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A Study of Taiwan Background Atmosphere

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ABSTRACT

In this paper, the field observation data collected by the research team of the Climate and Air-quality Taiwan Station (CATS) from June 1991-October 1991 are analyzed. During this period, a mobile laboratory equipped with highly sensitive instruments was used to monitor the level of chemical species at Hsinwu, located on the northwestern coast, and at Kenting, at the southern tip of Taiwan. The results show that the mean hourly-averaged SO_2 level at the rural northwestern coast was about 1-4 ppbv. When the southwesterly prevailed, the background mean SO_2 level in the Taiwan Strait was about 0.1-1 ppbv, which represented a well-diluted air of anthropogenic origin possibly from southern Taiwan. The CO level was about 220-260 ppbv during the later period. Meanwhile, at the southern tip of Taiwan, the measured ozone level varied with the movement of the large-scale airmasses. In September, each time a typhoon or a tropical depression approached, both the surface pressure and the ozone level dropped. The lowest hourly-averaged ozone level recorded was about 7 ppbv. Meanwhile, the peroxyacetyl nitrate (PAN) level dropped with the decrease in ozone concentration, with the lowest level about 7 pptv. On the other hand, in October, the continental High dominated, and the northeasterly prevailed. The ozone level varied between 38 and 50 ppbv with an insignificant diurnal variation. Backward air-parcel tracing suggested that the observed high ozone level was associated with the airmass originating

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from regions of higher latitude near northern China, Korea and Japan. In all, Taiwan, being at the edge of eastern Asia and the western Pacific, is affected simultaneously by the polluted continental airmass and the clean maritime air. Current measurements have clearly supported this concept.

(Key words: Tropospheric chemistry, Background atmosphere, Long-range transport)

1. INTRODUCTION

Since the beginning of the industrial revolution, atmospheric trace gases and aerosols from anthropogenic sources have increased significantly. One great potential consequence is the alternation of the Earth's climate, as trace gases and aerosols can modify the radiation energy balance of the earth-atmosphere system. The trace gases, such as CH_4, N_2O, CFCs, and tropospheric ozone, may have an impact on climate similar to that from the projected increase in CO_2. (Houghton *et al.*, 1990, 1992)

The trends and budget of many trace gases are still unclear though their influences on climate and atmospheric chemistry are certain (World Meteorological Organization (WMO), 1991). One major obstacle to the study is the lack of a comprehensive database of these trace gases. Only an international network of background observatories and cooperative research programs can fill this data gap. Since there is no such research-oriented observatory in the Taiwan region, a permanent "Climate and Air-quality Taiwan Station (CATS)" could fill a major gap in the global database and contribute significantly to international programs (Liu and Chang, 1989).

The proposal to establish CATS was materialized during the "Workshop on Long-term Air Quality Changes and Their Climatic Impact" on November 14-15, 1989 in Taipei. The following scientific objectives were identified (Liu, 1989):

(1) To carry out reliable measurements of important gases, aerosols and associated meteorological variables for the assessment of air quality and climate change.

(2) To contribute to the international understanding of climate and environmental changes on both global and regional scales.

Meanwhile, Taiwan, being at the subtropical latitudes and at the edge of eastern Asia and the western Pacific, has a significant seasonal variation in its weather system which changes from the dominant wintertime continental airmass to the summertime Pacific High. Also, being one of the advanced developing countries, Taiwan has some serious air pollution problems in urban and industrial areas, particularly in the western plain where over 95% of the population reside. The eastern part has lower population and industrial activities, and hence, cleaner air.

The above-described characteristics of the climate and the environment of Taiwan pose a challenging task in the monitoring of the background atmosphere, since not only the large-scale transport of upstream chemical species, but also the localized pollution affect the air-quality at a measurement site. Hence, careful procedures must be taken: selecting a remote clean site; collecting data only when large-scale flow dominates; applying highly sensitive instruments to measure the low concentration of chemical species; and relating the observed phenomena with the upstream sources. In order to tackle these problems, the CATS team installed a mobile laboratory capable of monitoring chemical species at various selected sites during different seasons. In this paper, the field measurement data collected at Hsinwu (June-July, 1991) and Kenting (September-October, 1991) are analyzed. The results are very fruitful in providing a better understanding of the general characteristics of the transport of chemical species from the upstream sources to the Taiwan region.

In October, 1994, the Central Weather Bureau (CWB) took over the task of monitoring the background atmosphere and has since set up a permanent baseline station at an off-coast island, Lanyu, which is at the southeastern corner of Taiwan. Items such as CO, SO_2, O_3 are being measured continuously, while CH_4, CO_2, HC(C_2-C_{12}) and aerosols are measured weekly.

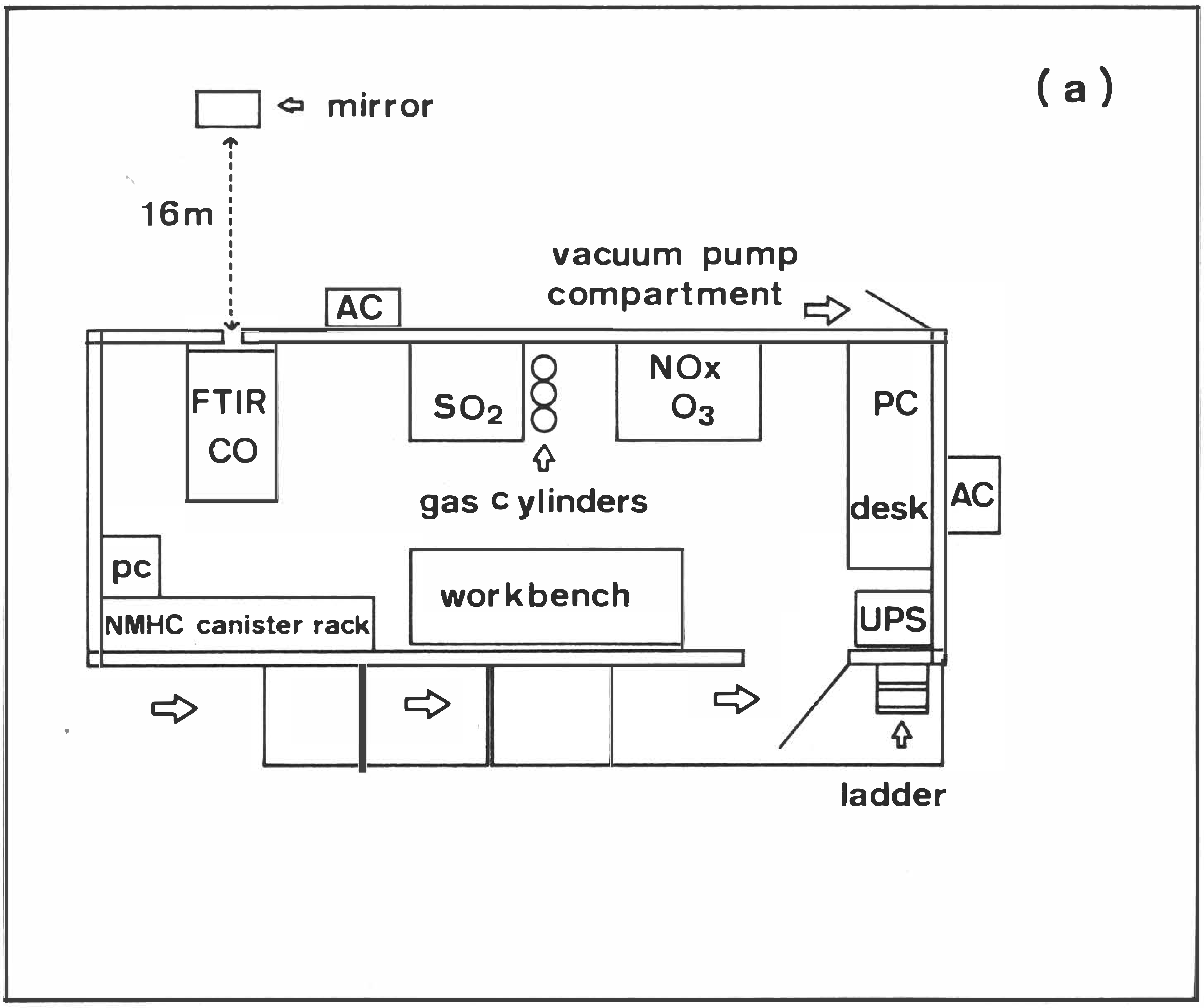
2. INSTRUMENTAL SETUP

The mobile laboratory which served as the base for all of the measurements was built into a 20 foot sea-container mounted on a flat-bed trailer. The interior of the laboratory was equipped with instrument racks, benches and air conditioning. The sample inlets used for the chemical species measurements were 6 mm o.d. Teflon tubing, which were passed through a bulkhead on the container and attached to a sample inlet box mounted on an expandable tower. The sample inlet box contained Teflon solenoid valves which were used for standard addition calibrations at the sample inlet, and 5 mm Teflon filters on each of the inlets. The tower was expanded to hold the sample inlets 7 meters from the surface. The meteorological instruments (wind direction, wind speed, temperature and humidity sensor) were mounted slightly higher at the top of the tower (Buhr *et al.*, 1993). Figures 1a and 1b show the design of this mobile laboratory (Liu *et al.*, 1994).

Table 1 outlines the instruments used to measure the level of O_3, peroxyacetyl nitrate (PAN), SO_2 and CO as well as the surface meteorological parameters, and the accuracy and sensitivity. Ozone was measured using an Environics Series 300-pressure and temperature corrected UV absorption analyzer (Environics S300). The instrument response was checked periodically by the addition of zero air and known amounts of ozone in this zero air from the Environics S100 calibrator. The ozone analyzer was compared to a primary standard UV absorption instrument at the National Center for Atmospheric Research (NCAR) and was found to operate within specifications. The precision and accuracy was about ± 2 ppbv (Ridley *et al.*, 1992).

PAN was measured using a 0.53 mm capillary gas chromatography (GC) system with an electron capture detector (Shimadzu mini-2). The GC was equipped with an automated gas sampling valve and a closed-cycle refrigerator cryogenic focusing system (Bertman *et al.*, 1993). Sample injections of 5 ml were made once every two hours during the Kenting experiment period. The detection limit for PAN was about 0.01 ppbv with a precision of 0.005 ppbv. The PAN instrument was calibrated by introducing into the sample inlet a dilute PAN in air standard produced from a synthetic PAN standard in n-tridecane contained in a diffusion cell which was placed in ice water. The PAN standard was calibrated in turn using an NO_y converter and a NO chemiluminescent detector (Buhr *et al.*, 1988).

A pulsed-UV light source SO_2 fluorescence monitor (model 43S, Thermal Environment Corp.) with a 230-190 nm band pass filter was used to measure gaseous SO_2. Air samples were drawn through a PTFE Teflon tube (external diameter 6.35 mm) into the monitor. A Teflon filter was installed at the entrance of the air sample. Zero air was used to dilute the 10-ppm certified SO_2 standard gas without further purification. The detailed calibration system is described in Chen *et al.* (1994). The sulfur chemiluminescence detector (model 350B, Sievers Research) was coupled to a gas chromatography (model GC-9A, Shimadzu) through



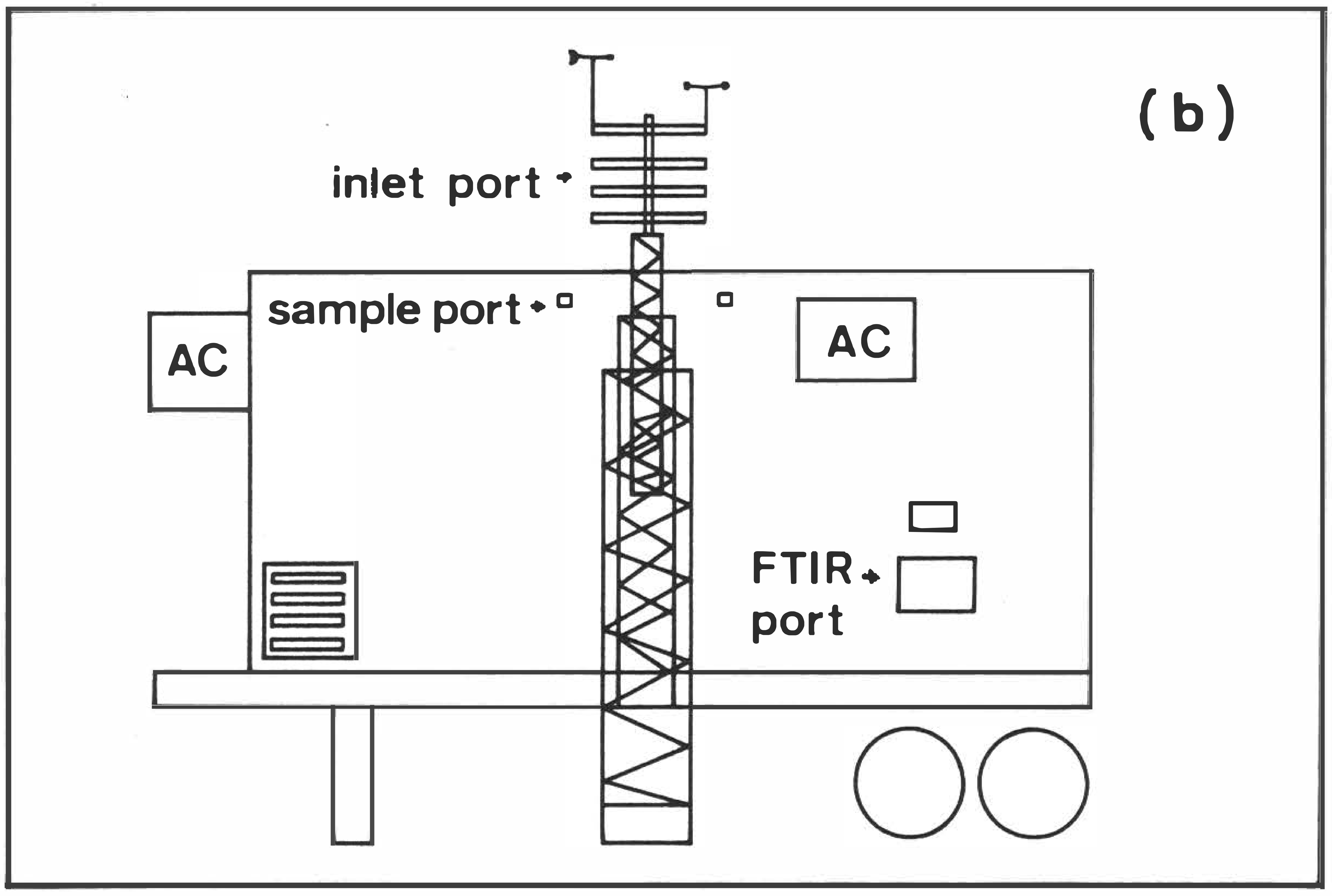


Fig. 1. Diagram of the movable laboratory (a) top view, (b) side view. (from Liu *et al.* (1994))

Table 1. Instruments on-board the CATS mobile laboratory.

Items	Technique/ Instrument	Sensitivity/ Accuracy
O_3	UV absorption; Environics S300.	± 2ppb
PAN	Gas chromatography with an electron capture detector (Shimadzu mini-2)	0.005ppbv
SO_2	Chemiluminescence; Thermal Environmental Inc., Model 43S.	0.1ppb
CO	Long path FTIR; Infrared Analysis Inc.	5.2ppb (2169.4 cm^{-1})
Weather Sensors	(1) Setra Barometer Pressure Sensor Model 270; (2) Wind Direction Sensor Model 431A; (3) Handar Wind Speed Sensor Model 430A; (4) Handar Relative Humidity/Air Temperature Sensor; (5) Handar 540A-a Data Collection System.	(1) ±0.3mb (2)±5° (3)±5% RMSE (4) T: ±0.2°C RH: ±2%(0-80%) ±5%(80-100%)

a ceramic probe assembly attached to the flame ionization detector (FID). Chromatograms were recorded on a integrator (model C-R4A, Shimadzu).

A portable open path Fourier-transform infrared spectrometer (POPFT-IR) with multi-reflection long-pathlength optics was used to measure the level of CO (Chang and Tso, 1994, Liu *et al.*, 1994). The FT-IR spectrometer and the nesting mirror (8" diameter spherical mirror) were installed in the movable laboratory, while two collecting mirrors (8" diameter spherical mirrors) of the white cell optics were put out in the sampling air and were 15.5 m from the nesting mirror. The air in between the nesting mirror and the collection mirrors absorbed the infrared beam which was to be measured continuously. All of the mirrors were silver-coated with ceramic overcoated protection and had a reflectivity of about 99% (Infrared Analysis, Inc.). A homemade Nernst glower gave a collimated infrared beam which was modulated by a Michelson interferometer (MIDAC Corporation) capable of a spectral resolution as high as 0.5 cm^{-1}. The IR beam was directed onto the entrance of the white cell and then multiplied and reflected back and forth between the nesting mirror and the collection mirrors. The IR beam exiting the nesting mirror was sent to the liquid-N_2 cooled photoconductive HgCdTe (MCT) detector (Infrared Associates, Inc.). The interferogram signal from the MCT detector was digitized, collected and a Fourier-transform was processed.

Beer's law was applied to determine the level of carbon monoxide with the calibration spectra being provided by the Infrared Analysis Inc. Meanwhile, an alignment He-Ne laser collinear with the IR beam was used to adjust the passes of the IR beam between the nesting mirror and the collection mirrors. Also, the number of passes could be calculated by counting the number of laser dots. Routine data collection was carried out at 54 and 62 passes, which were 837 and 961 m pathlength, respectively. Chang and Tso (1994) showed that the detection limit for CO was about 2-7 ppbv with the center frequency ranging from 2103.6 cm^{-1} to 2169.4 cm^{-1} at a 961 m pathlength. For each measurement, it provided a value averaged over five minutes.

3. BACKGROUND ATMOSPHERE OVER NORTHWESTERN TAIWAN

From June 19 - July 7, 1991, an intensive field observation program was carried out at Hsinwu (marked as S in Figure 2), which is located on the northwestern coast of Taiwan. The selected site was in a farm field very close to the coast and was far away from the densely populated area. Liu *et al.* (1994) reported the measurements in detail, and compared the collected dataset with the air quality data gathered by the local Environmental Protection Administration (EPA) in nearby urban areas. The major findings are summarized in the following:

During the measurement period, two types of wind pattern were noted. From June 27 to 30, the large-scale airflow was weak and a local land-sea breeze circulation dominated (Figures 3a,b). The nighttime land-breeze came from the south, while the daytime sea-breeze came from west. The wind speed increased after 8:00 LT and reached a maximum of about 2 - 6 ms^{-1} at 14:00 local time (LT). The wind speed during the nighttime was generally lower than 3 ms^{-1}. The condition during this period could represent the general mean of the rural environment very well. The measured hourly-averaged SO_2 levels ranged between 0.2 and 12 ppbv (Figure 3c). The maximum levels occurred at 11:00 LT and at mid night, which might have been related to nearby emission sources such as trailers, ships or boilers equipped with diesel or heavy-oil engines. The diesel fuel contained about 0.5% sulfur, but heavy-oil 1%. Meanwhile, the SO_2 levels in a nearby city, Chungli (marked as C in Figure 2), varied between 10 and 100 ppbv with the maxima occurring at 8:00 LT and at mid night. The maximum level at Hsinwu was much lower than at Chungli. The differences can be used to distinguish the urban environment from the rural area. In all, according to Figure 3c, the rural mean hourly-averaged SO_2 level during the measurement period was about 1-4 ppbv, while the mean level plus the standard deviation on the positive side was at most 12 ppbv.

From July 1 to 7, a completely different wind pattern occurred with a strong south-westerly prevailing throughout (Figures 4a,b). Still, the wind speed varied diurnally. The maximum windspeed of 5-10 ms^{-1} occurred at 11:00 LT, and the minimum windspeed of 2-6 ms^{-1} appeared at mid-night. During this period, the hourly-averaged SO_2 levels ranged from 0.1-20 ppbv (Figure 4c). The SO_2 levels higher than 4 ppbv occurred mainly before 12:00 LT and after 20:00 LT, while between these times, the SO_2 levels remained in 0.1-1 ppbv, which represented a well-diluted air of anthropogenic origin possibly from southern Taiwan. The 0.1-1 ppbv level was slightly higher than that measured in the remote tropospheric region but was lower than those observed at rural areas in the United States (NAPAP, 1991). During the same period of time, the CO level, determined by a Fourier Transform Infrared Radiometer (FTIR), ranged from 220-670 ppbv, with the lowest levels of about 220-260 ppbv occurring mainly between 12:00 and 20:00 LT. The high SO_2 and CO condition before noontime might

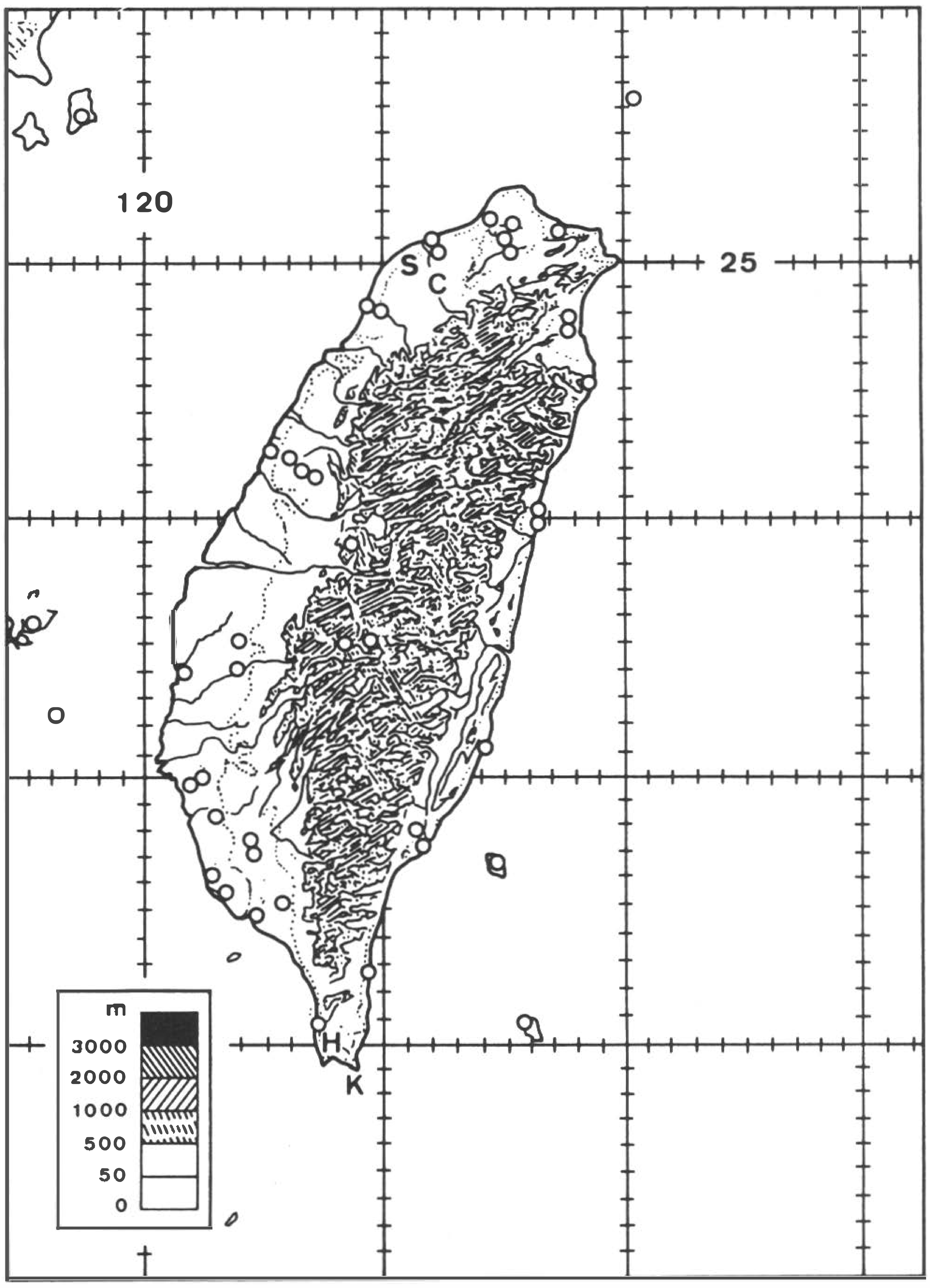


Fig. 2. Map of Taiwan. S is marked for the Hsinwu station, K for the Kenting site, C for the Chungli City and H for the Henchung CWB station.

have been related to nearby unexpected anthropogenic emission sources, while the low SO_2 and CO condition in the afternoon represented the background environment in the Taiwan Strait well.

4. BACKGROUND ATMOSPHERE OVER SOUTHERN TAIWAN

Between September and October 1991, a field observation program was carried out by the CATS team at Kenting (marked as K in Figure 2), the southern tip of Taiwan. The selected site was, being far away from the polluted western plain, an internationally known resort with a large number of tourists all year round. Fortunately, the period of this field trip was during the off-season period for the tourists.

During the field observation period, chemical species such as O_3, PAN, SO_2, CO etc. were measured. Among them, the evolution of the ozone level was clearly associated with the transport by the large-scale airmasses.

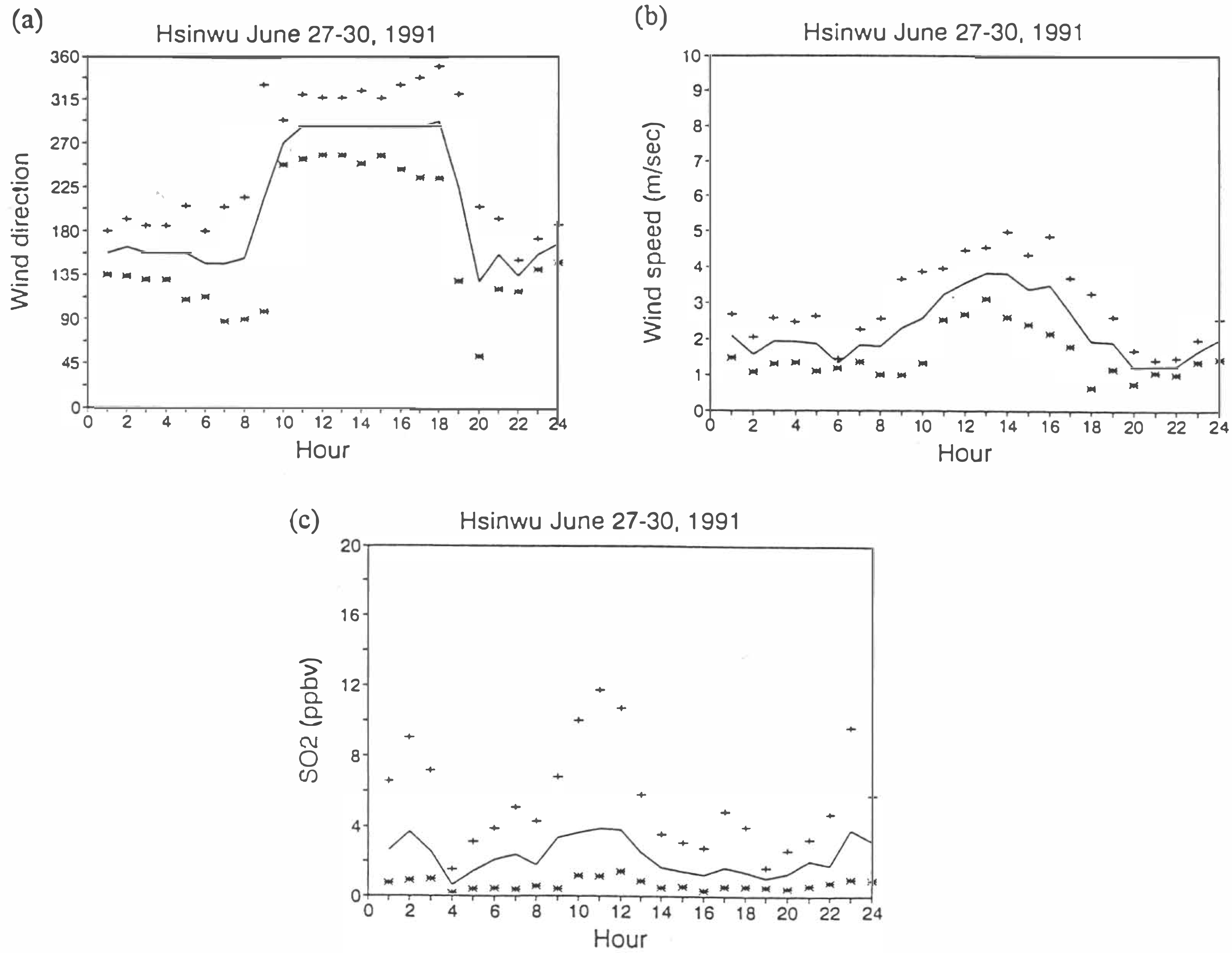


Fig. 3. Mean (a) hourly wind direction, (b) hourly wind speed and (c) hourly-averaged SO_2 level at Hsinwu from June 27-30, 1991. The "+" sign represents the level of mean value plus the standard deviation on the positive side, while the "*" sign represents the level of mean value minus the standard deviation on the negative side. The positive (or negative) side is defined as those values larger (or smaller) than the mean values.

4.1 General Meteorological Environment

In general, during the early autumn, the northern continental airmass has not extended its coverage to Taiwan. The disturbance from the inter-tropical convergence zone has a significant effect on the local weather. In September, 1991, a series of typhoons formed and moved nearby Taiwan. Among those typhoons, Nat landed at Kenting on September 23. After October 5, the continental airmass dominated the Taiwan region. The prevailing wind was from northeast throughout the whole month. The September-October observation period has proven to be a fruitful season to allow for the identification of airmasses from the region of either higher or lower latitudes.

The quality of the data of the measured meteorological parameters such as surface pressure, relative humidity, air temperature, wind direction and wind speed, were checked with those observed at the Henchung Meteorological Station (HMS, marked as H in Figure 2), which is routinely operated by the CWB. In short, the Kenting site is located at about 100 m higher than the HMS, hence, the surface pressure at Kenting was about 10 mb lower. But

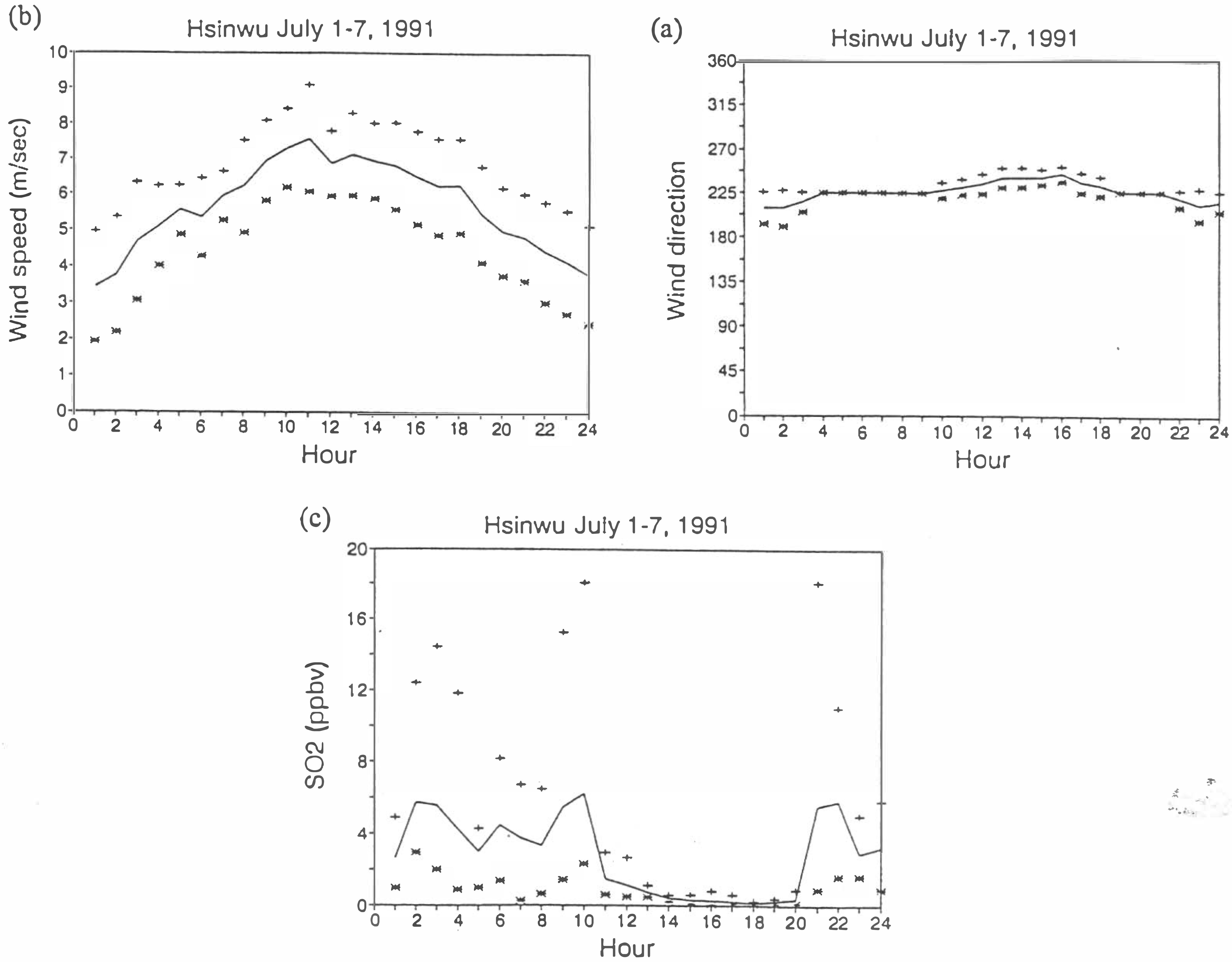


Fig. 4. Same as Figure 3, except for the period of July 1-7, 1991.

the general temporal variation of the surface pressure, air temperature and relative humidity at these two sites were in phase consistently throughout the observation period. As to the wind flow, when the prevailing wind was strong such as in the case of the northeastern flow, both stations observed similar wind patterns. But on days with variable wind flows and slow wind speed, wind directions recorded at these two stations could be different, as they are separated by a mountain range about 200-300 m high. At the same time, since the HMS is in the downtown area, the air temperature was a few degrees higher than that observed at Kenting. The maximum difference could have even been up to 1.2°C on clear sunny days. For the same reason, the wind speed recorded at Henchung was lower than that observed at Kenting with a difference of up to 6 m/sec.

Throughout the observation period, the authors observed a significant decrease in the surface pressure each time a typhoon approached. On September 23, the pressure dropped to its lowest value of 978 mb, and accompanying this was a significant increase in the relative humidity, associated with cloud covering and rainfall. In October, however, the surface pressure remained above 990 mb with a relatively drier air, and no rainfall was recorded.

4.2 CO and SO_2

The level of CO was measured only from September 9-15 (Figure 5) and was a five-minute averaged value for each measurement. From September 9-11 when the air flow came from the South China Sea (Figure 6a), the CO levels varied between 75 and 175 ppbv. After

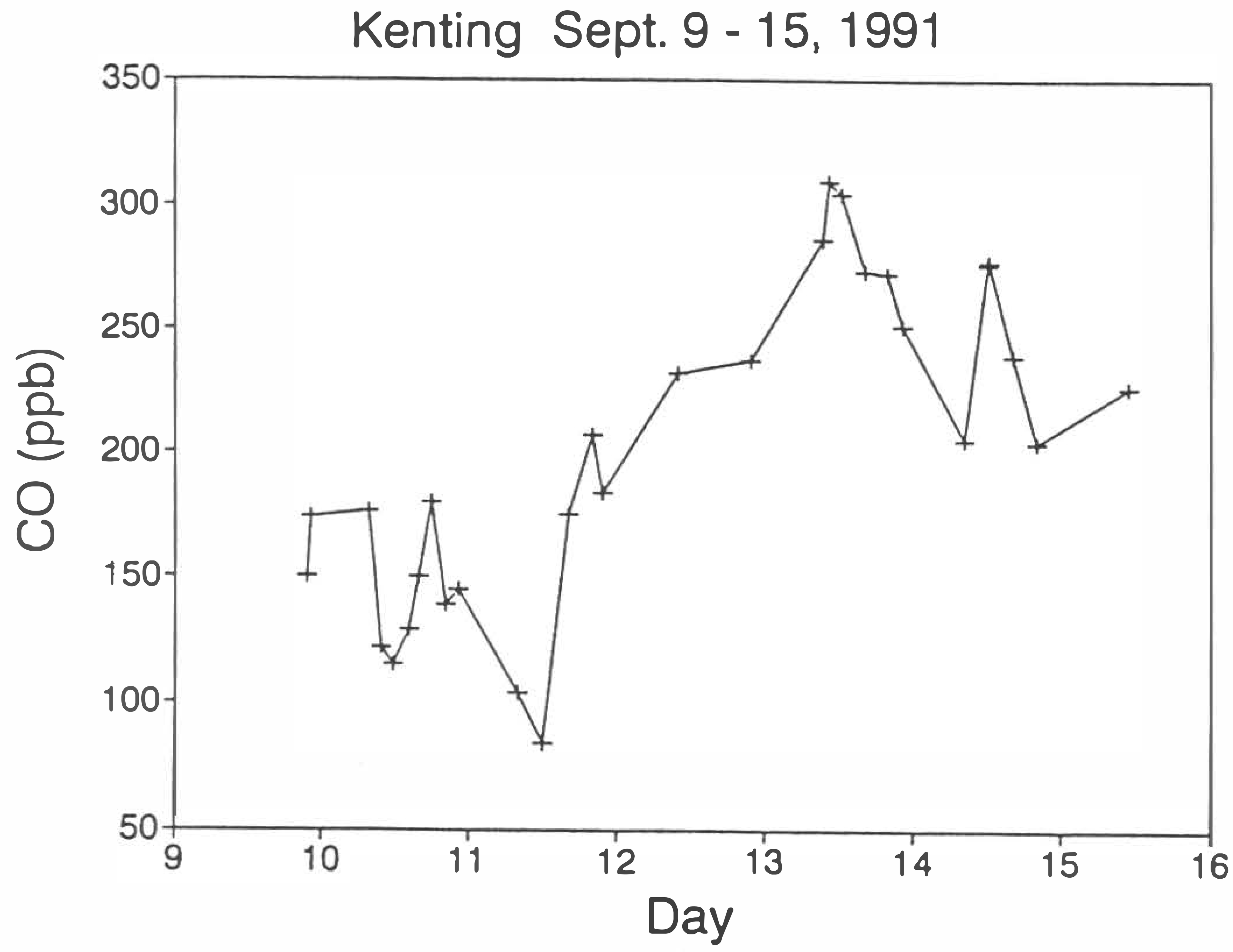


Fig. 5. The CO level at Kenting during the period of September 9-15, 1991.

September 11, when a cold front over mid-China moved toward Japan and typhoon Kinna moved northward along 130°E (Figure 6b), the air flow came from southern Japan and the East China Sea, causing the CO levels to vary between 200 and 315 ppbv. It is clear that with air coming from the south of Kenting, the CO level of 75-175 ppbv was considerably low, as compared to the background CO level of 220-260 ppbv on the northwestern coast of Taiwan (Sec. 3). In contrast, with air coming from the north of Kenting, the observed CO level of 200-315 ppbv was comparable to that on the northwestern coast of Taiwan.

The hourly-averaged SO_2 levels varied between 0.03 and 8 ppbv (Figure 7a). The maximum level was much lower than that measured in northwestern Taiwan (Figures 3c and 4c). The daily mean SO_2 levels ranged between 0.1 and 2.2 ppbv with the daily standard deviation (s.d.) generally lower than 0.5 ppbv (Figure 7b), except for September 20 and October 16 and 17 when the daily variation of the SO_2 level was significant. From September 6-11, the hourly-averaged SO_2 level was between 0.1 and 1.7 ppbv with the daily-mean level being about 0.3-0.8 ppbv, which was close to the 0.1-1 ppbv level measured on the northwestern coast for the background atmosphere of the Taiwan Strait (Figure 4c). However, in October when the northeasterly prevailed, the hourly-averaged SO_2 level was about 0.03-8 ppbv with the daily-mean level being about 0.5-2.2 ppbv, suggesting that the SO_2 levels from the north of Kenting were slightly higher than those from the south of Kenting.

4.3 Ozone

The hourly-averaged ozone concentration observed between September and October, 1992, is shown in Figure 8a. Before October 6, the ozone levels varied significantly in the range of 3-94.4 ppbv. The maximum concentration occurred at noontime on September 26, while after October 6, the ozone level remained between 30 and 65 ppbv with insignificant diurnal variation. The diurnal variation of ozone can be distinguished by calculating the daily-mean ozone concentration and the daily standard deviation (s.d.) (Figure 8b). The maximum daily s.d., 22 ppbv, occurred on September 26 when the maximum hourly ozone

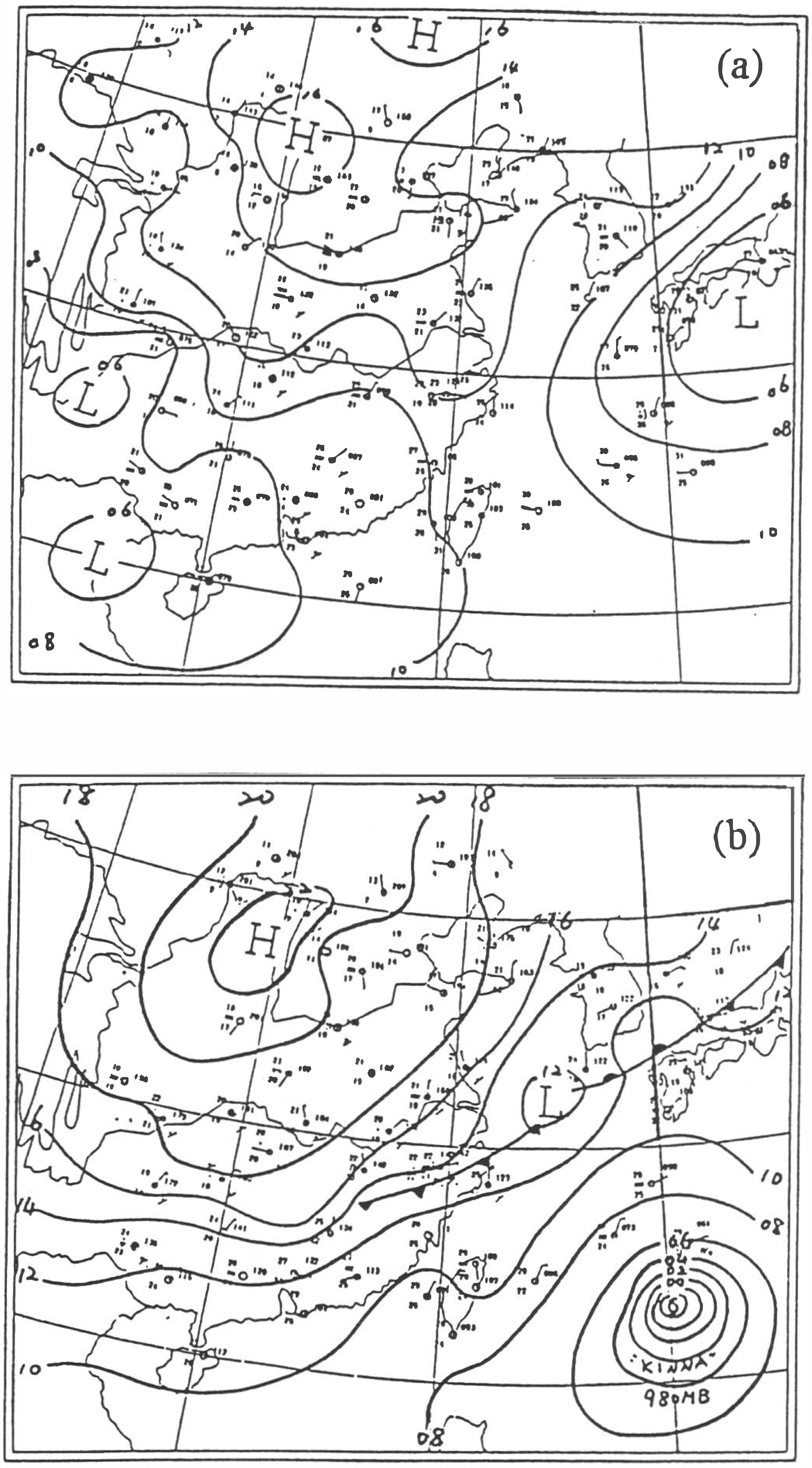


Fig. 6. The surface weather map on (a) September 9, and (b) September 12, 1991.

level was observed. After October 5, however, the s.d. value remained below 7 ppbv, which was much smaller than the daily-mean level of 38-50 ppbv. In general, the larger the s.d. value, the more significant was the diurnal variation pattern. During the two-month period, the ozone s.d. value most of the days was less than 7 ppbv, suggesting an insignificant diurnal pattern and a minor photochemical productivity. The long-range transport of ozone molecules from upstream sources could therefore be important in maintaining a steady ozone level at Kenting.

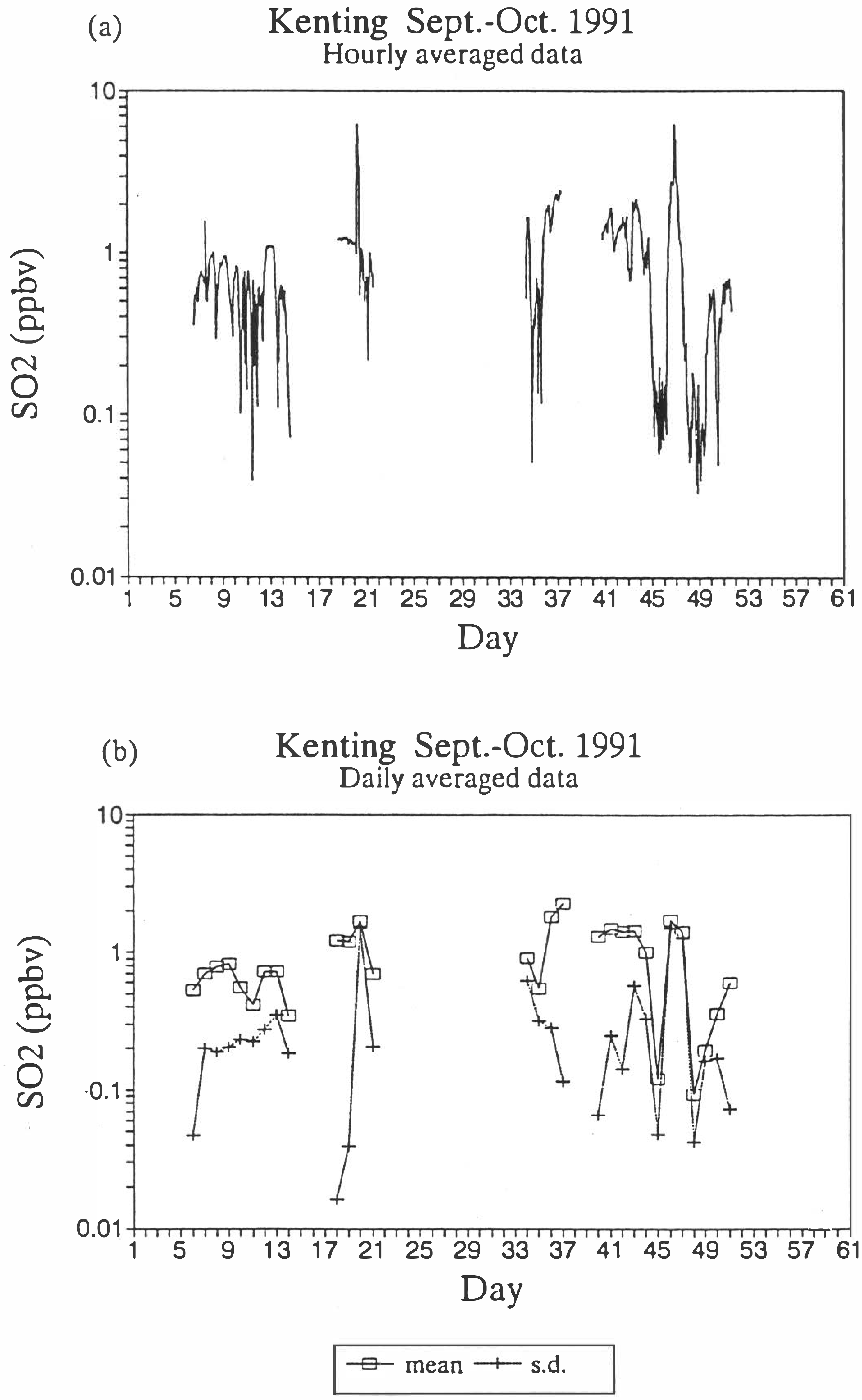


Fig. 7. The (a) hourly-averaged, and (b) daily-mean and daily standard deviation (s.d.) of the SO_2 level at Kenting during the period of September-October, 1991.

By correlating the daily-mean ozone level with the daily-mean surface pressure (Figure 9a) and relative humidity (Figure 9b), the authors notice that before October 4, the ozone level was positively correlated with the surface pressure but negatively with the relative humidity. The correlation coefficient between the ozone level and the relative humidity was about -0.81. Clearly, each time a typhoon or a tropical depression approached, the surface pressure at Kenting dropped, the relative humidity increased and the local ozone level decreased. This could have resulted from the following effects: the transport of maritime clean air from lower latitude region toward Kenting; the upward transport of ozone molecules by the

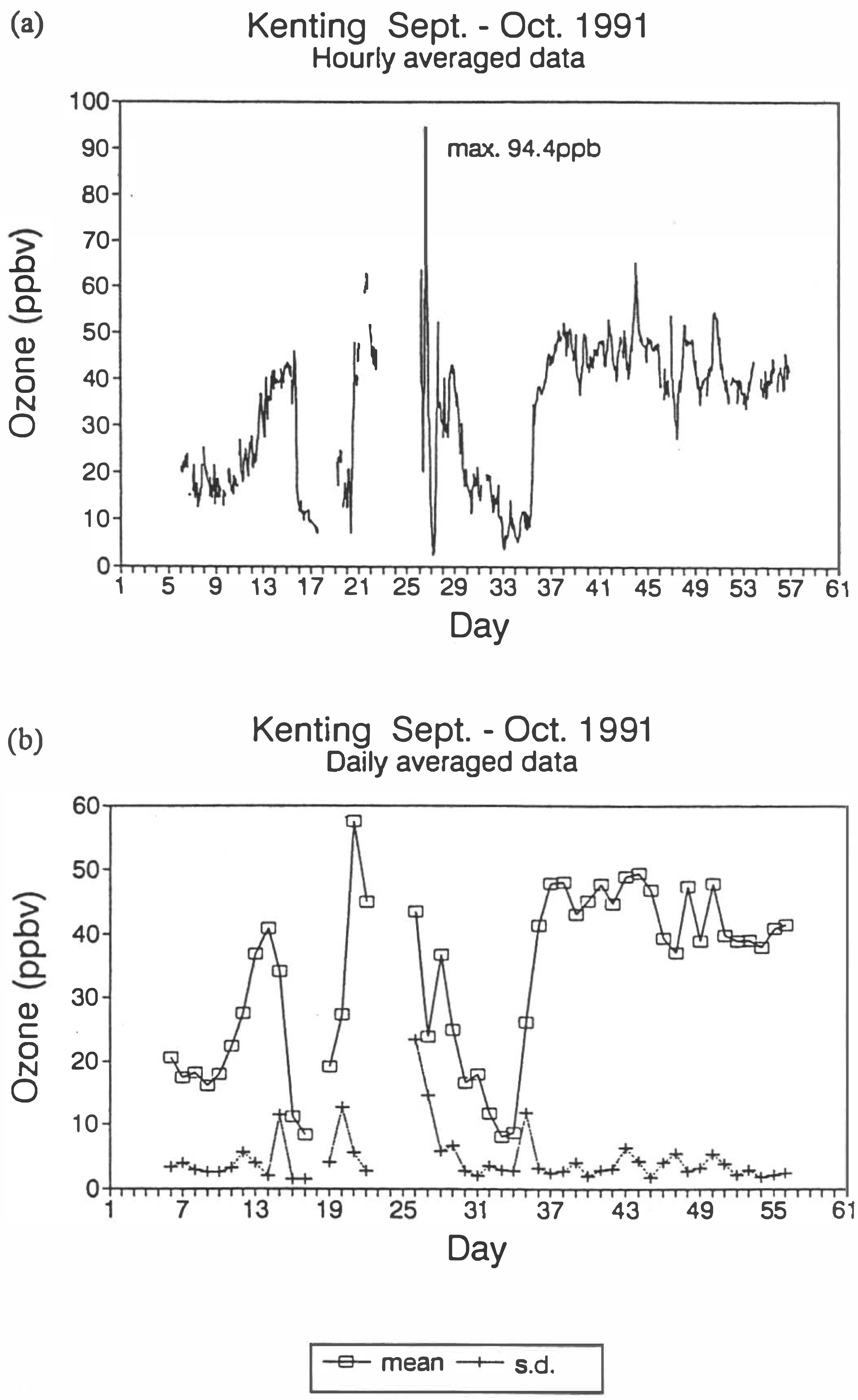


Fig. 8. The (a) hourly-averaged, and (b) daily-mean and daily standard deviation (s.d.) of the ozone level at Kenting during the period of September-October, 1991.

strong convective activities along the typhoon walls; and the inefficient productivity of ozone below clouds. Wang *et al.* (1993) noted that a strong surface convergence and, hence, updraft occurred during those low ozone level periods. The lowest daily-mean ozone level recorded was about 7 ppbv on September 17 and October 3. On September 23, the intrusion of typhoon Nat caused a power cut-off and the loss of two-days of ozone data. But judging from the well-correlated relationships among the ozone level, surface pressure and relative humidity, the authors estimate that the ozone level was below 7 ppbv on September 23. This subject is further explored in the following section.

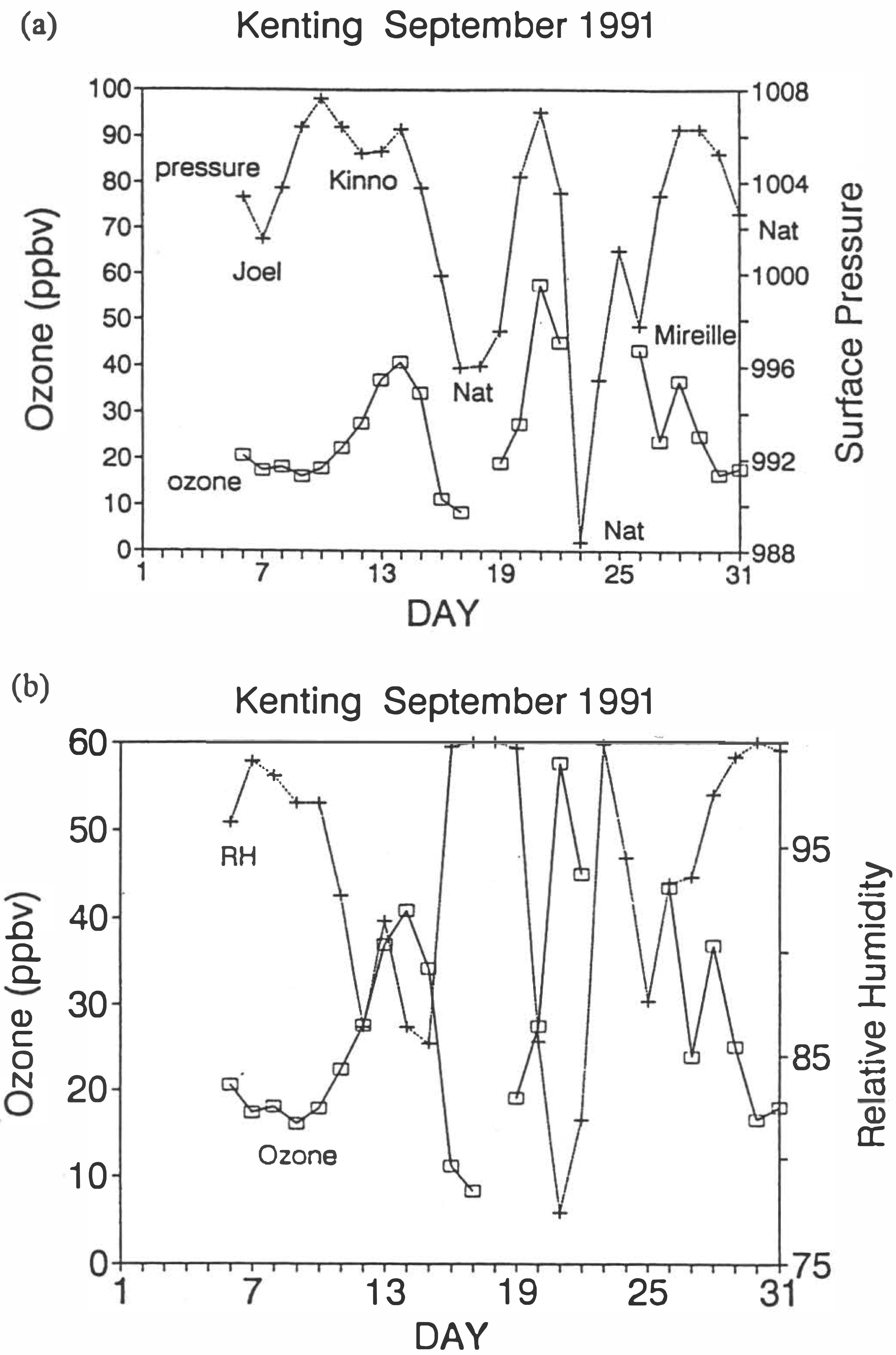


Fig. 9. The variation in the daily-mean ozone and (a) surface pressure, and (b) relative humidity in September. In Fig. 9a, the names of typhoons that affected Kenting are listed.

Meanwhile, before October 6 the ozone level tended to increase when the surface pressure increased and the relative humidity decreased. A few reasons could be related to such a phenomenon: the ozone molecules being transported directly from the upstream sources; the downward transport of the higher ozone level from upper altitudes; or, the photochemical production of ozone on a clear sunny day. The differences resulting from these effects could be identified from the magnitude of the daily s.d. value. If the ozone molecules were transported solely from the upstream sources, the daily s.d. value would be low, e.g. on September 21. In contrast, on days of efficient photochemical productivity, it usually associated with low wind speed, strong downdraft, drier air, low cloud amount and high value of daily ozone s.d., such as on September 26 when Wang *et al.* (1993) noted that a significant downdraft occurred, which was important in maintaining a photochemically productive environment.

After October 6, the daily-mean ozone level stayed between 38 and 50 ppbv and had an insignificant diurnal pattern. In the same period, the mean wind flow was dominated by the northeasterly (Figure 10) with a high mean wind speed of 4-14 m/sec. This is a typical pattern of a dominant continental high pressure system. The mean air temperature hence dropped from 26.8°C on October 5 to 23.5°C on October 15 and again on 21. Clearly, the observed steady high ozone level must have resulted from the transport of ozone molecules from upstream regions of higher-latitude.

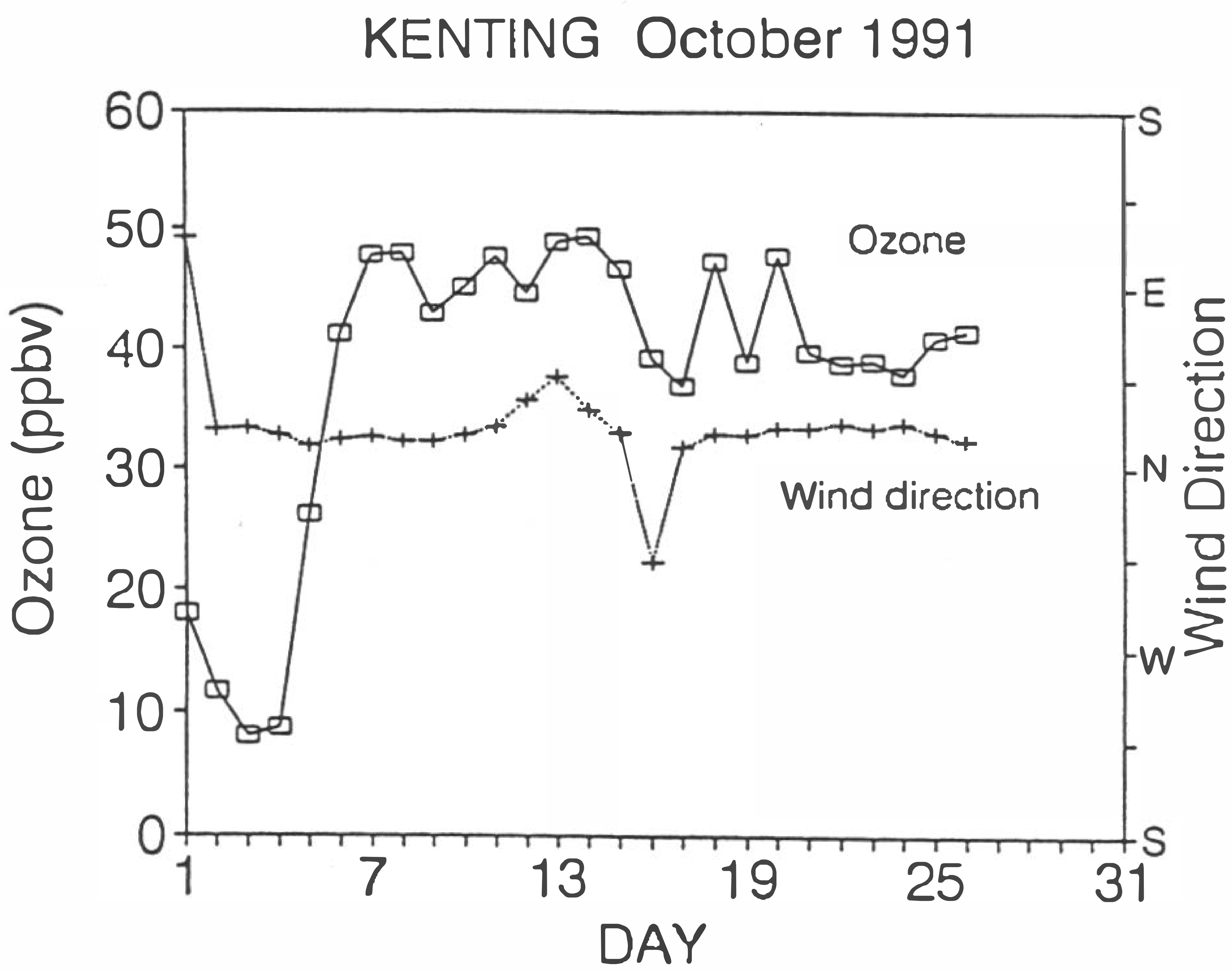


Fig. 10. The variation in the daily-mean ozone and wind direction in October.

4.4 PAN

The hourly-averaged and daily-mean PAN level is shown in Figures 11a and 11b, respectively. The hourly-averaged levels ranged between 0.007 and 8 ppbv, while the daily mean levels varied between 0.03 and 3 ppbv. The diurnal variation of PAN was more significant than that of ozone and SO_2.

From September 5-October 3, a positive correlation existed between ozone and PAN (Figure 12). This phenomenon indicates that the variations of ozone and PAN were affected by similar dynamic and chemical processes discussed in the previous section. The highest level of 8 ppbv occurred on September 26, when the peak ozone appeared and efficient photochemical processes accounted for a significant diurnal variation in ozone. However, low ozone and PAN levels occurred each time when Typhoon Joel, Kinno, Nat or Mireille (Figure 9a) approached Kenting.

After October 8, the correlation between ozone and PAN was not clear. Rather, the variation in PAN was close to that of SO_2 (Figure 7a) since a steady northeasterly prevailed throughout this period. The lower life time of PAN in comparison with that of ozone suggested that PAN was transported from the north of Kenting but from a distance shorter than that of the ozone source. Some mesoscale model simulation work is required to support this hypothesis.

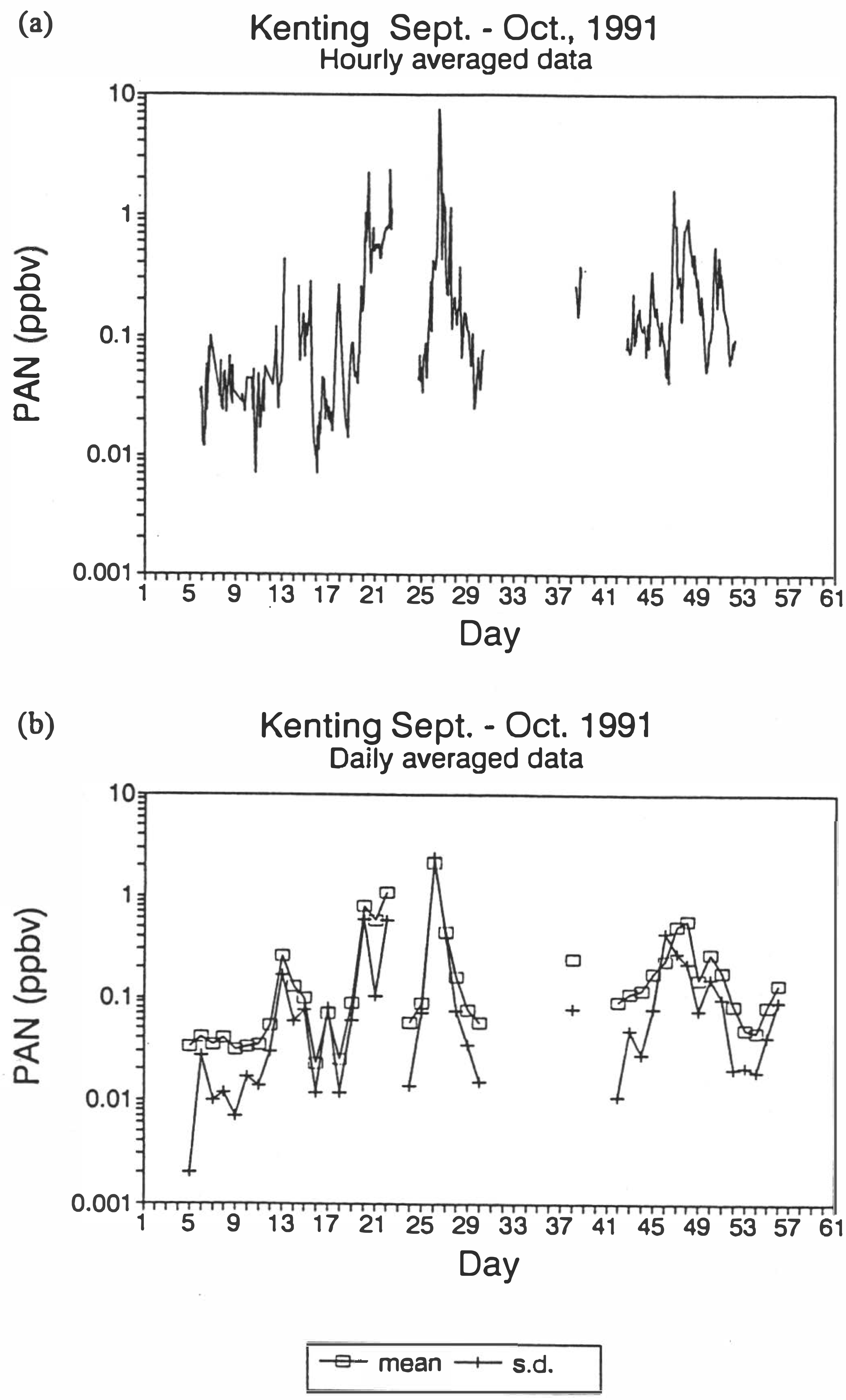


Fig. 11. The (a) hourly-averaged, and (b) daily-mean and daily standard deviation (s.d.) of the PAN level at Kenting during the period of September-October, 1991.

4.5 A Case Study of Typhoon Nat

Among the four typhoons affecting the weather in Taiwan, Nat lasted for a period of 19 days. Figure 13 shows the trajectory of Nat from first being developed from a tropical depression. On September 17-18, Nat caused the surface pressure at Kenting to drop to about 996 mb. It wobbled in the Basi Channel and finally struck Kenting on September 23 causing a complete shut-down of local power for one and a half days. During those 19 days, a decrease in both the ozone and PAN concentrations occurred each time Nat approached (Figures 12 and 9a). From September 15 to 17, the hourly-averaged ozone concentration dropped from

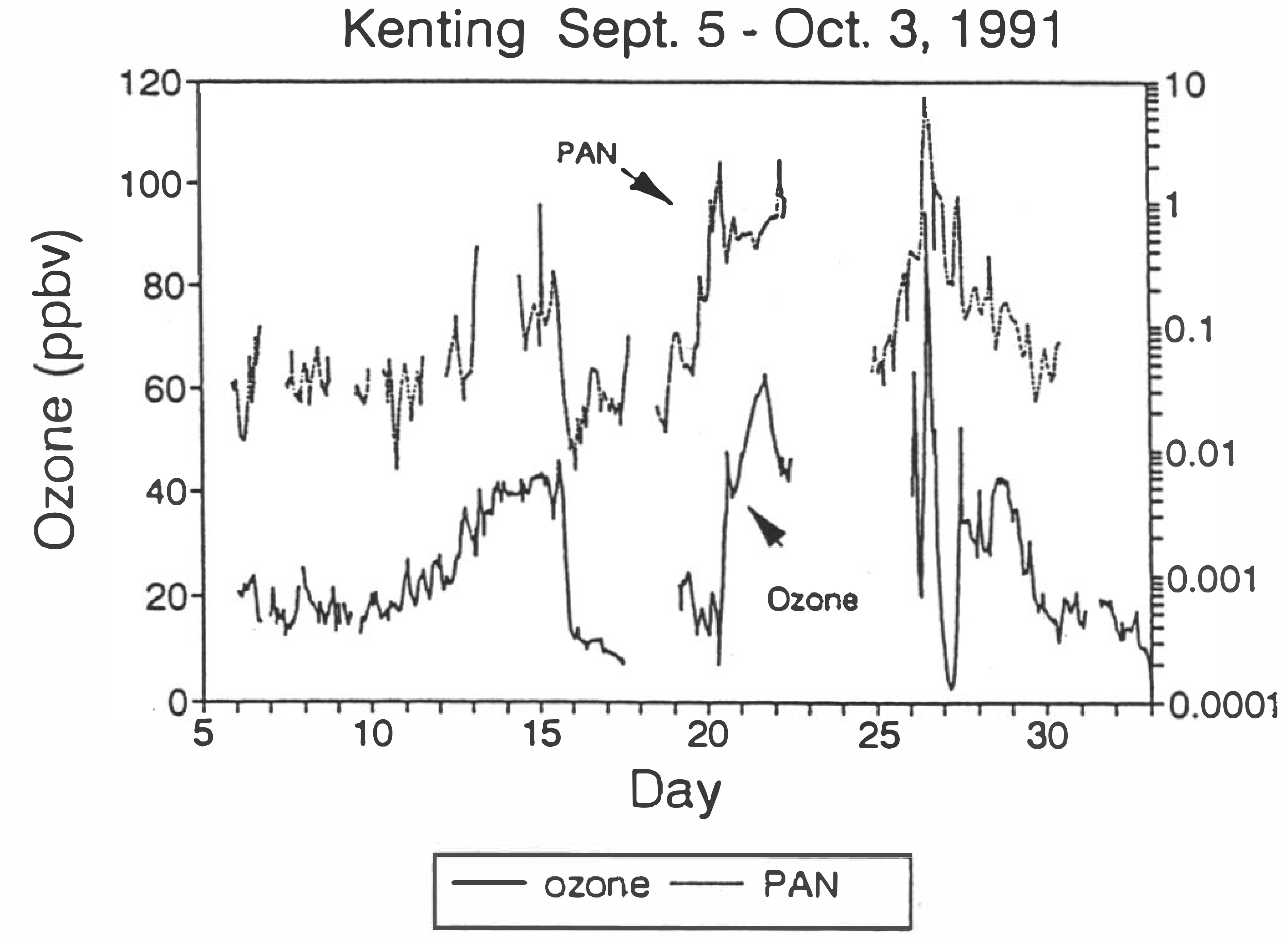


Fig. 12. The variation of the hourly-mean ozone and PAN in September.

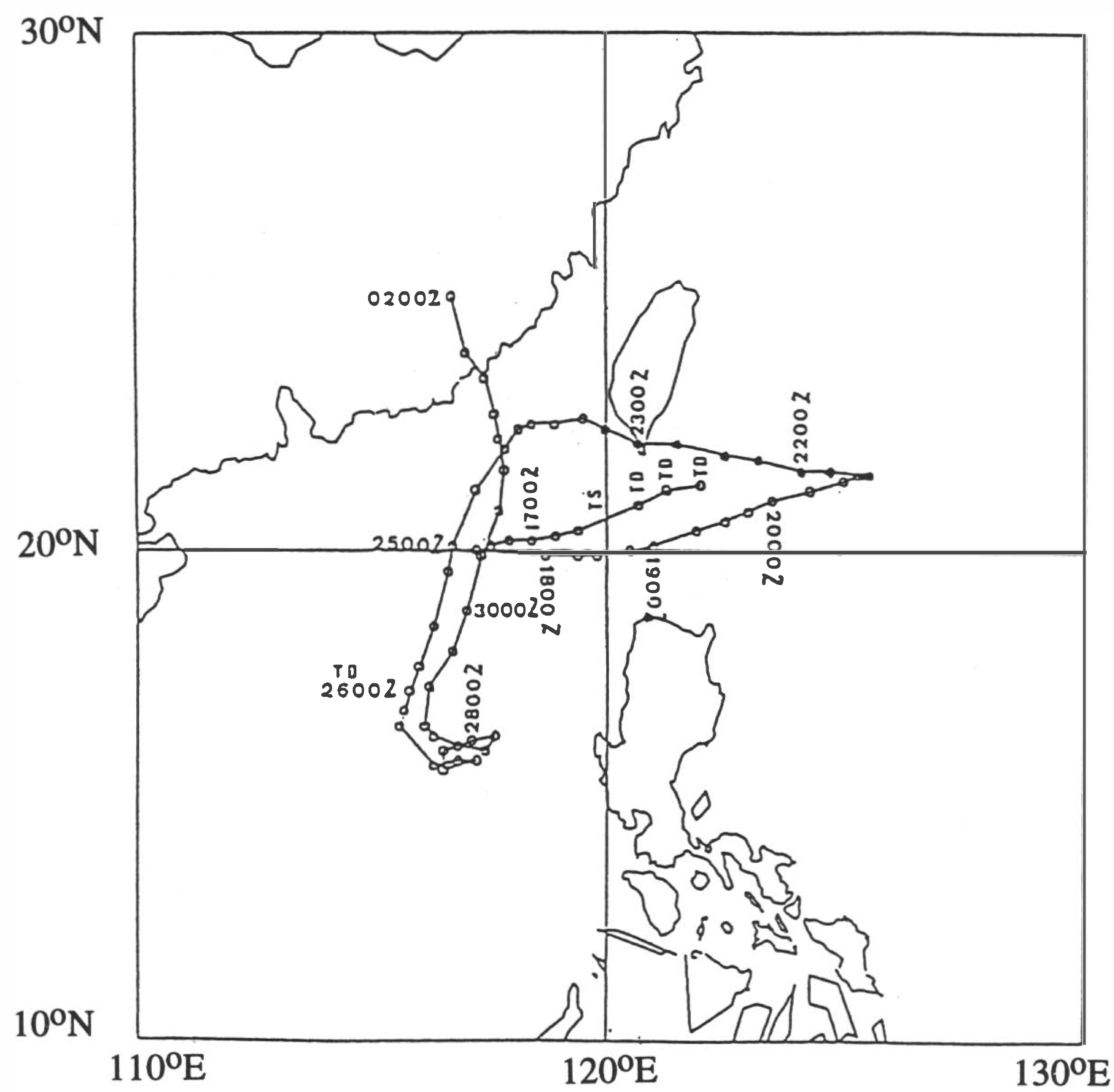


Fig. 13. The trajectory of Typhoon Nat from 00z on September 16 (marked as 1600z), to 00z on October 2 (marked as 0200z), 1991. The first two digits such as 1600z indicate the date, while the last two digits show the GMT time.

45 ppbv to 7 ppbv, PAN dropped from 1 ppbv to 0.007-0.02 ppbv, while the surface pressure dropped from 1007 mb to 996 mb. After September 20 when Nat moved gradually away from Kenting, the level of ozone and PAN along the surface pressure all started to increase and reaching their maximum around September 21. Afterwards, they started to decrease again as Nat was heading toward Kenting. Both the ozone and PAN instruments were turned off on September 22, but the PAN instrument was able to collect data at the later hours of September 24 and registered a low value of about 0.04 ppbv. By applying a linear regression method on the ozone and PAN data collected during the September 5-October 3 period, the authors were able to estimate that the hourly-averaged ozone level was about 12 ppbv at the later hours of September 24. The correlation coefficient between the ozone and PAN concentration was about 0.63. Since the ozone level on September 21 and 22 was about 65-42 ppbv, a decrease in the ozone level must have occurred when Nat landed on Kenting, which was in phase with the decrease in the PAN concentration from 3 ppbv on September 22 to 0.04 ppbv on September 24. Even though there was no direct observation, judging from the positive correlation between the ozone level and the surface pressure from September 15-20, the authors estimate that the ozone concentration should have dropped to below 7 ppbv on September 23.

During the September-October, 1991 period, a background station located at Oki Island, Japan once observed a significant drop from 55 ppbv to 5.5 ppbv in the hourly-mean ozone concentration within one day (Newell *et al.*, 1995). This event happened on September 27, when Typhoon Mireille struck Japan while moving northeastwardly from the East China Sea toward Hokkaido. The 5.5 ppbv ozone level was exceptionally low in the Japan region since the mean level at Oki between September 17 to October 23 was 40 ppbv.

4.6 Backward Air Parcel Trajectories

Using the NOAA/NMC data, Merrill (1994) traced the air parcels backward from the Kenting region for 3-5 days on an isentropic surface from September-October, 1991. Such a technique provided useful three-dimensional information about the upstream source region and the itinerary of the air coming to Kenting. However, since the spatial and temporal resolution of the NMC dataset is good only to resolve the synoptic environment, the tracing results are questionable in the analysis of a mesoscale feature. Wang *et al.* (1993) made a similar estimation during the Kenting field observation period for air parcels traveling along the surface for about 24 hours. Talbot *et al.* (1995) applied the trajectory outputs by Merrill (1995) for the air-parcels along the DC-8 flight tracks during the PEM-west period to distinguish the continental or maritime origin and to analyze the differences in chemical species. Akimoto *et al.* (1995) also used the outputs by Merrill (1995) of the ground stations to relate the surface ozone level to the upstream sources.

In Table 2a, the Kenting backward tracing trajectories have been carefully organized into six different categories, i.e. Route 1-6 (Figure 14), and the whole observation period have been separated into 11 short periods. During each short period, the backward trajectories from Kenting were similar to each other and can be represented by any one of the six trajectories shown in Figure 14. Also listed in Table 2a are the ranges of the measured hourly-averaged ozone levels and their synoptic conditions. The four short periods listed in Table 2b represent the transition periods for one traveling route changing to another kind.

Route 1 originated in the southern Mid-South Peninsula passing through the South China Sea and the Basi Strait to reach Kenting. It passed by the western side of Luson Island. Route

Table 2. The air parcel trajectory is grouped into six different routes (Figure 14). (a) lists the routes for air parcels arriving in the Kenting area during different periods. Also listed are the observed ozone ranges and the synoptic conditions. (b) lists the days when a swift change in the weather system occurred.

(a)

Date	Route No.	Ozone range (ppbv)	Synoptic condition
Sept. 5 - 10	Route 1	12 - 25	Typhoon Joel was over Hong-Kong and moved toward southern China.
Sept. 11 - 12	Route 4	18 - 30	A cold front was over mid-China and moved toward Japan. Typhoon Kinna was over 140°E, 25°N.
Sept. 13 - 15	Route 5	38 - 46	Typhoon Kinna was over Okinawa and moved toward Japan. The continental High dominated over China and Taiwan.
Sept. 16 - 17	Route 3	7 - 12	Typhoon Nat was over the Basi Strait
Sept. 19 - 20	Route 4	12 - 25	Typhoon Nat was over the South China Sea. Typhoon Luke was over southern Japan. The continental High dominated over China.
Sept. 21 - 22	Route 5	40 - 64	The continental High dominated over most regions.
Sept. 26 Sept. 27	Route 6	3 - 94.4 3 - 53	Typhoon Mireille was over Okinawa.
Sept. 28	Route 5	30 - 43	The continental High dominated.
Sept. 29 - Oct.1	Route 2	12 - 20	Typhoon Nat was over western Luson Island and moved toward southern China.
Oct. 2 - Oct. 5	Route 3	4 - 12	Typhoon Nat disappeared. There was no dominant system.
Oct. 6 - 26	Route 5	27 - 66	The continental High dominated.

(b)

Date	Route No.	Ozone Variation (ppbv)
Sept. 15	Route 5 changing to Route 3	46 changing to 12
Sept. 20	Route 4 changing to Route 5	12 changing to 48
Sept. 29	Route 5 changing to Route 2	35 changing to 17
Oct. 5	Route 3 changing to Route 5	10 changing to 39

2 moved from the southern South China Sea toward the Philippines, then turned northward to pass the eastern side of Luson Island. Table 2a shows that from September 5-10, air parcels moved along Route 1 with measured ozone levels of about 12-25 ppbv, whereas from September 29-October 1, air parcels were along Route 2 with ozone levels of about 12-20 ppbv, which was just slightly smaller than that observed with Route 1. By checking

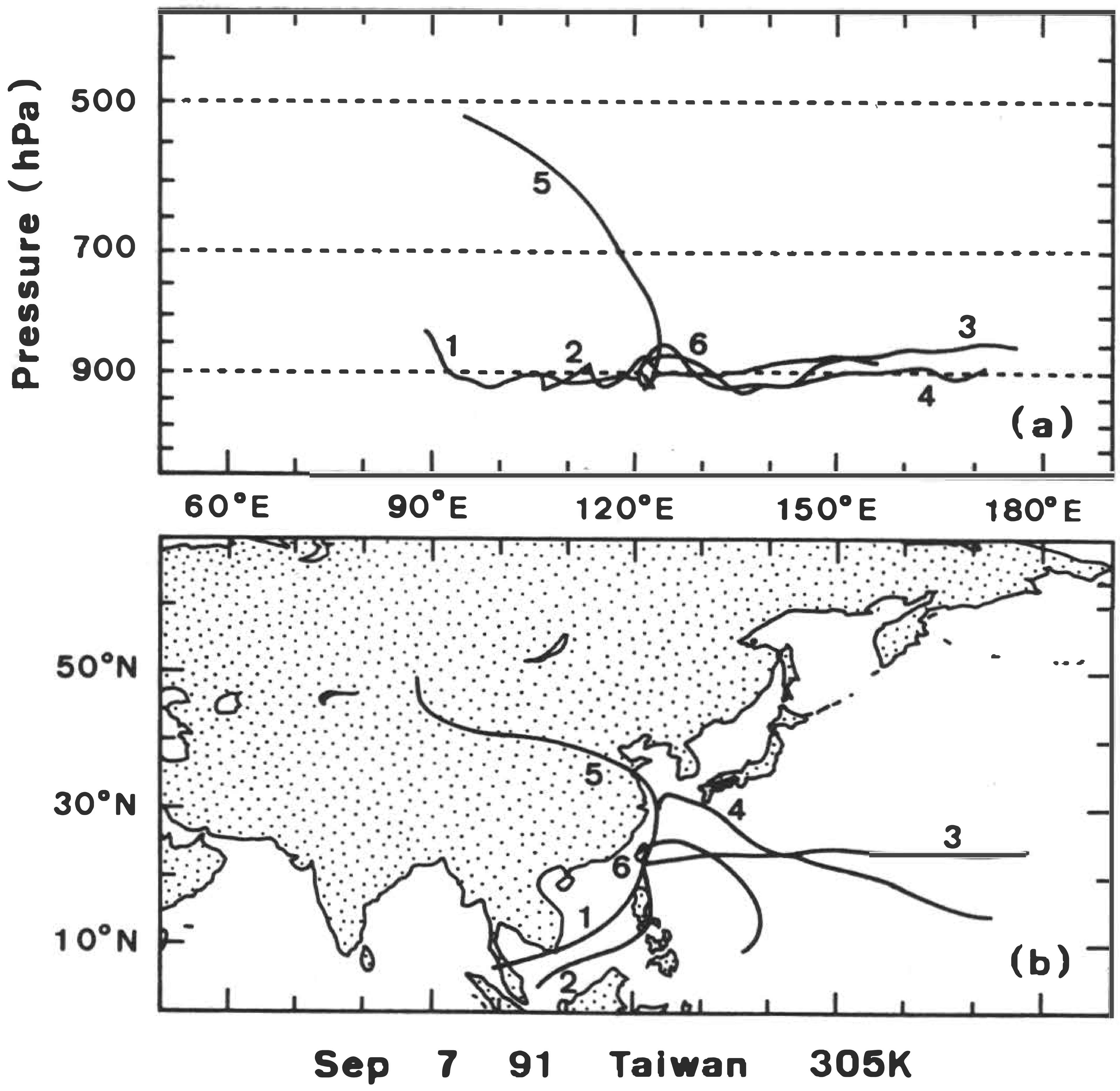


Fig. 14. Six different air parcel trajectories traced backward from the Kenting area for three days, starting September 7, 08 LT (Route 1); September 29, 20 LT (Route 2); October 5, 08 LT (Route 3, backtraced for five days); September 20 08 LT (Route 4); October 6, 20 LT (Route 5); and September 26, 20 LT (Route 6). LT stands for the local time. (a) shows the pressure-longitude profile. (b) shows the latitude-longitude plane.

the synoptic condition during these two periods, the authors noticed that both routes were associated with a typhoon over the South China Sea, which eventually entered southern China. The slight difference in the strength and position of the Typhoon resulted in the differences in the air parcel route and the ozone levels at Kenting.

Route 3 originated from the mid-Pacific and moved westward toward Kenting, hence representing a clean maritime origin. Table 2a shows that during the periods of September 16-17 and October 2-5, Route 3 dominated the air parcel trajectories with measured ozone levels about 7-12 and 4-12 ppbv, respectively. Obviously, these ozone levels were much smaller than those associated with Routes 1 and 2.

Route 4 also originated from the Pacific. However, it first moved northwestwardly toward the East China Sea, then turned southward toward Taiwan. Table 2a shows that from September 11-12 and September 19-20, Route 4 dominated, and the observed ozone levels varied in the range of 18-30 ppbv and 12-25 ppbv, respectively. These ozone levels were much higher than those observed when Route 3 dominated. Since the trajectory remained in the lower layer (Figure 14a), the observed high ozone concentration must have resulted from the air in the area near Japan, Korea and mainland China.

Route 5 was from northern Asia and was from levels around 500 mb (Figure 14a). This pattern occurred frequently and dominated the air parcel trajectories during the September

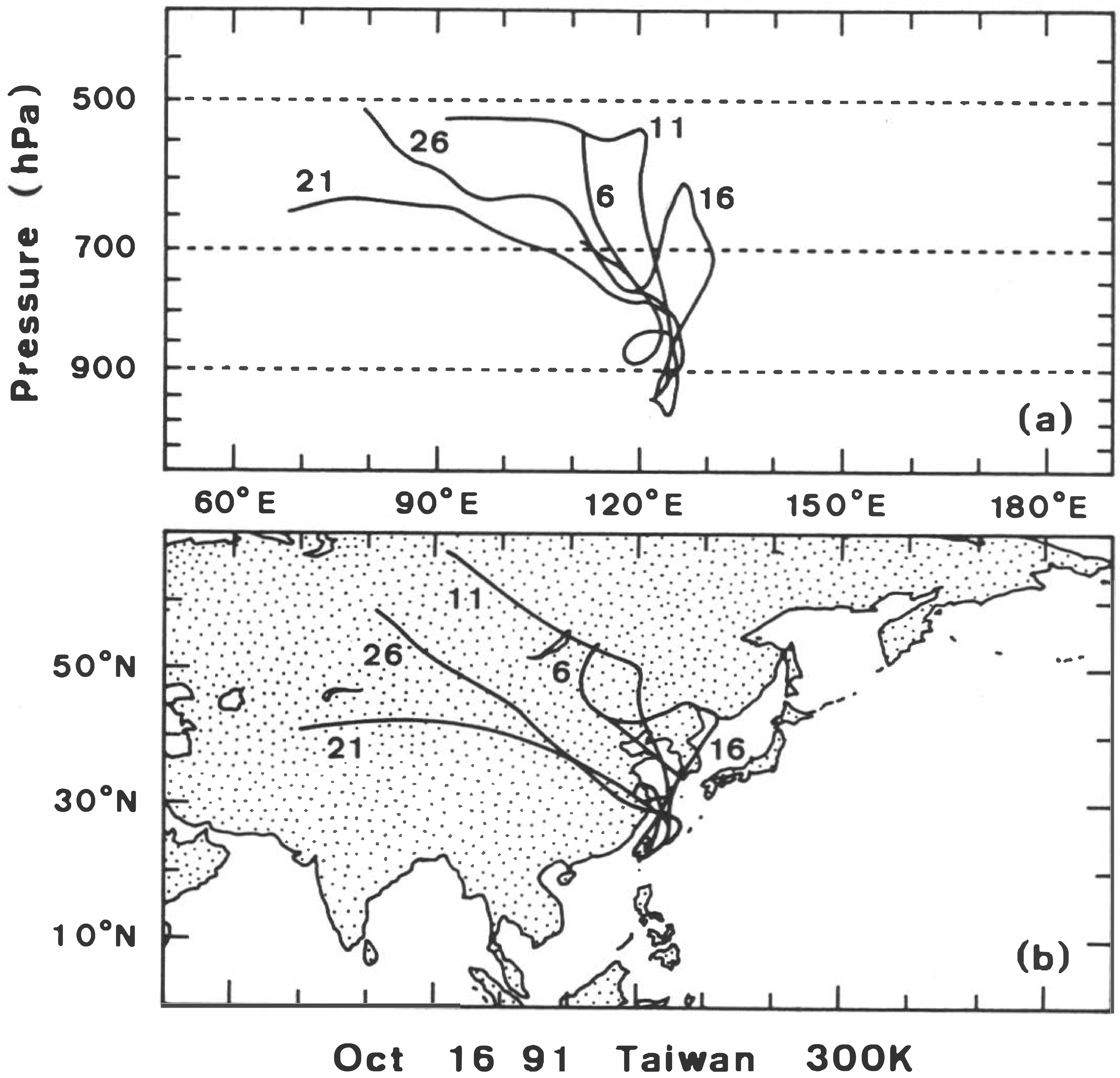


Fig. 15. Air parcel trajectories traced backward from the Kenting area for three days, starting from 12 LT on October 6, 11, 16, 21 and 26. (a) shows the pressure-longitude profile. (b) shows the latitude-longitude plane.

13-15, September 21-22, September 28 and October 6-26 periods. Actually, Route 5 could have been varied slightly from that shown in Figure 14. Figure 15 illustrates the trajectories of air parcels arriving at Kenting at 8:00 LT on October 6, 11, 16, 21 and 26. The main feature was that these air parcels were all from levels above 700 mb and even up nearly 500 mb. Since the ozone concentration increased with respect to altitude and latitude, it is not surprising to observe the ozone level ranged from 27 to 66 ppbv when Route 5 occurred (Table 2a). Certainly, the ground level sources in the area near Japan, Korea and mainland China could also have contributed to the high level of ozone observed as the Route 4 observation indicates. Akimoto *et al.* (1995) reached a similar conclusion in their explanation of the high surface ozone level at Okinawa, Oki, etc. when similar backward air parcel trajectories were noted.

Route 6 only occurred on September 26 and 27 and was associated with Typhoon Mireille when it moved northward from eastern Taiwan to the East China Sea. Even though the air originated from the Pacific Ocean, before arriving at Kenting the air had passed by western Taiwan where major pollution sources were located. Also on September 26 and 27, meso-scale subsidence dominated southern Taiwan (Wang *et al.*, 1993). The clear sunny condition was favorable for the production of ozone over the Taiwan Strait. The observed ozone level showed a clarified diurnal pattern with a low ozone concentration of 3 ppbv in the nighttime and a peak noontime ozone level of 94.4 and 53 ppbv, respectively, on September 26 and 27 (Table 2a).

During the two-month period, a dramatic change in the weather system occurred frequently. The air parcel trajectories showed these swift alternations. Table 2b summarizes these phenomena. Generally, the observed ozone level changed when the origin of the air parcel varied. This provides a strong support to the idea that ozone concentration is an important indicator of the long-range transport of chemical species from upstream sources. The reason that ozone can be used as a tracer in the Taiwan region is that Taiwan is on the edge of the polluted continental airmass and the clean maritime air, and the contrast in the ozone levels between the continental and maritime air is quite significant.

5. SUMMARY AND CONCLUSION

The key findings reported in this paper can be summarized as follows:

(1) At the northwestern Taiwan, the hourly-averaged SO_2 level in the rural region was about 1-4 ppbv where the peak SO_2 level was about 12-20 ppbv. In the urban area, the SO_2 level ranged from 10-100 ppbv. The differences between these two areas were significant.

(2) When the southwesterly prevailed, the background SO_2 level over the northern Taiwan Strait was about 0.1-1 ppbv, whereas the CO level was about 220-260 ppbv.

(3) At the southern tip of Taiwan, Kenting, the observed SO_2 level varied with the change in the origin of the air. From the north of Kenting, the air was with an hourly-averaged SO_2 level of about 0.03-8 ppbv and a daily-mean level of about 0.5-2.2 ppbv. In contrast, coming from the south of Kenting, the air was cleaner and had an hourly-averaged SO_2 level of about 0.1-1.7 ppbv and a daily-mean level of about 0.3-0.8 ppbv. A similar phenomenon was noted in the CO dataset. For the air from the north of Kenting, the mean CO level was about 200-310 ppbv, in contrast to the level of 75-175 ppbv for the air coming from the south of Kenting.

(4) The variation in the ozone level at Kenting was related to the large-scale airmass transport. When a typhoon approached, the levels of both ozone and PAN dropped simultaneously with the surface pressure. In one instance, a low ozone level of 7 ppbv and a low PAN level of 7 pptv were observed. A similar phenomenon was noted at Oki Island in Japan when Typhoon Mireille struck. The ozone level dropped from a mean 40 ppbv level to about 5 ppbv.

(5) When the continental high dominated the synoptic weather system, the northeasterly prevailed over the Taiwan region. A steady high ozone level ranging between 38 and 50 ppbv was observed at Kenting. There was an insignificant diurnal variation in the ozone level during this period. This phenomenon was probably caused by the long-range transport of ozone molecules from regions near northern China, Korea, Japan and the East Sea.

(6) Backward tracing of air parcels arriving at Kenting provided useful information about the long-range transport of airmasses. Six different traveling routes for air parcels arriving in southern Taiwan were identified. They are plotted in Figure 14. Among them, the fifth route might have a few different patterns as can be seen in Figure 15. The observed ozone level associated with the different air-parcel traveling routes is outlined in Table 2. In general, for the air coming from the Mid-Pacific (Route 3), the observed ozone level was very low (7-12 ppbv). For air coming from the south of Kenting (Routes 1 and 2), the ozone level was about 12-25 ppbv, while for the air passing by regions of higher latitude (Route 4), even with an origin in the Pacific, the observed ozone level was about 12-30 ppbv. For the air from higher latitudes and

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