cm, thickness: 0.23 cm and pore size: 100-μm) coated with 5%, (w/v) sodium carbonate and 4% (w/v) citric acid to absorb acidic and basic gases, respectively, and a three-stage filter pack (Figure 4). The filter pack consists of a 4.7 cm Teflon filter (Gelman Science, 2-μm) to collect fine particles, a 4.7 cm nylon filter (Gelman Science, 1-μm) to collect HNO_3 and HCl, and a 4.7 cm glass fiber filter (AP40, Millipore Inc.) coated with citric acid to collect NH_3 that volatilized from the collected particles on the Teflon filter. Particulate NO_3^- and Cl^- concentrations were determined as the sum of those collected on the Teflon filter and the nylon filter, respectively. The flow rate was maintained at 2 l min^{-1}. Samplers were placed at schools and

TABLE I

Meteorological data of the SBIP at the time of sampling

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sampling date	Aug. 2, 9:00 am – Aug. 2, 9:00 pm (2000)	Sep. 7, 9:00 am – Sep. 7, 9:00 pm (2000)	Oct. 5, 9:00 am – Oct. 5, 9:00 pm (2000)	Nov. 9, 9:00 am – Nov. 9, 9:00 pm (2000)	Dec. 27, 9:00 am – Dec. 27, 9:00 pm (2000)	Jan. 10, 8:00 am – Jan. 10, 8:00 pm (2001)	Feb. 16, 8:00 am – Feb. 16, 8:00 pm (2001)	Mar. 23, 9:00 am – Mar. 23, 9:00 pm (2001)	Apr. 19, 9:00 am – Apr. 19, 9:00 pm (2001)	May 24, 9:00 am – May 24, 9:00 pm (2001)	Jun. 7, 9:00 am – Jun. 7, 9:00 pm (2001)	July 31, 9:45 am – July 31, 9:45 pm (2001)	Aug. 23, 9:00 am – Aug. 23, 9:00 pm (2001)	Sep. 24, 1:00 pm – Sep. 25, 1:00 am (2001)	Oct. 18, 9:00 am – Oct. 18, 9:00 pm (2001)
Weather	Cloudy	Sunny	Sunny	Sunny	Sunny	Sunny & Cloudy	Sunny	Sunny & Cloudy	Sunny & Cloudy	Sunny	Sunny	Sunny	Cloudy	Cloudy	Sunny & Cloudy
Ave. Temp. (°C)	32	32	32	27	23	20	19	24	27	30	33	32	32	28	31
Ave. RH (%)	62	54	64	66	53	67	62	68	70	51	55	64	66	88	64
Ave. wind speed (m sec^{-1})	1.4	7.0	3.4	6.4	1.6	1.9	7.2	1.8	1.5	2.8	2.4	2.0	1.7	7.7	5.8
Wind direction	DT: R NT: R	DT: NE NT: NE	DT: NW NT: NW	DT: NE NT: NE	DT: NE NT: NE	DT: NE NT: NE	DT: NE NT: NE	DT: R NT: R	DT: NW NT: E	DT: R NT: SE	DT: W NT: R	DT: R NT: R	DT: R NT: R	DT: NE NT: NE	DT: NE NT: NE

DT: Day time (from 6:00 am to 6:00 pm); NT: Night time (from 6:00 pm to 6:00 am); R: Random wind direction

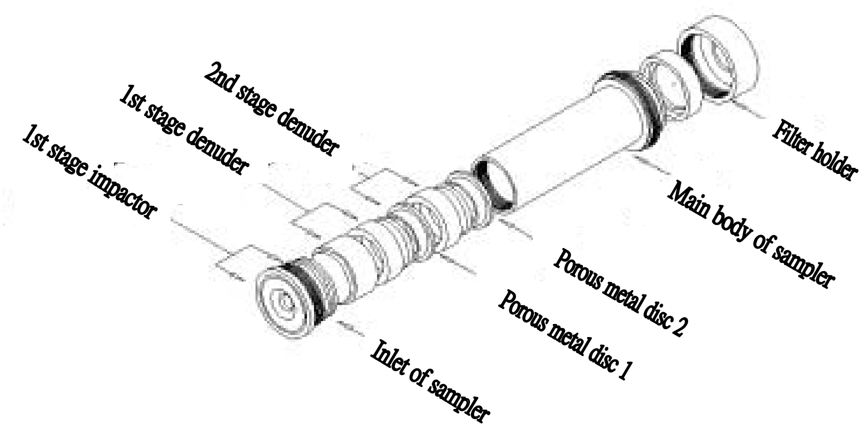


Figure 4. Schematic diagram of the personal denuder.

residential buildings at an average height of 1.5 to 2 m from the ground level. The sampling was performed simultaneously in all 13 sites around the SBIP once every month for a period of 12 hrs during the whole study period, i.e. August 2000 to October 2001. Sampling day and time, and meteorological data are given in Table I. Figure 5 shows the wind direction during the whole study period.

2.3. Analysis

After sampling, the denuder samplers were rapped in Parafilm and brought to the laboratory. In the laboratory the Teflon, nylon and glass fiber filters were extracted with 6 ml, whereas porous metal filters were extracted with 15 ml of de-ionized water, by an ultrasonic bath for 20 min and the samples were kept in a refrigerator, and subsequently analyzed by ion-chromatograph (model4500i, Dionex Corp.) within 24 hrs of sampling as described in earlier work (Tsai *et al.*, 2000). The QA/QC measurements (detection limit, recovery test, data reproducibility test, etc.) were carried out to ensure the accuracy and reliability of analysis. All chemicals used were of analytical grade reagent (Merck).

2.4. Calculation of simulation data

The Industrial Source Complex Short Term 3 (ISCST3) model employed by US-EPA (1987) was the tool, used for assessing air quality around the park. In this work, the simulated data obtained from the model were used to test the spatial distribution of the sampling data. The calculations of this model are based on source location, source emission data, and meteorological data. In this study, these

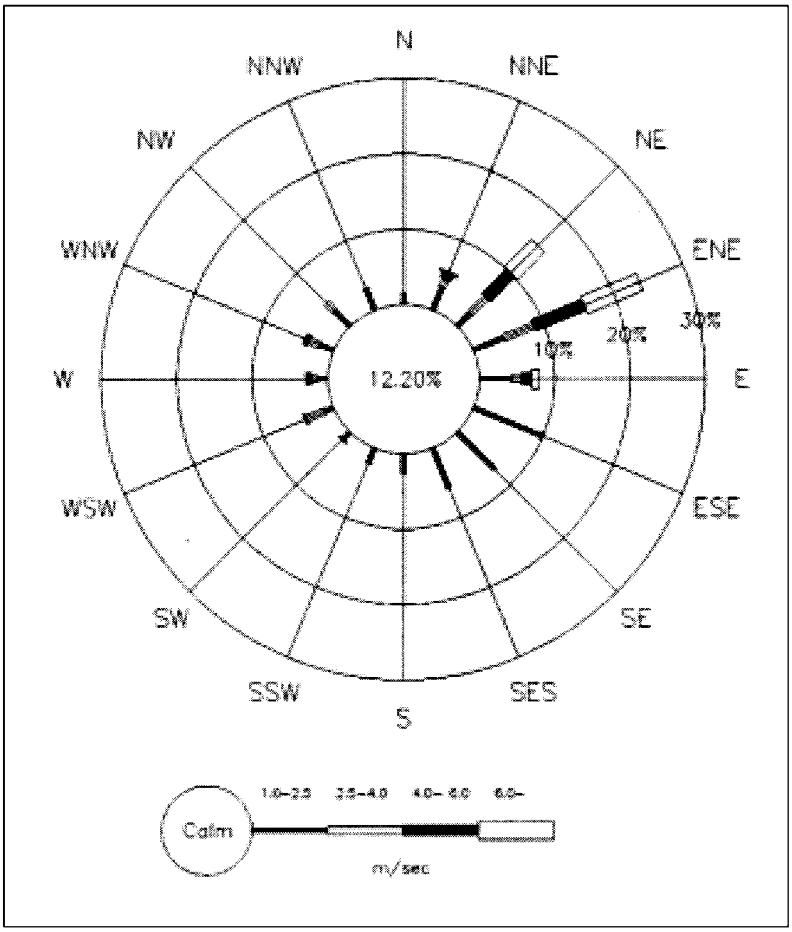


Figure 5. Wind-direction of the park during August 2000 to October 2001 (the data were collected from Hsinchu Environmental Bureau).

data were taken from company's air pollution permits. There is no attempt to obtain accurate simulation results since the ISCST model does not take into account the chemical reactions or depositions, and emission data of acidic and basic chemicals remain to be validated.

3. Results and Discussions

3.1. Spatial variation in average concentration of pollutants

A total of 195 samples for gases, i.e. HCl, HF, HNO_3, HNO_2, SO_2 and NH_3, and for fine particle species, i.e. Cl^-, F^-, NO_3^-, NO_2^-, SO_4^{2-} and NH_4^+ were collected from all 13 sites during the whole period of investigation. Wind speed was found

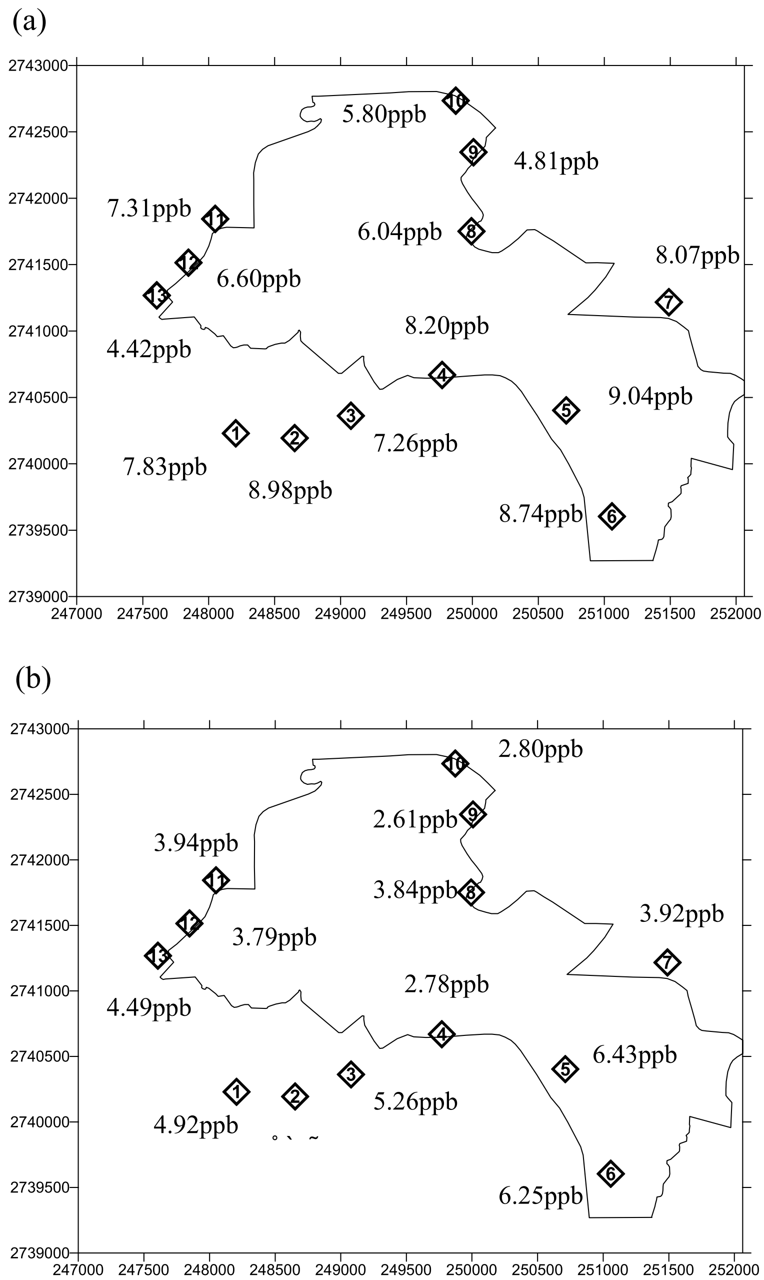


Figure 6. Concentrations of HF at 13 sites in (a) August 2001 (wind speed = 1.7 m sec^{-1}); (b) September 2001 (wind speed = 7.7 m sec^{-1}).

to affect significantly the concentration level of pollutants. Figures 6 (a), (b) and 7 (a), (b) show the influence of wind speeds recorded in two consecutive months August (comparatively low wind speed, 1.7 m sec^{-1}, and random wind direction) and September (comparatively high wind speed, 7.7 m sec^{-}, and North-Easterly wind) on the spatial variation in concentration of HF and SO_4^{2-}, respectively. The meteorological data shown in Table I, indicate the random nature of the wind direction in the low wind condition. In the low wind condition, the concentration of pollutants was higher and became uniformly distributed around the park. The prevailing wind in the NE and ENE direction from September to April is usually strong, Figure 5. Strong prevailing wind in the NE direction reduces pollutant concentrations and the downwind locations (sites S1-S6) usually had higher concentrations than the upwind sites.

The concentration of HF and SO_4^{2-} in all 13 sites was found to be 0.77 to 2.36 and 2.49 to 7.23 fold, respectively, higher in low wind condition (August, 2001) than the high wind condition (September, 2001).

3.2. Temporal variation in average concentration of pollutants

Figures 8 (a)–(e) show the temporal distribution of the pollutants measured at the 13 sites during August 2000 to October 2001. The concentration level of pollutants was found to be comparatively lower during February to June 2001 mainly due to the decline in production in this period. The production volume is directly related to the corporate sale of the SBIP. Thus to study the influence of production volume on the ambient concentration of pollutants, a graph between monthly variation in ambient concentration of the pollutant, and in the corporate sale (in million of US dollars) is also plotted, Figure 8 (a). The graph shows a good correlation between the corporate sale (or production volume) of the SBIP and ambient concentration of total F^-, which is unique and can be used as an index pollutant in the SBIP. The ratio of HF/(total F) was calculated for each month and was found to be around 0.98–0.99, which indicates that fluoride mainly existed as HF in air. There are no good correlations between the corporate sale and other pollutants.

The concentration of SO_4^{2-} was found to increase significantly in the month of August 2001, Figure 8(b), due to very low wind and moderate production volume in this month. However, during the other months of the study, its concentration was found to spatially uniform and low despite that H_2SO_4 is the maximum consumed acid of all acids in the park. This is mainly due to the low volatility of H_2SO_4 and assumed that its emission sources are regional rather than local sources. Similarly, the concentration of HNO_3 was found to be spatially uniform and low, except in the month of September 2000, Figure 8(c). Again suggesting regional sources for HNO_3.

The temporal variation in the concentration of HCl in sites S1-S3 and S11-S13 was the maximum as compared to other sites, Figure 8(d), which is due to the geographical factor and the influence of local sources is apparent. Figure 8(e)

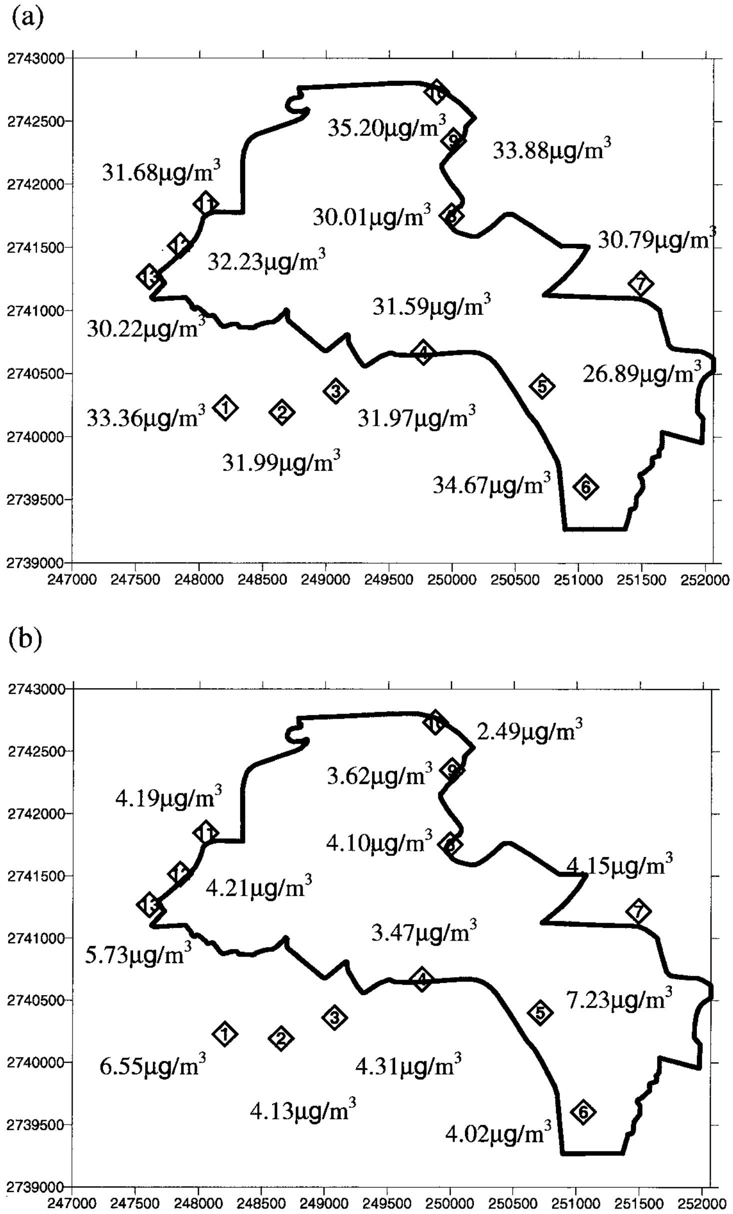
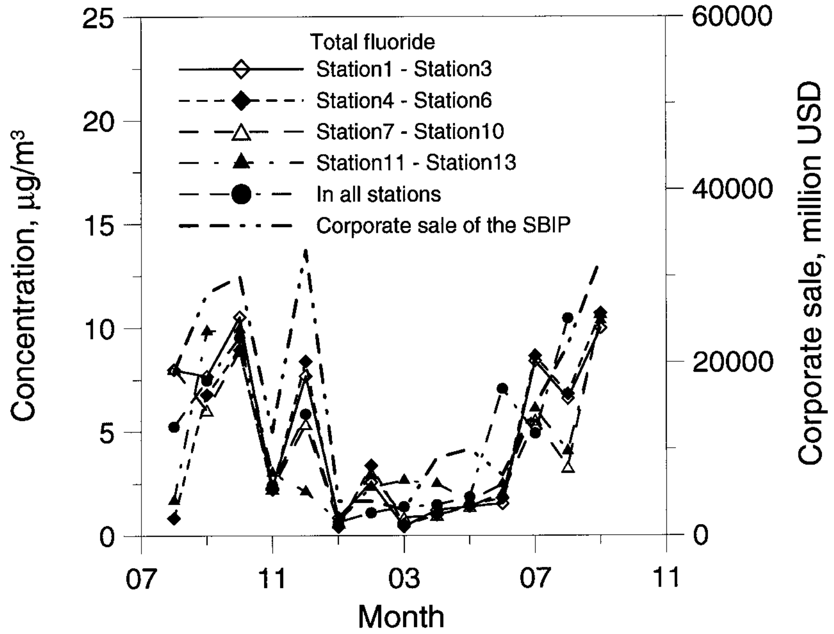


Figure 7. Concentrations of SO_4^{2-} at 13 sites in (a) August 2001 (wind speed = 1.7 m sec^{-1}) (b) September 2001 (wind speed = 7.7 m sec^{-1}).

(a)



(b)

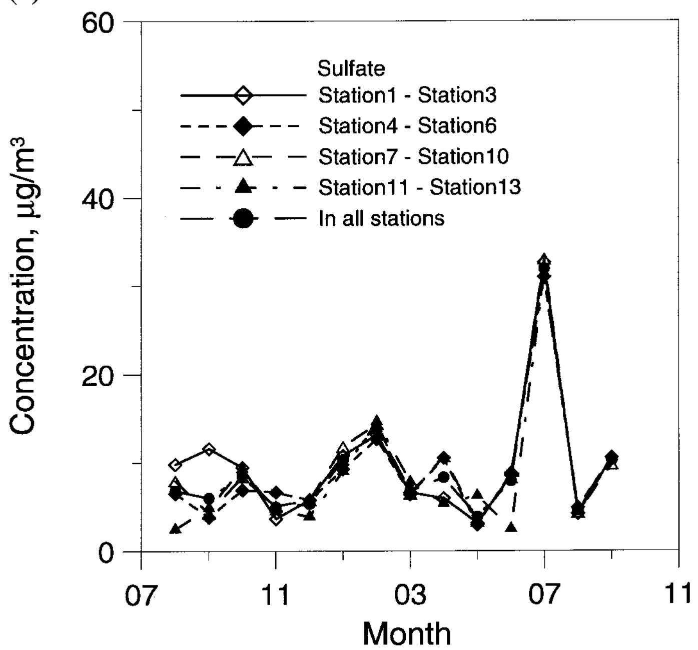
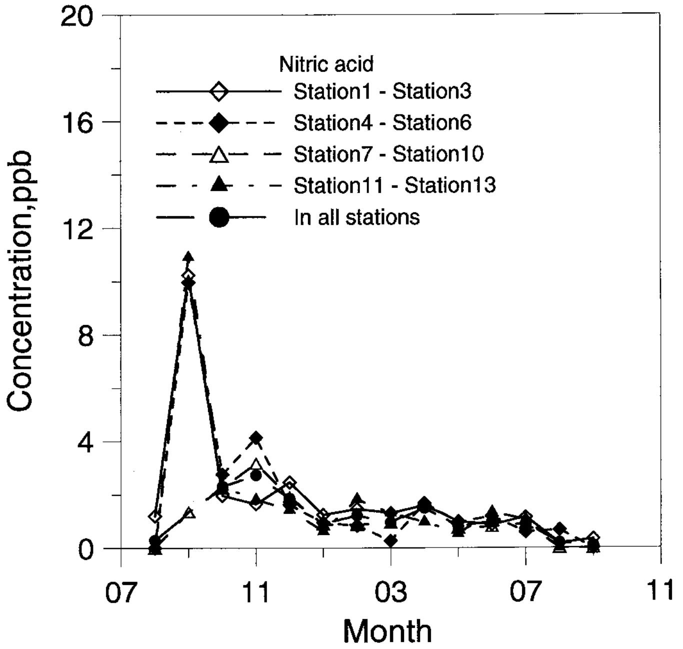


Figure 8. Monthly (from August 2000 to October 2001) variation in average concentration of (a) HF versus monthly corporate sale (in million USD) of the SBIP; (b) SO_4^{2-}; (c) HNO_3; (d) HCl; (e) NH_3.

(c)



(d)

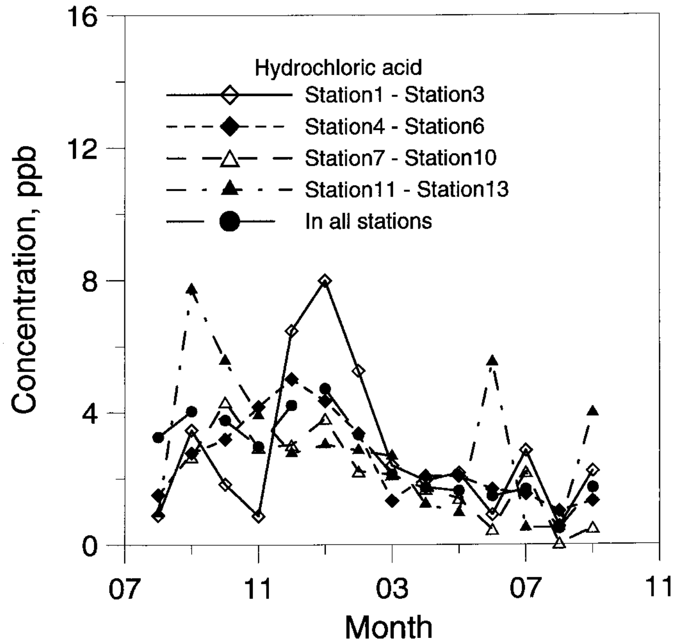


Figure 8. continued.

(e)

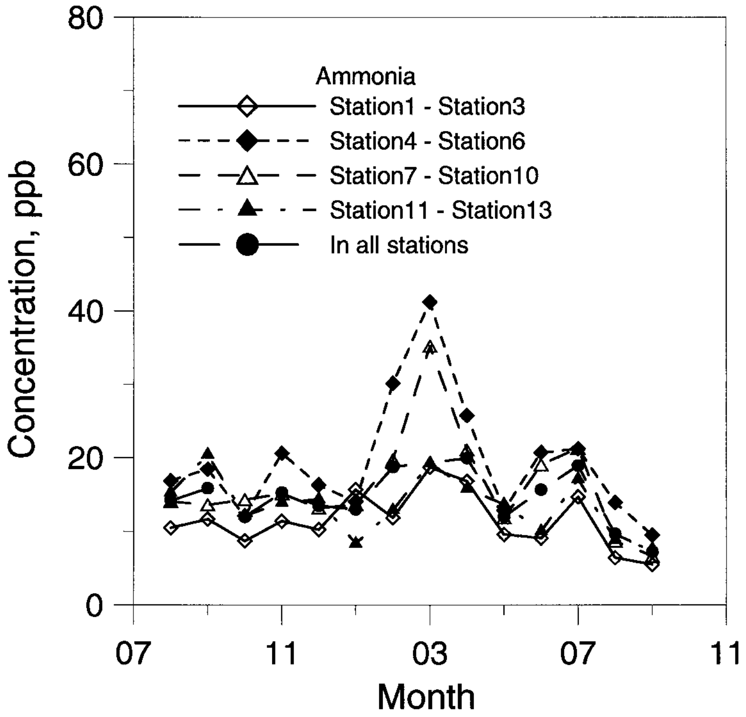


Figure 8. continued.

shows relatively much higher temporal variation in the concentration of NH_3 due to the presence of local sources in the park. For example, sites S1-S3, which are next to a semiconductor, usually have the highest NH_3 concentration in the park. The variation of HCl and NH_3 concentrations can be the caused of gas phase reaction of these two pollutants (Countess and Heicklen, 1973; Seinfeld and Pandis, 1998).

3.3. Comparison with factory-surrounding air quality standard of Taiwan

Table II shows the factory-surrounding air quality standard of Taiwan and AALG. During the whole period of investigation, the concentration level of most of the species was found to be lower than the factory-surrounding air quality standard of Taiwan except that some sites have total F^- level higher than the regulated value of 10.0 μg m^{-3}. Table II shows that although the level of inorganic pollutants was found to be lower than the factory-surrounding air quality standards of Taiwan, in some cases HNO_3 was higher than the AALG. In this study, only SO_4^{2-} but not H_2SO_4 was measured. Therefore, there are no data available to compare the H_2SO_4 concentration with current standard or AALG.

TABLE II
Comparison of air quality standards

Species	Factory-surrounding air quality standard of Taiwan (Taiwan EPA, 1999)	Ambient Air Level Goal (Calabrese and Kenyon, 1991)
H_2SO_4	50 μg/m^3	2 μg/m^3 8-hr TWA[a]
Total F^- ($HF + F^-$)	10 μg/m^3	–
HCl	0.1 ppm	0.1 ppm
HNO_3	40 ppb	8 ppb (21 μg/m^3) 8-hr TWA[a]
H_3PO_4	20 ppb	–
SO_2		
NH_3	1 ppm	2.5 ppm 8-hr TWA[a]

[a] Time Weighted Average.

TABLE III
Comparison of pollutants concentrations with other industrial parks and areas

Pollutants	Hong Kong				Tsushima	Taiwan	
	Hong Kong (total)	Kwai Chung (industrial)	Kwun Tong (industrial)	Tsuen Wan (industrial)	Remote area	Tainan SBIP	Hsinchu SBIP (present study)
SO_4^{2-} (μg/m^3)	8.52	9.07	9.49	8.19	7.69	–	10.14
NH_4^+ (μg/m^3)	2.48	2.64	2.88	2.39	2.36	–	4.06
NO_3^- (μg/m^3)	1.95	2.00	1.94	1.78	1.20	–	2.94
NH_3 (ppb)	–	–	–	–	–	<11[a]	18.7[b] 14.1[c]

[a] = March 2003.
[b] = March 2001.
[c] = Average of whole study period.

3.4. Comparison of the concentrations with other industrial parks

Tainan SBIP is another Science-Based Industrial Park in southern Taiwan, similar to Hsinchu SBIP (Figure 1) built-up in 1996. At present about 100 hi-tech companies are operating in this park. The administration of Tainan park reported ambient concentration of NH_3 was <11 ppb in month of March 2003, which is about 1.5-time lower and slightly lower than that of Hsinchu SBIP ambient data (Table III) of March 2001 and average data (whole period), respectively. Whereas, the park administration reported that the other acids concentration was found to be lower than the detection limits of the sampling method used (Tainan Science-Based Industrial Park web page). Qin *et al.* (1997) have studied the characteristics of chemical compositions of atmospheric aerosols collected from 11 different sites located at industrial, residential and commercial areas of Hong Kong (northwestern side of Taiwan) between 1990 and 1994. They reported that SO_4^{2-}, NH_4^+ and NO_3^- are secondary aerosols and they account for 23.4% of respirable suspended particulate (RSP) in Hong Kong. On comparison of average ambient concentration of SO_4^{2-}, NH_4^+ and NO_3^-, it is found that SO_4^{2-} measured in SBIP, Taiwan is slightly higher, whereas NH_4^+ and NO_3^- concentrations are about 70 to 90% higher than those measured in different parks nearby Hong Kong (Table III), mainly due to difference in kinds of industries and meteorological conditions as well. Similarly, Wakamatsu *et al.* (1996) have measured the ambient aerosol concentration in the remote area of Tsushima, which is an island located between southern Japan and South Korea (northeastern side of Taiwan) and has no known large air pollution sources. Obviously on comparison with Tsushima's ambient aerosol concentrations, it is found that SO_4^{2-}, NH_4^+ and NO_3^- concentrations measured at SBIP, Taiwan are higher about 65 to 90% (Table III).

3.5. Simulated results of ISCST3 model

The ISCST3 data were calculated for HCl, HF, HNO_3, NH_3, and SO_4^{2-} for the month of February 2001 to September 2001. Figure 9 shows the distribution of Cl^- concentration around the SBIP calculated from sampling data (Figure 9 (a)) and by ISCST3 simulation (Figure 9 (b)). Similar types of distribution patterns were also obtained for other species. However, the distribution patterns and concentration levels calculated by ISCST3 model are found to be closer to the experimental data at high wind conditions rather than at low wind conditions.

4. Conclusions

The spatial and temporal distribution of air pollutants concentration around the SBIP was found to be dependent mainly on altitude of the sites, speed/direction of winds, and production volume of the park. The spatial distribution shows that

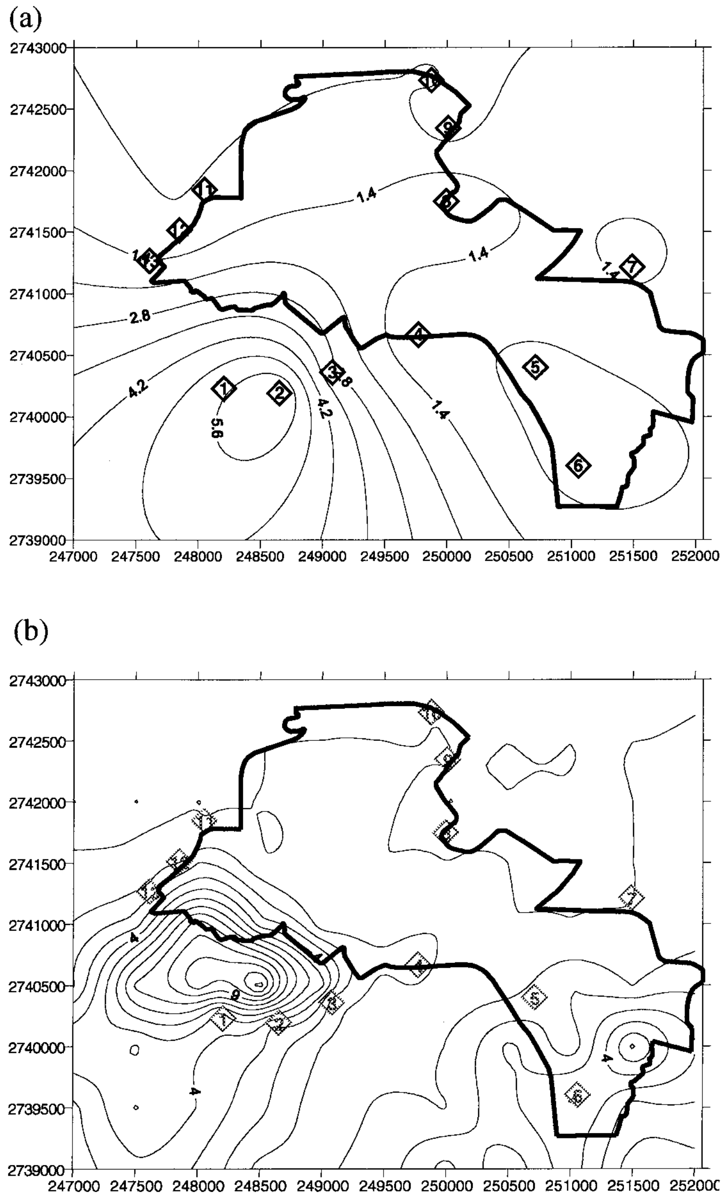


Figure 9. Comparison of sampling data (a) with ISCST3 simulated results; (b) for Cl(μg m^{-3}) in the month of September 2001.

the concentration level of pollutants was found to be higher on the sites situated at lower altitude (i.e. WS part of the SBIP, altitude ≈50–80 m), in the downwind location or close to the factories. The prevailing winds, which usually flow in the NE and ENE direction from September to April, are strong and reduce pollutant concentrations, Figure 5.

The results of temporal distribution show that the concentration levels of the index pollutant, HF, are found to be low during February to June 2001 mainly due to the decline in production in this period (HF shows good correlation with corporate sale). This study also concluded the sources of SO_4^{2-}, HNO_3 were regional rather than local, whereas the sources of HCl, HF, NH_3 were mainly local, despite of no good correlation between the corporate sale (or production volume) of the SBIP and HCl, NH_3 concentrations. This indicates the gas-phase reaction of these two pollutants in ambient environment.

During the investigation period the concentration level of most of the species was found to be lower than the factory-surrounding air quality standard of Taiwan.

The correlation (Figure 8 (a)) between the monthly production volume of the SBIP and ambient concentration of total F^- indicates that however the samples were collected at each site only one day in each month, but they are representative of the whole month.

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