

Airborne Measurements of Chemical Species Near Taiwan During Mid-autumn

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ABSTRACT

Between September and October, 1991, scientists from the US, Japan, Taiwan, Korea, China and Hong Kong participated in the intensive observation of the PEM-west program. Intensive airborne measurements of forty different kinds of chemical species were made by scientists aboard the NASA DC-8 aircraft. On October 4, 1991, the DC-8 made a special effort to fly around Taiwan. The synoptic condition was Taiwan on the edge of the cold continental High and the subtropic High. The prevailing wind was northeasterly over western Taiwan and easterly over eastern Taiwan. The DC-8 flew from Hong Kong toward the northeastern corner of Taiwan, and then along the eastern coast, before heading back to Hong Kong from the southern tip of Taiwan. The data collected show that a locally emitted plume was detected

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over northern Taipei at an altitude of 3 km, and was characterized by high levels of chemical species, such as $[O_3]$ 60 ppbv, $[NO_y]$ 4500 pptv, $[CO]$ 275 ppbv, etc. Over eastern Taiwan, most of the chemical species had a vertical profile of increasing concentration with respect to altitude. Below 4 km, the low level of chemical species was typically associated with a clean maritime airmass. The level of ozone was about 20 ppbv, with $[NO]$ below 20 pptv, $[NO_y]$ around 300 pptv, $[CO]$ below 80 ppbv, etc. The mean vertical profile of each species is listed in this paper, and it can be used as the initial state for model simulation. The data discussed in this paper provide important information to local scientists.

(Key words: Airborne measurements; Tropospheric chemistry)

1. INTRODUCTION

Due to human activity, the composition of the atmosphere is undoubtedly changing. Greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFC_s) have increased significantly in the atmosphere, and affect the global radiation balance and the climate (IPCC, 1992). Meanwhile, a significant enhancement of other gases, such as carbon monoxide (CO), tropospheric ozone (O_3), nitrogen oxide (NO_x), non-methane hydrocarbons (NMHC) etc. have also been observed (WMO, 1991). The reasons for these changes and their impacts are the major foci of many international research programs (IGBP, 1990).

The Pacific Exploratory Mission-west (PEM-west) program sponsored by NASA and APARE (east Asia/north Pacific Regional study) of IGAC (International Global Atmospheric Chemistry), have as their objective to investigate the atmospheric chemistry of O_3 and its precursors (NO_x , CO , CH_4 , and NMHC) over the western Pacific and to examine the budget of these species and the impact of anthropogenic sources (NASA, 1991). Also, PEM-west investigates some important aspects of the atmospheric sulfur cycle over the western Pacific with the emphasis on the identification of the relative importance of continental and oceanic sources.

Between September and October, 1991, scientists from the US, Japan, Taiwan, Korea, China and Hong Kong participated in Phase-A of the intensive observation of the PEM-west program. Each country was responsible for the operation of at least one ground air-quality station (Liu *et al.*, 1992). The CATS (Climate and Air-quality Taiwan Station) was stationed at Kenting during the two-month period. Meanwhile, air-borne measurements with instruments aboard the NASA DC-8 aircraft were carried out during a number of survey and intensive flights. Part of the Phase-A results were reported by Bradshaw *et al.* (1993), Singh *et al.* (1993), Browell *et al.* (1993), Newell *et al.* (1993), and Rowland *et al.* (1993). A special issue of PEM-west will be published by the Journal of Geophysical Research in 1995. Among those papers, the main discussions are about stratospheric intrusions, typhoon effects, comparison of maritime and continental sources, model calculations of the level of tropospheric OH (hydroxyl radical), estimation of the ozone trend, characterization of the air mass plume, etc.

On October 4 of 1991, the DC-8 made a special flight around Taiwan. In this paper, the atmospheric chemistry data collected by the DC-8 are described in detail, so as to understand the spatial distribution of different chemical species near Taiwan during the mid-autumn

period. Such data are very valuable for ROC scientists, since a similar air-borne program with so many state-of-art instruments are not likely to occur frequently. Further, if there is a similar flight in the future, the comparison of the data collected will provide a clear record of any changes in the regional atmosphere.

2. GENERAL BACKGROUND

On October 4, the DC-8 left Hong Kong at about 10:00 local time (LT) and flew around Taiwan from 10:00-18:00 LT (Figure 1). Below 700 mb, a continental high pressure system centered in northern China was moving slowly southeastward. A surface cold front was on the northwestern side of Taiwan and extended northeastward to the Japan Sea at 8:00 LT (Figure 2a). The cold front was moving very slowly southeastwardly (Figure 2b) and was barely recognizable at two sounding stations in the northern part of Taiwan. Land-sea breeze circulation occurred along the coast before 16:00 LT. Afterwards, the prevailing wind over Taiwan was dominated by northeasterlies on the western side and easterlies on the eastern side. No rainfall was reported. From 700 mb up to 200 mb, there was no approaching trough or ridge (Figures 2c and 2d). Taiwan was in a region where the air flow was characterized by variable wind directions and weak wind speed, in comparison with the strong westerlies in other regions.

The DC-8 first flew northeastwardly to the northeastern corner of Taiwan (flight track I in Figure 1), then made intensive observation flights along the eastern coast (flight track II). Around 17:00 LT, it flew in the boundary layer and was very close to Kenting. After that, it flew back to Hong Kong (flight track III). The reasons for making intensive observations along the eastern coast were to monitor the continental airmass at layers above 700 mb and the maritime air at lower levels, and to compare the aircraft data in the boundary layer with the Kenting surface measurement. In the following sections, data collected along the track I, II, and III are analyzed, respectively.

The major atmospheric species measured by scientists aboard the DC-8 are listed in Table 1. The measurement technique of each species and the precision or accuracy of the data are also given in the table, along with the names of the scientists in charge of the measurement and the references that describe the instruments. The meteorological and navigational parameters are provided by the DC-8 Data Acquisition and Distribution System (DADS) (NASA, 1991).

3. WESTERN TAIWAN (Flight Track I)

Between 10:00-11:30 LT on October 4, the DC-8 flew northeastward toward Taipei along an altitude of 6.5 km, then descended to 3 km near the Chiang Kai-Shek (CKS) airport, maintaining the same altitude while flying around the northern coast to reach the northeast (NE) corner of Taiwan (Figure 1a,b). During that period, air flow was from the southwest with a wind speed of about 10 m/s (Figure 3a). Backward trajectories on the isentropic surface show that the air originated from the central Pacific, passing by the northern Philippines and turning northeastward to the Taiwan Strait (Figure 3b). Such an air parcel trajectory is typical for the air moving between the subtropics and the continental high pressure systems. Hence, the air was from the maritime clean region with ozone levels of 20-33 ppbv at 6.5 km altitude and below (Figure 3a).

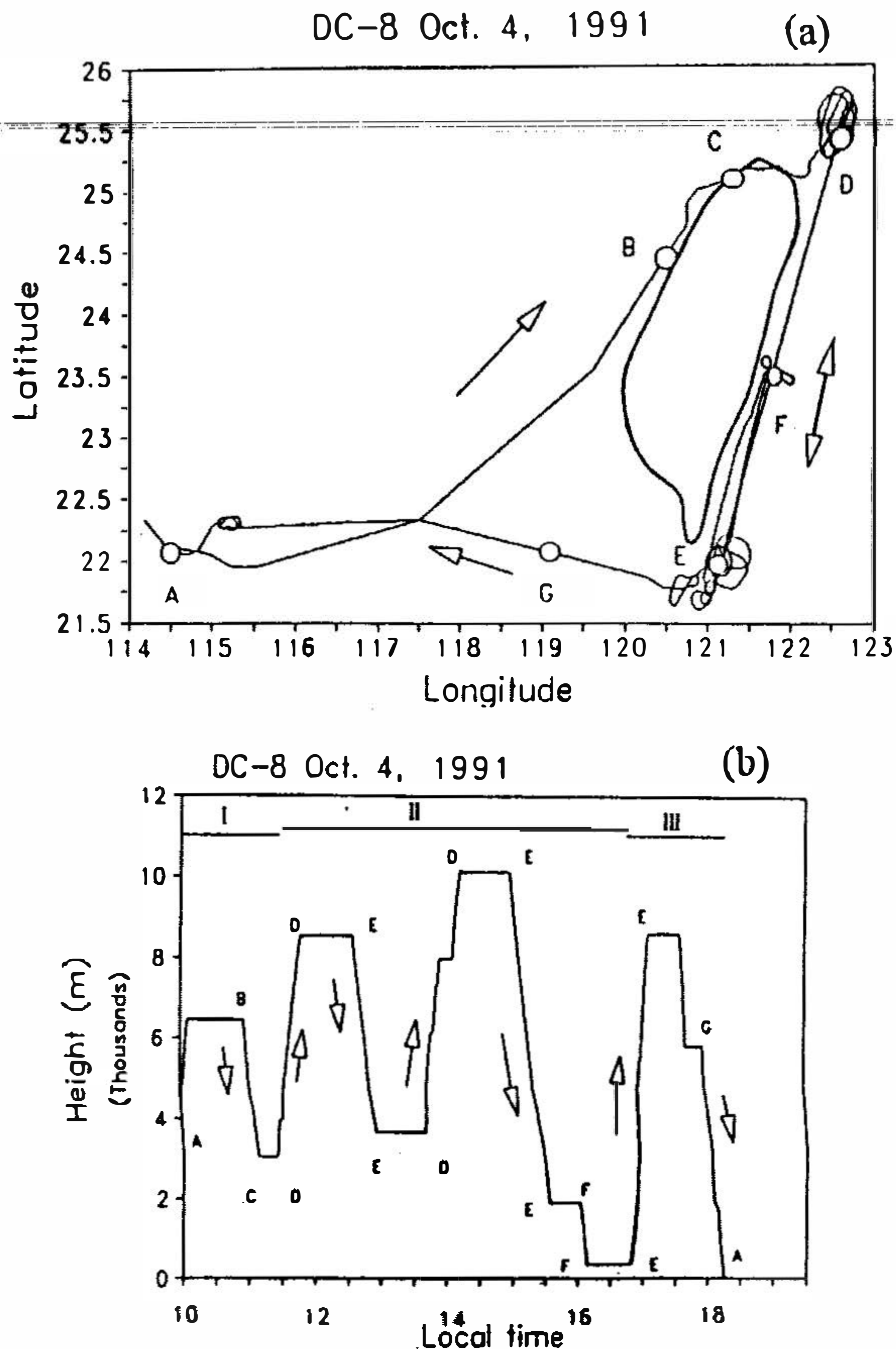


Fig. 1. The flight track of DC-8 on Oct. 4, 1991, (a) on the latitude-longitude plane, and (b) on the height-time profile. Points A, B, C, C, E, F, and G are marked to assist matching the geographic point with the local time. Tracks I, II, and III are separated as being the flight track over the western, eastern and southwestern Taiwan region.

Over northern Taiwan, a sharp ozone peak of 60 ppbv was observed just north of Taipei (Figure 3a) at 3 km altitude, which indicates a local pollution signal. Similar increases in the concentration levels were also observed in the NO, NO₂ and NO_y (the sum of all odd nitrogen species) data (Figure 4a). The peak NO level of 117 pptv was a dramatic increase from the 20 pptv of maritime clean air along the same altitude. The peak NO_y level of 4400 pptv was consistent with the data recorded at other pollution areas and was a sharp increase from the 1000 pptv of the clean maritime air along 3 km altitude. Meanwhile, the PAN (peroxyacetyl nitrate) concentration was decreasing from the 26 pptv at an altitude of 6.5 km over the CKS airport to the 5 pptv at an altitude of 3 km in the NO_y peak area (Figure 4b). Such a vertical profile of PAN is related to the thermal decomposition of PAN; hence lower level of PAN was observed at lower altitude where the air temperature was high. However, because PAN is formed in a polluted airmass, the low level of 5 pptv being in phase with the high peak of NO and NO_y, indicates that the polluted local air must be fresh in comparison with the aged air at higher level.

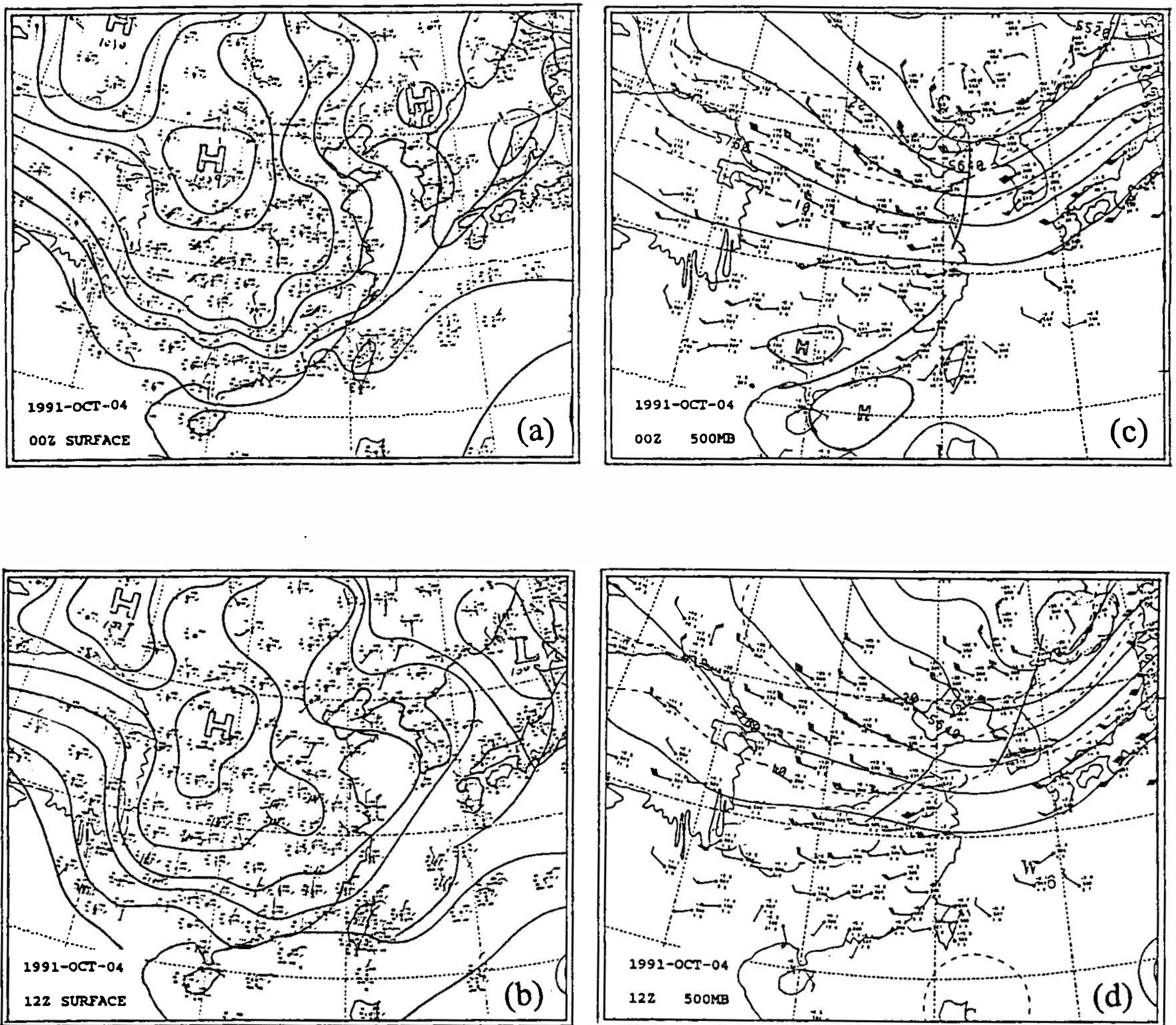


Fig. 2. The surface isobaric map on (a) 8:00 LT and (b) 20:00 LT, and the 500 mb map also on (c) 8:00 LT and (d) 20:00 LT, October 4, 1991.

Similar findings were also evident in the SO_2 (sulfur dioxide), CS_2 (carbon disulfide) and DMS (dimethyl sulfide) data (Figure 4c). Along an altitude of 6.5 km, the level of SO_2 , CS_2 and DMS was about 75, 3 and 3 pptv, respectively. In contrast, over northern Taipei at 3 km altitude, the concentration of SO_2 , CS_2 and DMS reached 1700, 40 and 11.5 pptv, respectively. It is interesting to note that the area where the peak DMS was observed, near 122.5°E (NE Taiwan), was far away from the SO_2 peak region. Discussions with a few oceanic scientists about this phenomenon leads to an interesting finding. The DMS peak region coincides with an active fishing field where updrafts from the deep ocean have been observed. Updrafts usually bring a lot of nutrients to the surface level, where phytoplanktons grow considerably. Fishes taking phytoplanktons as food will hence gather in this region (Fan, 1980; Chen, 1992; Liu *et al.*, 1992; Lee, 1994). Since DMS is a biogenic product emitted by phytoplanktons from the ocean, the observed high level of DMS over the NE

Table 1. Chemical species measured on DC-8.

Species	Measurement technique	Performance	Reference or Principal Investigator
O ₃	O ₃ -C ₂ H ₄ Chemiluminescence	Precision: 1-2 ppbv (2%) Accuracy: 5ppbv (5%) Data interval: 10sec.	Gregory et al. (1992)
H ₂ O vapor	Lyman OC Fluorescence		K. Kelly
NO, NO ₂ & NO _y	TP-LIF (Two -Photon Laser-induced Flourescence Technique)	Precision: NO (+ 15%) NO ₂ (+18%) NO _y (+20%) Integration time: 90s or 180s	Bradshaw et al., 1985 Gregory et al., 1990 Hoell et al., 1987 Sandholm et al., 1990
PAN, PPN & C ₂ Cl ₄	PANAK (PAN/Aldehyde/ Ketone); GC/EC	Detection limit: 4ppbv accuracy: +25%	Singh and Salas, 1983, 1989
HNO ₃ , HCOOH, CH ₃ COOH, CH ₃ (CO)COOH, SO ₂	Aqueous scrubber/Ion Chromatography	Uncertainties: HNO ₃ (25%) HCOOH (15%), CH ₃ COOH (18%), CH ₃ (CO)COOH (20%), SO ₂ (20%)	Talbot et. al., 1988, 1990a,b, 1992.
CO ₂	Non-dispersive IR Spectrometer	accuracy: 0.5ppmv	B. E. Anderson & G. L. Gregory
CO, CH ₄ , N ₂ O	DACOM (Differential Absorption CO Measurement); Diode Laser Absorption	Precision: CO (2%); CH ₄ & N ₂ O (0.1%)	Sachse et al., 1987, 1988
Hydrocarbons (C ₂ -C ₆); Halocarbons	Grab Sample/ GC (Gas Chromatography)	Precision: Alkanes (3% or 3ppbv); Alkenes (5% or 5ppbv); Halocarbons (0.7-4.2%).	Blake et al. (1994)
SO ₂ , DMS, CS ₂ , OCS	GC (Gas Chromatography) /MS (Mass Spectrometry)	Detection limit: 1ppbv Precision: 10%	Thornton et al, 1986 Driedger et al., 1987 Lewin et al., 1987
H ₂ O ₂ , ROOH	Grab samples / two- enzyme dual-channel fluorescence technique	Detection limit: 100pptv Precision: 10%	Heikes et al., 1987, 1988

corner of Taiwan can, therefore, be explained. Further study is needed to determine in detail the spatial and seasonal variation of DMS over this region.

The greenhouse gases CO₂, CH₄, N₂O and C₂CL₄ maintained relatively constant levels in the maritime clean airmass. The CO₂ level was about 352-353 ppmv, in contrast to 360 ppmv in the polluted air (Figure 4d). The CH₄ level was about 1710-1740 ppbv, in contrast to 1830 ppbv in the polluted air (Figure 4e). The N₂O level varied between 308.5-310 ppbv, in contrast to 311 ppbv in the polluted air (Figure 4e). The C₂CL₄ level was about 2.5-3 pptv (Figure 4b) during flight track I. The carbon monoxide (CO) was about 100 ppbv at 6.5 km altitude, typical for clean tropospheric air, while near northern Taiwan, CO reached up to 275 ppbv in the polluted plume (Figure 4e).

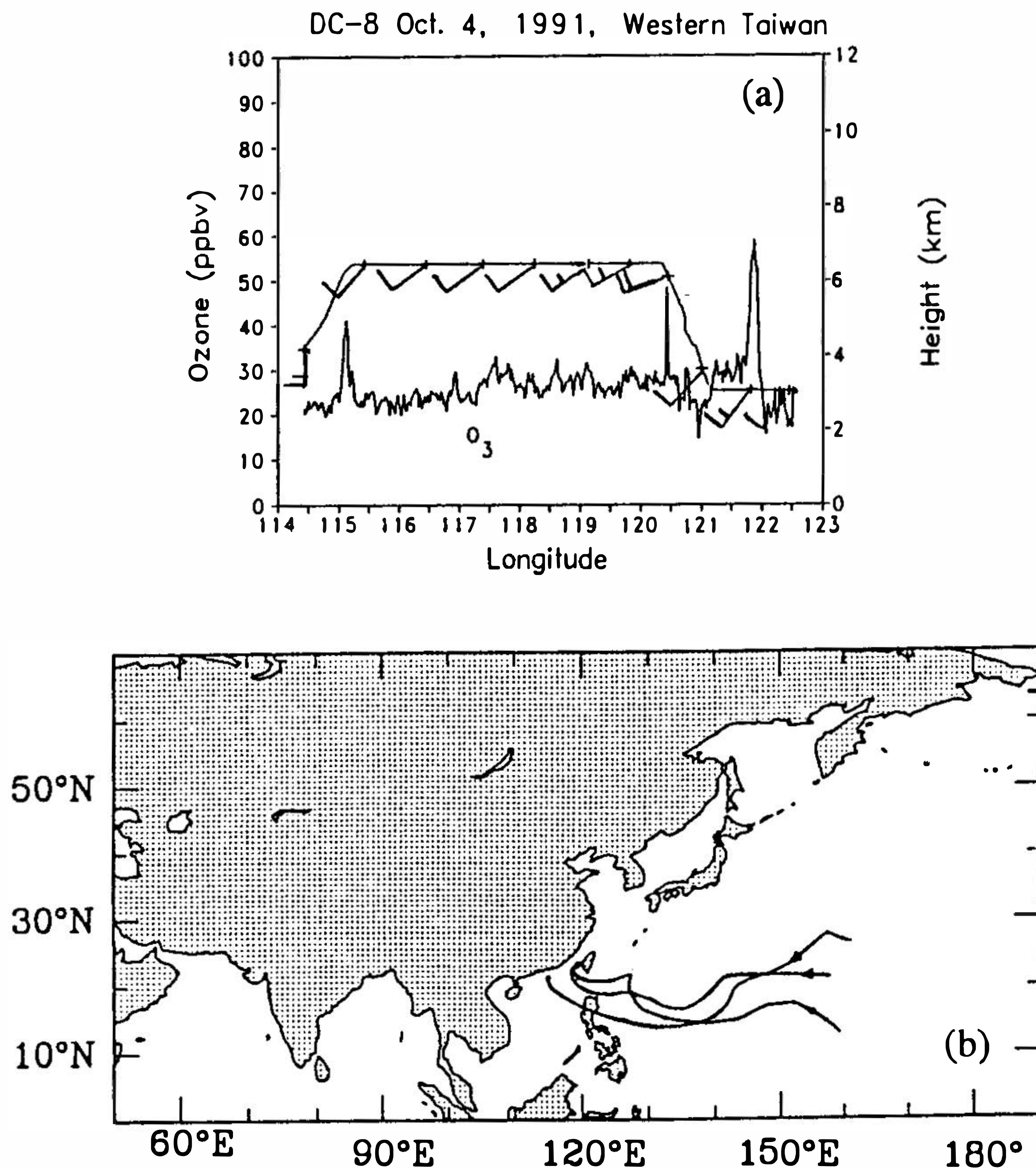


Fig. 3. (a) The variation of ozone and wind field along the flight track I on October 4, and (b) the air-parcel trajectories back traced from the flight track I along an isentropic surface.

During the flight, data of H_2O_2 , ROOH and total hydroperoxides (Figure 4f) show that the levels of these species generally decrease with altitude. In the polluted plume, they all maintained low concentrations, typical for fresh polluted air. Their concentrations varied between 600-2200 pptv, 250-750 pptv and 600-2700 pptv, respectively.

4. EASTERN TAIWAN (Flight Track II)

The DC-8 spent most of its flight (from 10:30-16:30 LT) monitoring eastern Taiwan with a flight track parallel to the east coast from (25.5°N , 122.5°E) to (21.7°N , 121°E) (Figure 1). During this period, the DC-8 made two spiral ascents at the northeast (NE) corner from 11:25-11:51 LT and 13:41-14:14 LT, and two spiral descents at the southeast (SE) corner from 12:35-12:56 LT and 14:58-15:35 LT (Figure 5a). Also, the DC-8 flew along the 10 km, 8.5 km and 3.7 km level, respectively. At the end of this flight, the DC-8 flew along the 2 km level from the SE corner to the middle of the east coast, then descended to the 0.35 km level and flew toward the CATS Kenting site. The purpose of this final route was to compare the DC-8 in-situ measurement data with the Kenting data.

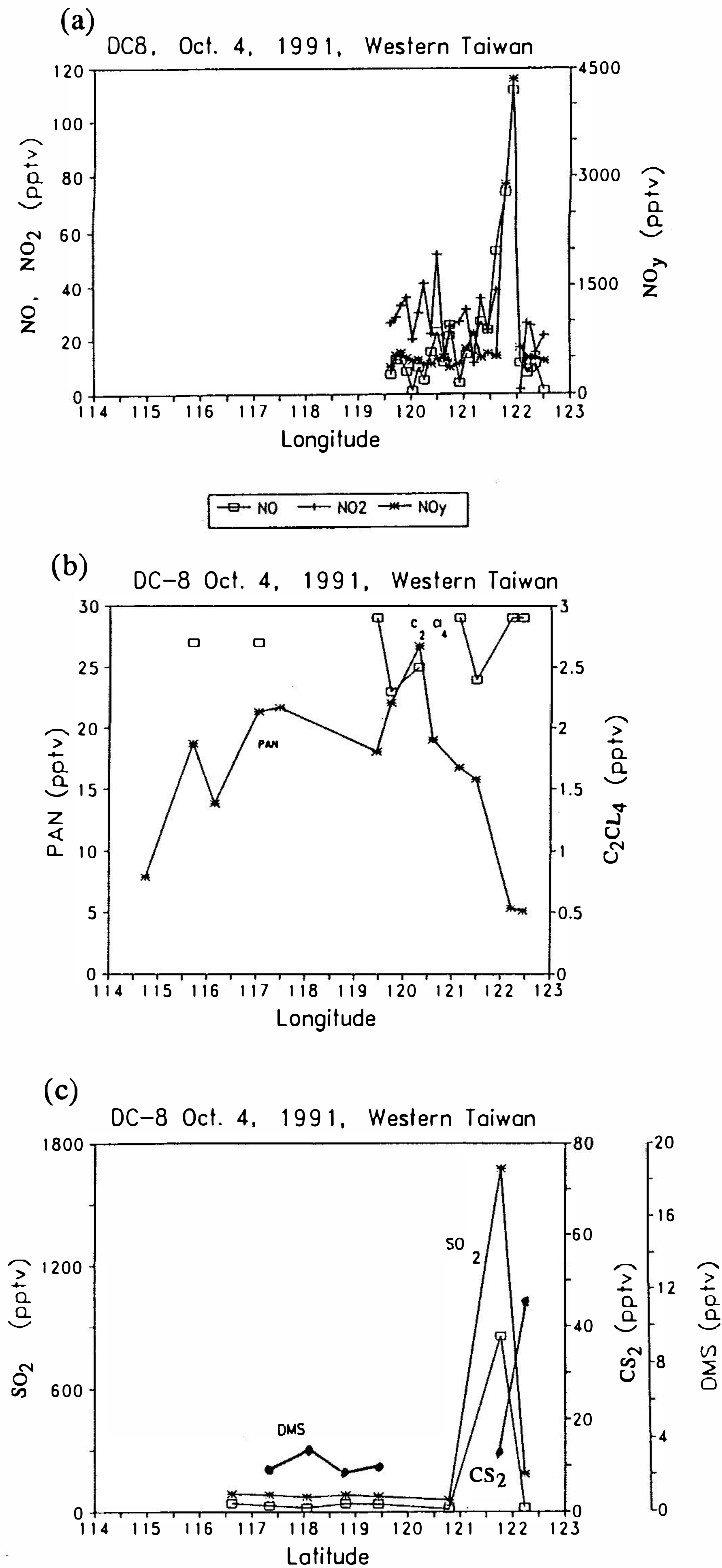


Fig. 4. The variation of (a) NO, NO₂ and NO_y, (b) PAN and C₂CL₄, and (c) SO₂, CS₂ and DMS, (d) CO₂, (e) CO, CH₄ and N₂O, and (f) H₂O₂, ROOH and total hydroperoxide along the flight track I on October 4.

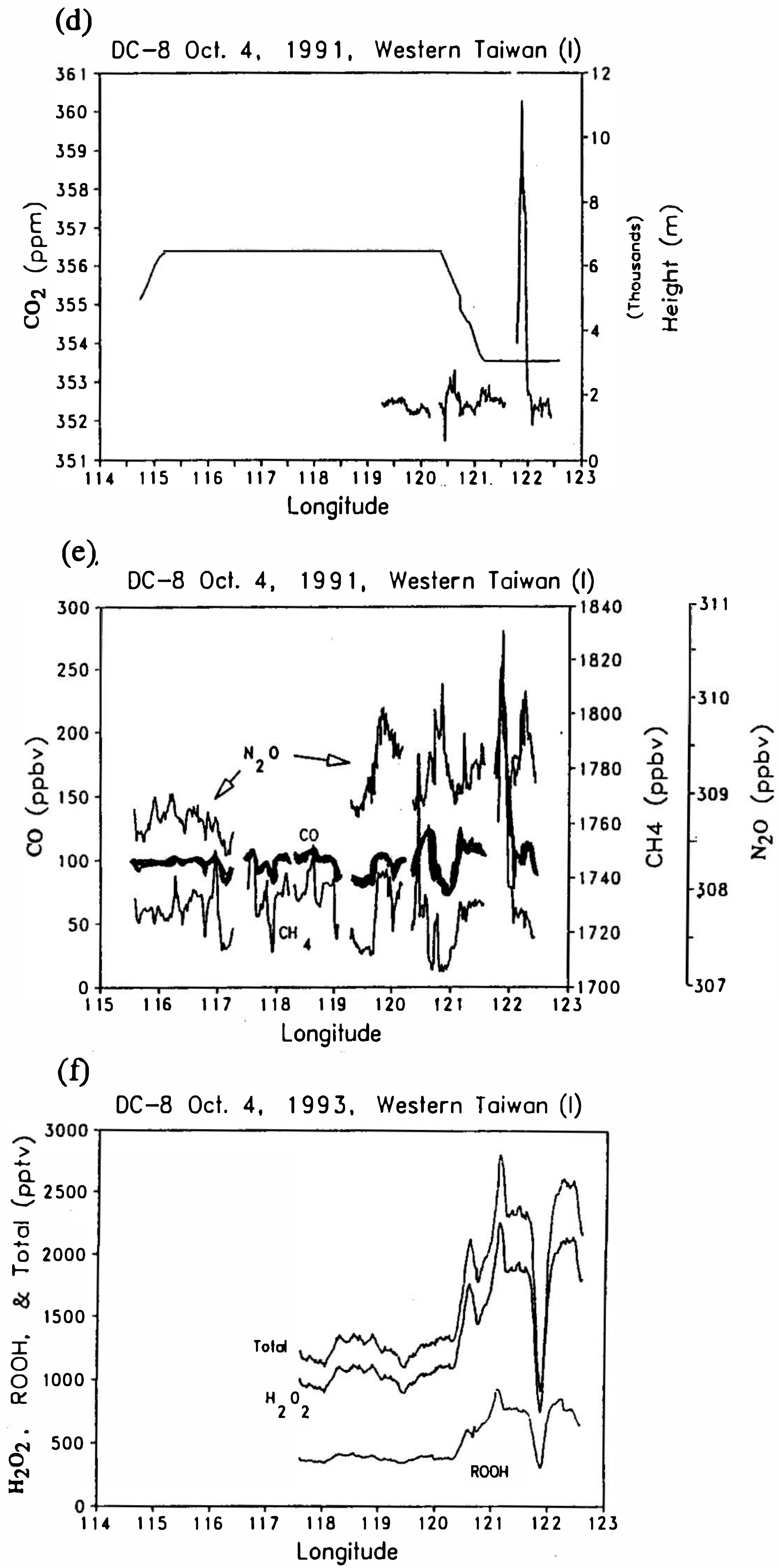


Fig.4. (Continued)

Wind flow along eastern Taiwan on October 4 was westerly at levels above 4 km. Wind speed was about 15-30 m/s at the NE corner, but was weak with variable wind directions at the SE corner (Figure 5a). Along the 10 km and 8.5 km levels, the wind speed was about 7-15 m/s which was considerably weak at that layer (Figures 2c and 2d). Below 4 km, it was southerly at the 3.7 km level, but changed to northerly at the 2 km level. The observed wind field reflected the fact that there was no dominant synoptic system over Taiwan. Meanwhile, there was a negligible change of temperature horizontally. The temperature decreased linearly with a lapse rate about $5.4^{\circ}\text{C}/\text{km}$ from surface toward upper levels (Figure 5b). Vertical profile of water vapor H_2O (Figure 5c) showed a decrease of concentration from 2.8×10^5 ppmv at 0.35 km to 3×10^2 ppmv at 10 km. Over the SE corner, a dry region appeared between an altitude of 2-3 km. The water vapor concentration dropped from an expected 1.5×10^5 ppmv level to the observed 0.5×10^5 ppmv level.

Backward air-parcel trajectories along the isentropic surface from the NE and SE corners of Taiwan show that the air originated from southern Asia at upper levels, but from the middle Pacific at lower levels (Figures 6a,b,c,d). It is noted that the upper layer air first passed by southern China near Hainan Island before reaching the Taiwan area. On previous days, typhoon Nat had entered southern China by the Hainan Island while moving northward from the South China Sea. The strong upward convection could bring the surface polluted air upward to the upper tropospheric region (Newell, *et al.*, 1994). Some of the chemical species measured on October 4 along the eastern Taiwan showed such a signal. The backward air-parcel trajectories used here were provided by Merrill (1995), who used the NMC data to perform such calculations. The accuracy is not high enough to give a microscale feature, but is sufficient to determine a general moving direction.

4.1 Vertical Profile of Chemical Species

4.1.1 Ozone

By putting all in-situ measured ozone data together with respect to altitude (Figure 7a), it is noted that below 6 km, the ozone concentration was about 10-50 ppbv with a mean level of about 20-30 ppbv, whereas, above 6 km, the variation of ozone was significant, ranging between 20-90 ppbv. In general, there was an increase of ozone level toward upper layers. At the NE corner, the ozone concentration jumped from a mean level of about 22 ppbv below 6 km to a mean level of about 55 ppbv at layers above 6.5 km and a peak level of 90 ppbv at 8 km (Figure 7b). Meanwhile, at the SE corner, the ozone level increased gradually from a minimum level of 20 ppbv at 4 km altitude to about 40 ppbv at 8 km and a peak of 85 ppbv at 9.5 km (Figure 7c), which is different from the vertical profile observed at the NE corner. It seems that the vertical mixing of upper-level air, which was characterized with high ozone concentrations, and that of lower-level clean maritime air (Figures 6a,b,c,d) which was associated with low ozone level, was more effective at levels between 4-6 km altitude over the SE corner of Taiwan.

In the middle of the east coast, the DC-8 descended from 2 km to 0.35 km between 16:02 LT and 16:40 LT. The ozone data show that there was a peak of 40 ppbv of ozone at about 1.3 km altitude. Careful analysis of the meteorological data there shows a swift change in the wind direction from northeasterly above 1 km to southwesterly below. High ozone levels occurred in the northeasterly region. In the following, it will be noted that the peaks of NO , NO_2 , NO_y , CO , etc. also occurred in the same area, which could all be associated

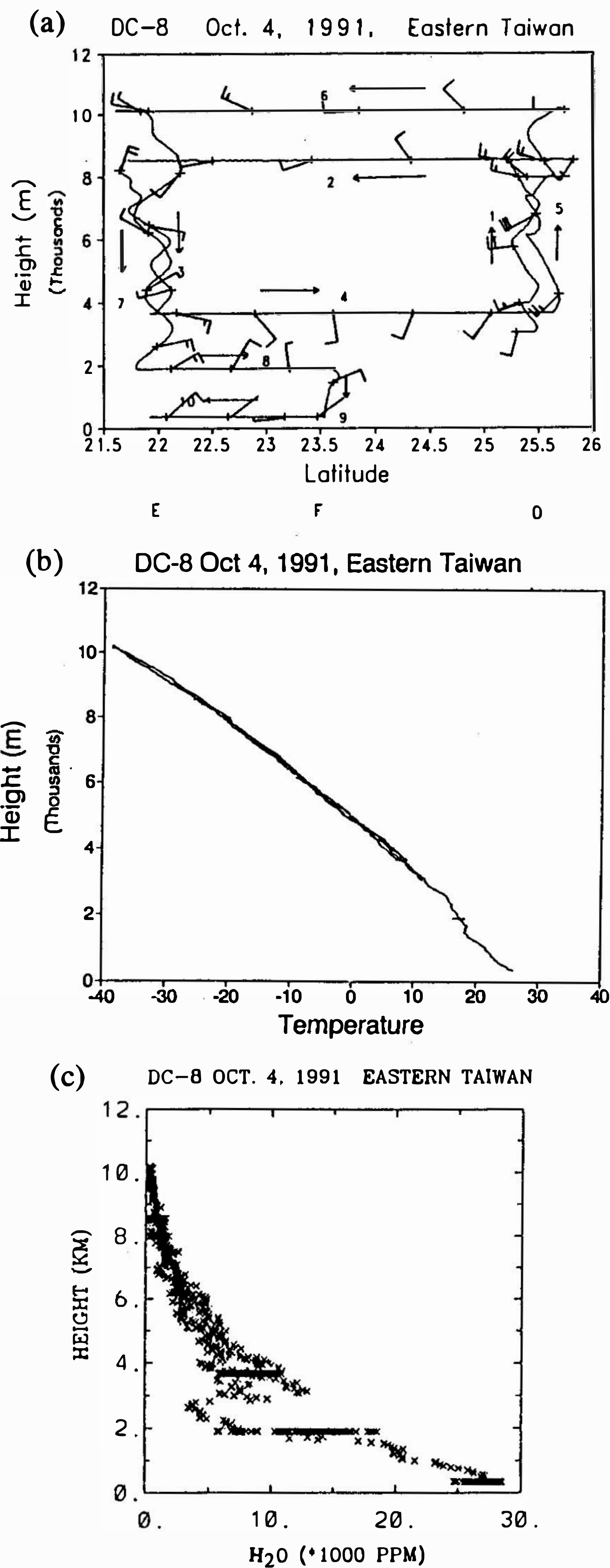


Fig. 5. Along the eastern Taiwan on October 4, (a) the flight track on the height-latitude profile, and the wind bars observed along the track; (b) the vertical profile of temperature and (c) water vapor.

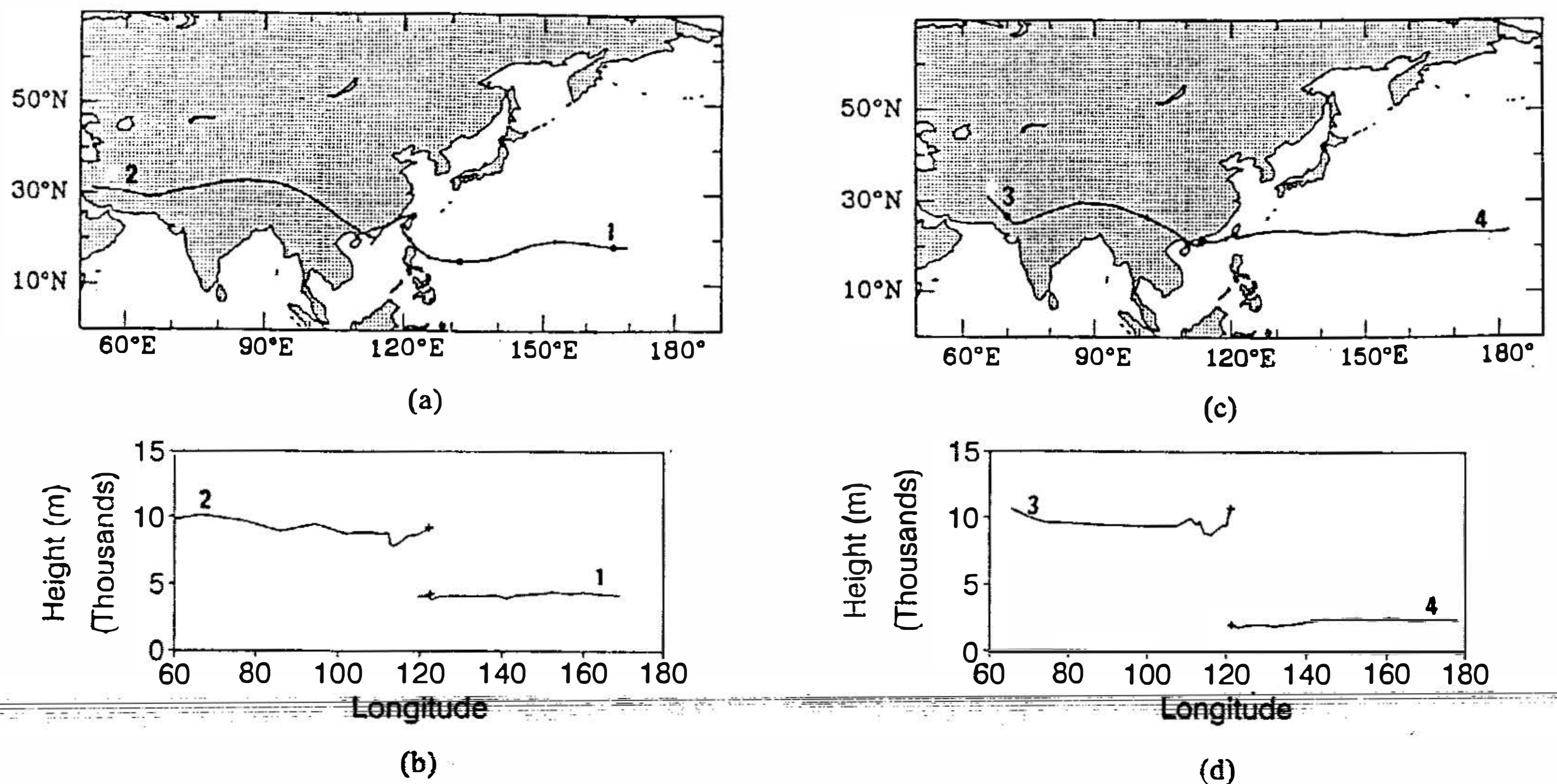


Fig. 6. Backward air-parcel trajectories from the NE corner of Taiwan along an isentropic surface on the (a) latitude-longitude and (b) height-longitude plane. The air-parcels were back traced from 11:29 LT (track 1) and 11:50 LT (track 2). Similar analyses were done for air-parcels from the SE corner of Taiwan and are shown in (c) and (d). The air-parcel was back traced from 14:48 LT (track 3) and 15:34 LT (track 4) on October 4.

with a polluted plume from upstream sources. It is difficult to identify sources of such a polluted plume with the sparse meteorological data over the ocean.

4.1.2 Nitrogen-containing Compounds

The nitrogen-containing compounds are important species in tropospheric chemistry. The nitrogen oxides (NO_x) are ozone-production precursors and influence the concentration of tropospheric OH (Logan, 1983). The ozone production rate in the troposphere is almost linearly related to the level of NO_x . Usually, NO_x consists of two species: NO and NO_2 . In the lower troposphere, nitric oxide (NO) is emitted by the anthropogenic sources, such as the burning of fuel at high temperature. Through chemical reactions, such as the oxidation of NO, NO_2 is formed. Meanwhile, there are other nitrogen-containing species such as PAN (Peroxyacetyl nitrate), PPN (proxypionyl nitrate), etc. are formed through reactions with OH and hydrocarbons. Usually, NO_y is taken as the sum of all odd nitrogen species including NO, NO_2 , nitric acid (HNO_3), inorganic aerosol nitrate (NO_3^-), nitrous acid (HNO_2), nitrate radical (NO_3), peroxy nitric acid (HOONO_2), chlorine nitrate (ClONO_2), dinitrogen pentoxide (N_2O_5), organic nitrate such as PAN (peroxyacetyl nitrate), proxypionyl nitrate (PPN), methyl nitrate (MN), etc. (Roberts, 1990). These can act as reservoirs of nitrogen and be transported to higher altitudes, where NO is released and is active in ozone production. Among all the nitrogen-containing species, HNO_3 is usually taken as the sink of nitrogen, since HNO_3 is the end product of the oxidation of the nitrogen oxides, and can be easily deposited to the ground through either wet or dry deposition processes.

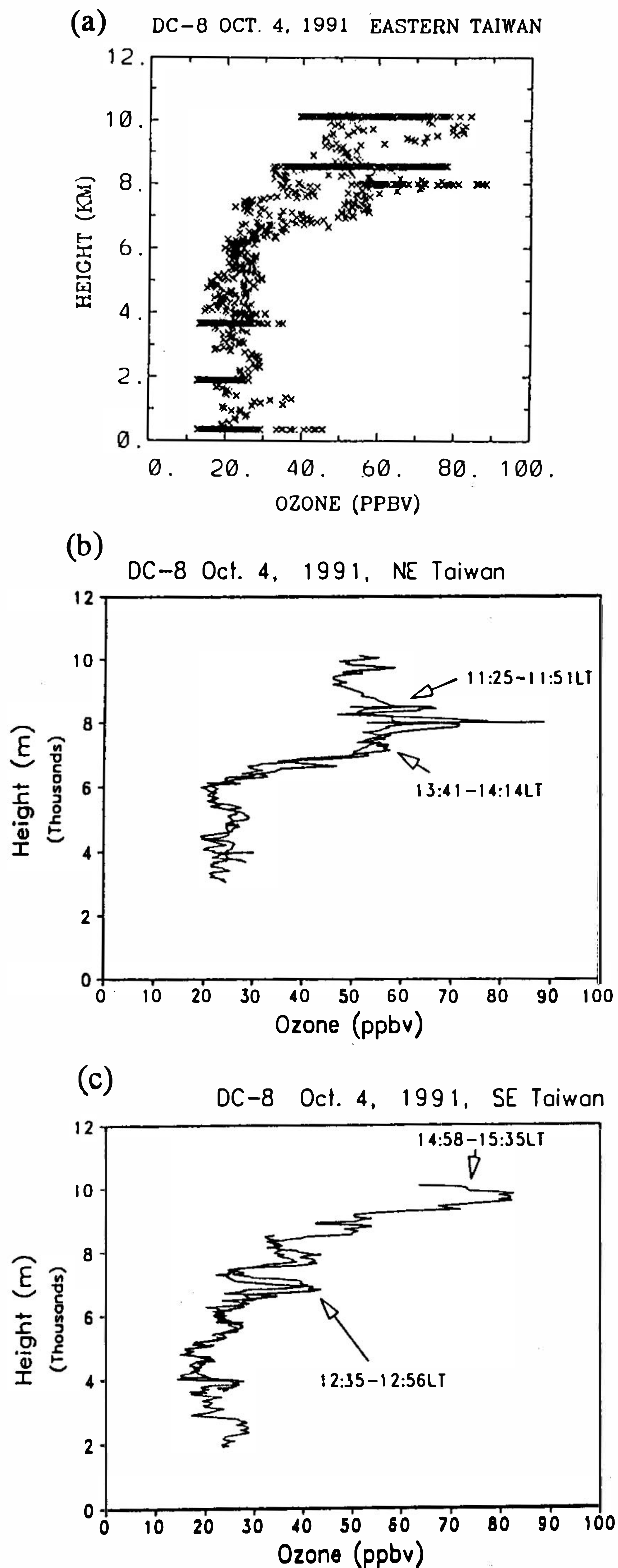


Fig. 7. Along the eastern Taiwan on October 4, the vertical profile of ozone, (a) all in-situ measurement data, (b) at the northeastern (NE) corner and (c) at the southeastern corner.

At the NE and SE corners of Taiwan, the level of NO increased with altitude (Figure 8a). At the NE corner, a peak concentration of 70 pptv was observed at 8 km where the concentration of ozone (Figure 7b) also reached a peak. Meanwhile, below 6 km, the NO level jumped from 5 pptv to 25 pptv at 4 km. At the SE corner (Figure 8a), a smooth increase in NO from 3 pptv at 2 km altitude to 11 pptv at 8.5 km was observed. Above 8.5 km, a jump of NO level from 11 pptv to 70 pptv at 9 km altitude occurred, while in the middle of the east coast, a peak level of 24 pptv appeared just above 1 km altitude. The vertical variations of NO were quite similar to those of ozone (Figures 7b and 7c).

The NO₂ level also increased with altitude (Figure 8b), and was in general larger than that of NO at levels below 8 km, which indicated that the air had gone through complete chemical reactions before arriving to Taiwan. The NO_y profile (Figure 8c) was similar to those of NO and NO₂, with the concentration being about one order of magnitude larger. The peak concentration of NO_y was about 800-900 pptv at layers above 8 km. The minimum concentration was about 300 pptv at 5.5 km in the NE corner, and 120 pptv at 2 km in the SE corner. Below 2 km, a peak NO_y level of 400 pptv occurred at about 1 km altitude. In general, levels of NO_y were larger than the summation of NO, NO₂ and PAN, which is because most of the nitrogen had transformed to HNO₃ (Roberts, 1990). However, during this field trip, the HNO₃ data which was measured and which is shown later, were unreasonably low. This could be due to some measurement problems.

There were only limited observations of PAN. Therefore all the observed data are plotted together. Figure 9a shows an increase in the PAN concentration from 1 pptv at 0.35 km altitude to a peak of 120 pptv at 8 km and 240 pptv at 10 km. Such a vertical profile, characterized by the concentration increasing with altitude, is consistent with previous observations, and is due to thermal decomposition of PAN. Hence, above 6 km PAN has a longer lifetime and can act as an important reservoir of nitrogen (Roberts, 1990). The ratio of PAN to NO_y was about 0.0005 at 0.35 km and 0.25-0.3 at 8-10 km. This suggests that more nitrogen containing compounds were transformed to PAN at upper altitudes. Meanwhile, the level of 1-8 pptv observed in the lower boundary layer is close to those observed at remote regions at lower latitudes (Walega *et al.*, 1992).

There is another nitrogen containing compound, i.e. nitrous oxide (N₂O), which is one of the important green-house gases. It is also a major source of stratospheric nitrogen oxides. The dominant source of nitrous oxide is denitrification in aerobic soils, which has a significant anthropogenic component owing to the deforestation and the use of nitrogenous fertilizers. The major sinks are stratospheric photodissociation and photooxidation. The vertical profile of N₂O over eastern Taiwan (Figure 9b) shows that its concentration varied between 308-315 ppbv, which indicates that this chemical species is well-mixed in the troposphere and is slow in reacting with other species. The observed level is close to the mean value of 310 ppbv observed in other regions (WMO, 1991).

4.1.3 Carbon Monoide and Carbon Dioxide

The major emission sources of carbon monoide (CO) are combustion and production in the atmosphere through the oxidation of methane and higher hydrocarbons. The direct emissions from ocean and from vegetation are less important. In the troposphere, it plays significant role in controlling the chemistry of ozone production and hydroxyl radical destruction in the lower atmosphere. Figure 9c shows that below 4 km, CO was less than 80 ppbv. Above 4 km, CO increased steadily to a maximum of about 150 ppbv at 10 km. Meanwhile,

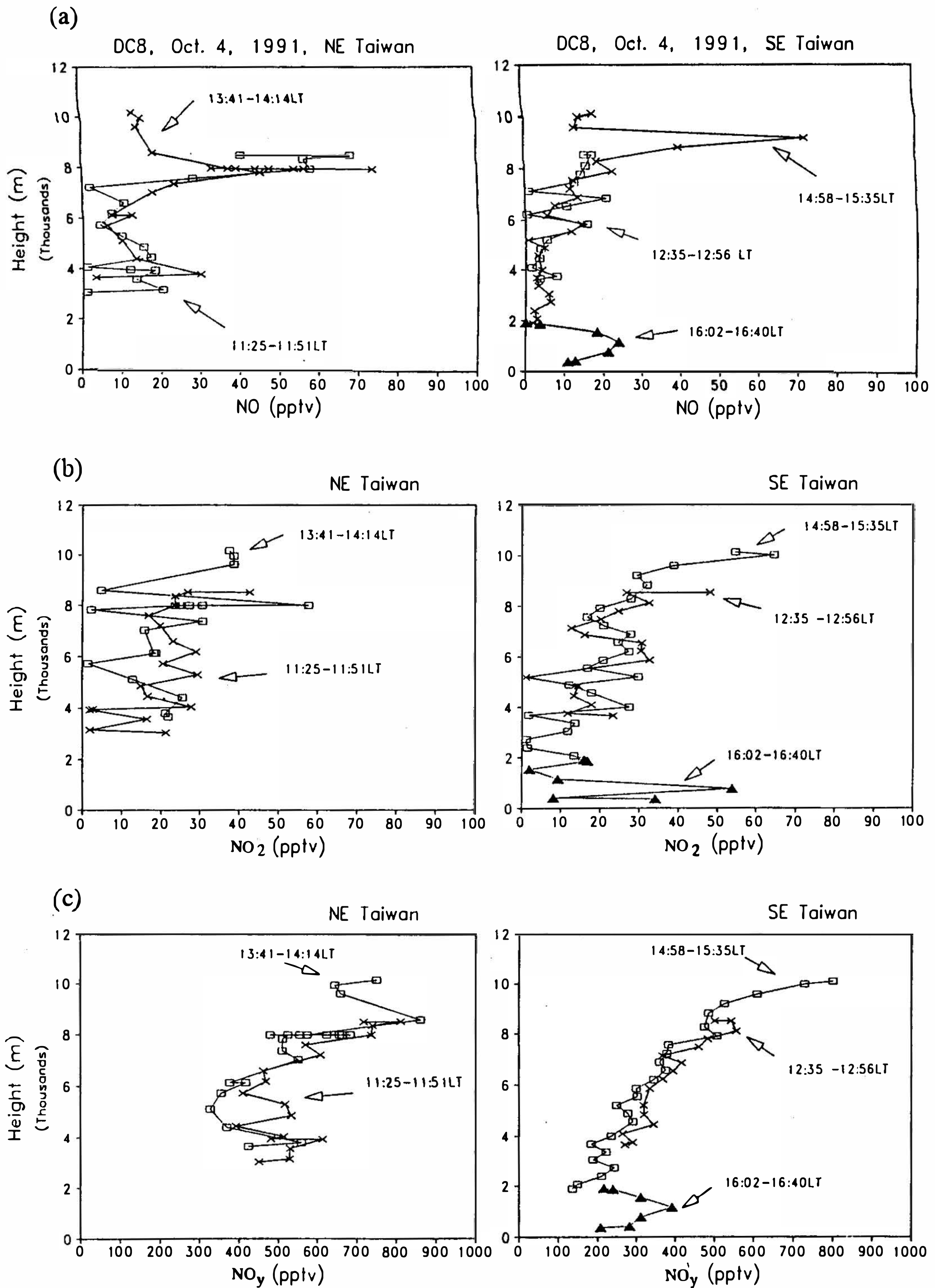


Fig. 8. Along the eastern Taiwan on October 4, the vertical profile of (a) NO, (b) NO₂ and (c) NO_y over the NE and SE corners.

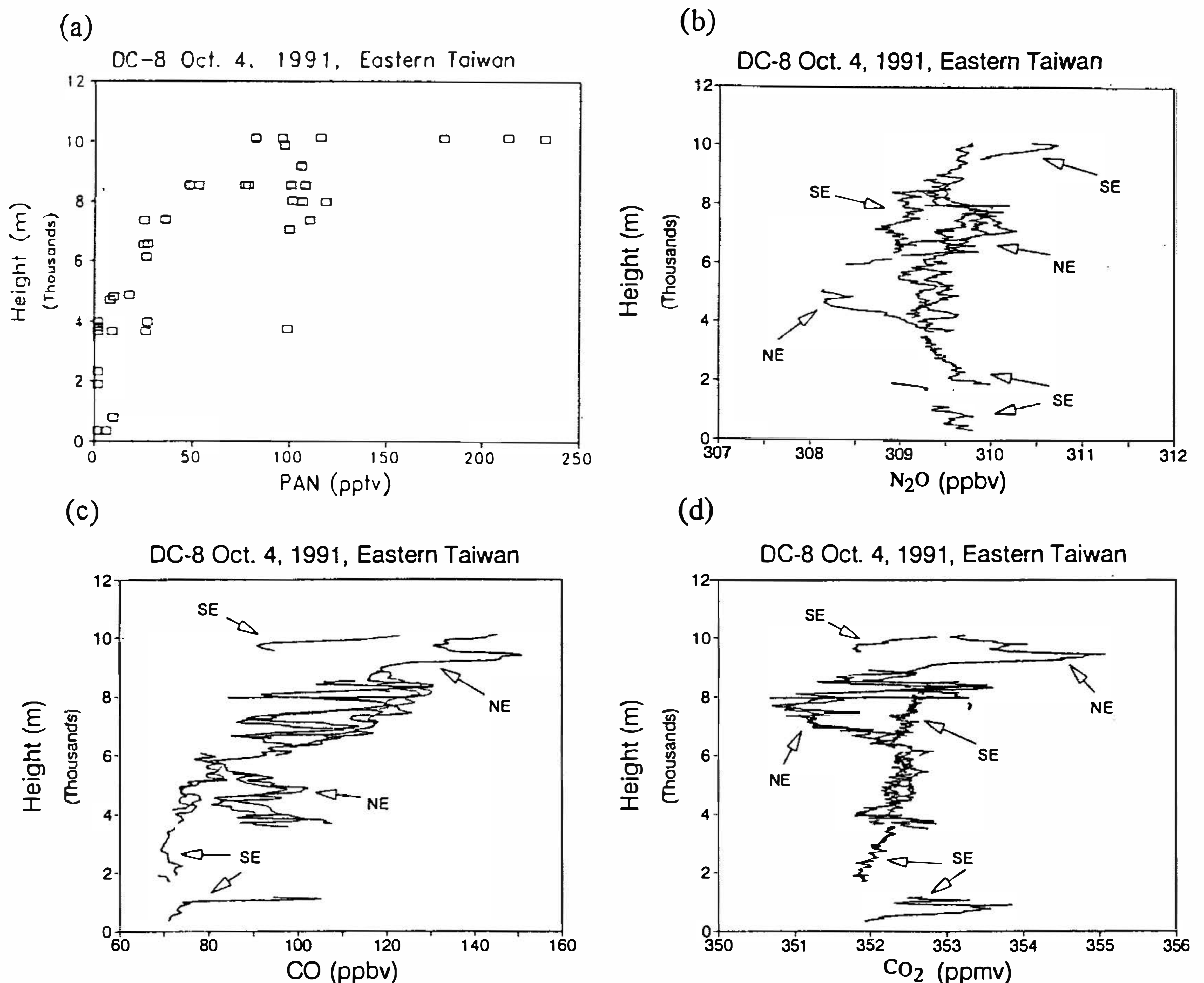


Fig. 9. Along the eastern Taiwan on October 4, the vertical profile of (a) PAN, (b) N₂O, (c) CO and (c) CO₂.

in the boundary layer, a peak of 105 ppbv occurred at about 1 km altitude. At Mauna Loa, CO ranges between 70-120 ppbv (WMO, 1991), which is close to what was observed here. At remote areas in the mid-latitudes, CO varies between about 80-130 ppbv (Parrish *et al.*, 1991). Hence, it is certain that during the intensive flight period over eastern Taiwan, the locally polluted plume had not been mixed with the up-stream, well-diluted air.

The greenhouse gas CO₂ (carbon dioxide), varied between 351-355 ppmv vertically (Figure 9d), which indicates that the gas is well-mixed in the troposphere and has a longer lifetime than the time scale of atmospheric motion. In the boundary layer, a peak of CO₂ is distinguishable at about 1 km altitude.

4.1.4 Sulfur-containing Compounds

The biogenic sulfur species DMS (dimethyl sulfide) is abundant near the sea surface. Figure 10a shows that at 0.35 km, the level of DMS varied between 3-8 pptv but was below the detection limit of 1 pptv between 2-8.5 km. Above 8.5 km, 2-3 pptv of DMS was observed. Such vertical profiles are consistent with measurements at other regions, except that the observed 8 pptv level in the boundary layer was smaller than data reported elsewhere.

For instance, Ferek *et al.* (1991) reported a level of 10-50 pptv over the ocean surface about 80 km off the Washington coast.

Another biogenic sulfur species, carbon disulfide (CS_2) had concentrations smaller than 1 pptv at lower altitudes (Figure 10b). Its concentration increased with altitude and reached a peak of 6.2 pptv at 10 km. Its profile was similar to those of ozone, NO_x etc. Carbonic sulfide OCS (S-O-C, or COS) maintained a constant level of 50 pptv in most regions (Figure 10c). Meanwhile, above 2 km, sulfur dioxide (SO_2) exhibited a vertical profile of increasing concentration with respect to altitude (Figure 10d). The peak concentration occurred at 10 km at about 175 pptv. Such vertical profiles were typical for a clean remote troposphere (Ferek *et al.*, 1991). Along 0.35 km, the SO_2 level varied considerably from 100 pptv to 500 pptv, which must have been the result of anthropogenic emissions at the surface. Possible sources are international freighters in the western Pacific.

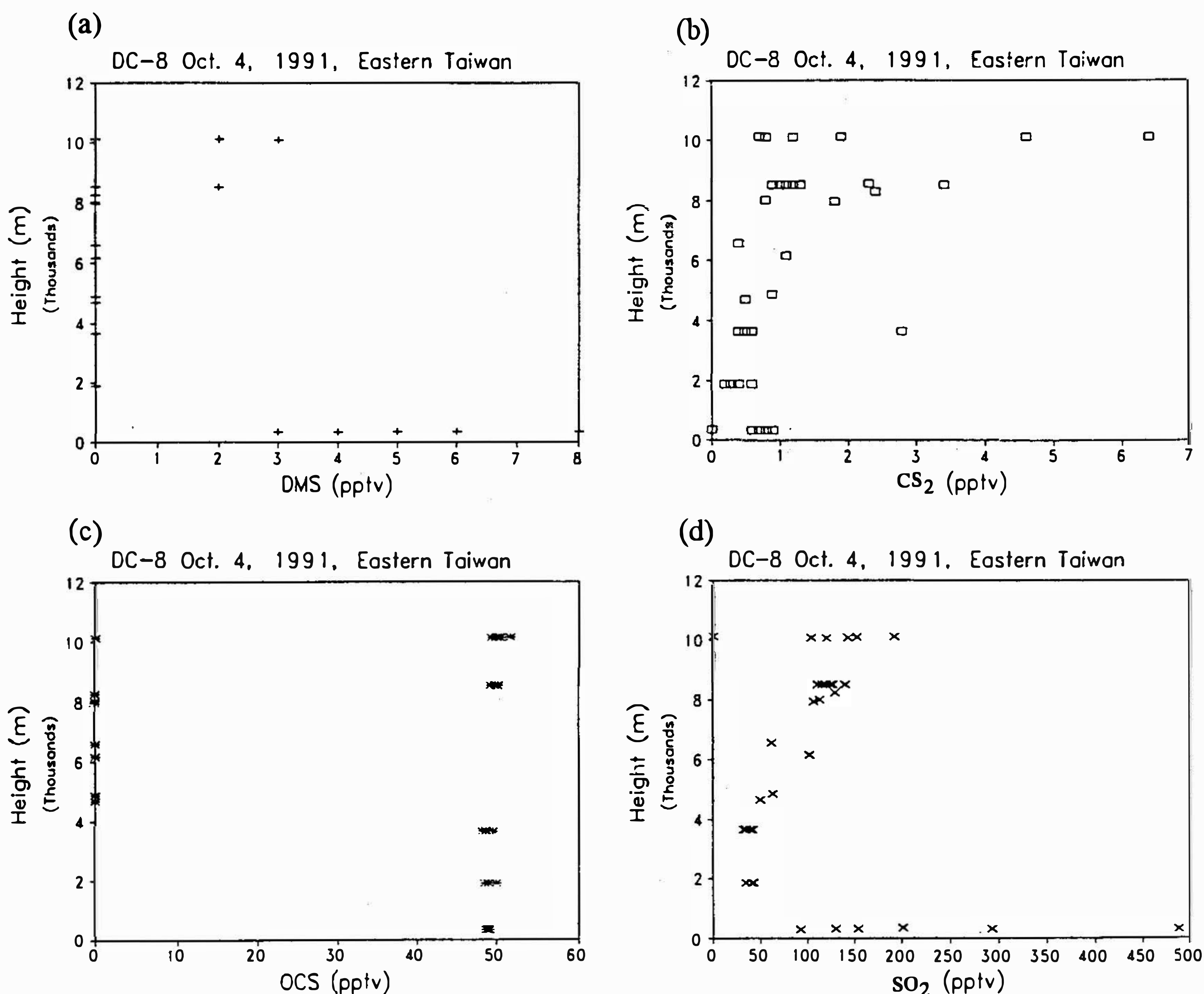


Fig. 10. Along the eastern Taiwan on October 4, the vertical profile of (a) DMS, (b) CS_2 , (c) OCS and (c) SO_2 .

4.1.5 Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are chemically inert in the troposphere but are destructive to ozone in the stratosphere. On the other hand, in the atmosphere, they are active in

absorbing infrared radiation and enhance the global greenhouse effect. Their lifetimes are much longer than the time scale of atmospheric motion. F-11 (CCl_3F), F-12 (CCl_2F_2), F-113 ($\text{C}_2\text{Cl}_3\text{F}_3$), methyl chloroform (CH_3CCl_3), and carbon tetrachloride (CCl_4), each comprises 23%, 28%, 6%, 14% and 13%, respectively, of the anthropogenic organochlorine loading of the troposphere (WMO, 1991). In eastern Taiwan, the level of F-11 ranged between 270-285 ppbv (Figure 11a), which is close to the 280 ppbv level observed in the northern hemisphere. Meanwhile, F-12 was 495-520 ppbv (Figure 11a), which is slightly higher than the 480-500 ppbv levels observed elsewhere (WMO, 1991). The peak concentrations of F-11 and F-12 were observed at around 10 km altitude, while the lowest concentrations occurred at 0.35 km. It is estimated that in the boundary layer, F-11 was about 273 ppbv, while F-12 was about 502 ppbv.

F-113 ($\text{C}_2\text{Cl}_3\text{F}_3$), methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4) and perchloroethylene (C_2Cl_4) are shown in Figure 11b and Figure 11c. Another measurement of C_2Cl_4 by Singh *et al.* (1993) is plotted in Figure 11d. In general, F-113 varied between 86-94 pptv, CH_3CCl_3 between 140-200 pptv, CCl_4 between 115-132 pptv, and C_2Cl_4 between 2-5 pptv. In comparison with global measurement data, these data are close to other observation, except for C_2Cl_4 . WMO (1991) reports that the global mean is about 80 pptv for F-113, 175 pptv for CH_3CCl_3 , 140 pptv for CCl_4 , and 30 pptv for C_2Cl_4 . Meanwhile, Figure 11d shows that C_2Cl_4 had two maxima. One was in the upper atmosphere, and the other was in the boundary layer. The upper-layer maximum indicates global-scale mixing, while the lower-layer maximum was from near-by pollution sources.

4.1.6 Hydrocarbons

Methane (CH_4) is one of the major greenhouse gases. It is produced from a variety of anaerobic processes and is removed primarily by reactions with OH in the troposphere. Figure 12a shows that a minimum concentration of 1700 ppbv occurred at 5 km altitude. Above this layer, methane increased to a maximum level of 1850 ppbv at 8 km; then it decreased slowly. Below 5 km, the change in the methane level was negligible. Peak CH_4 at 2 km was about 1730 ppbv, while at 0.35 km, CH_4 level was about 1710 ppbv. At the NE corner, peak CH_4 of 1840 ppbv occurred at 8 km altitude, which was much higher than the 1740 ppbv at the SE corner. These variations were similar to those of ozone, NO, NO_y , etc. The CH_4 data reported elsewhere show a significant seasonal variation with the difference between the yearly maximum and minimum being about 50 ppbv. Mauna Loa station reports a yearly mean of about 1712 ppbv (WMO, 1991), which is close to what was observed here.

The Non-Methane HydroCarbons (NMHCs) play an important role in OH chemistry and are an important source of CO. They can be classified into three different groups depending on their lifetime: relatively long lived (lifetimes longer than weeks), more reactive (lifetimes between 12 hours and 1 week), and extremely short-lived (lifetimes of hours), such as ethane (C_2H_6), C_2 - C_5 alkenes and isoprene, respectively.

Over eastern Taiwan, the level of ethane (C_2H_6) increased with altitude (Figure 12b) and peaked at 10 km at about 1050 pptv, while the minimum at 0.35 km was about 280 pptv. At about 1 km altitude, where peaks of ozone, NO, etc. were observed, a high level of 860 pptv was also observed. The temporal variation of ethane is plotted in Figure 12c. By matching Figure 12c with the altitude variation plot of the flight track (Figure 1b), the vertical profile can also be distinguish. The ethane to ethyne ratios are plotted in Figure 12d, which shows that the ratio can be as large as 18 at altitudes below 2 km, where low ethyne

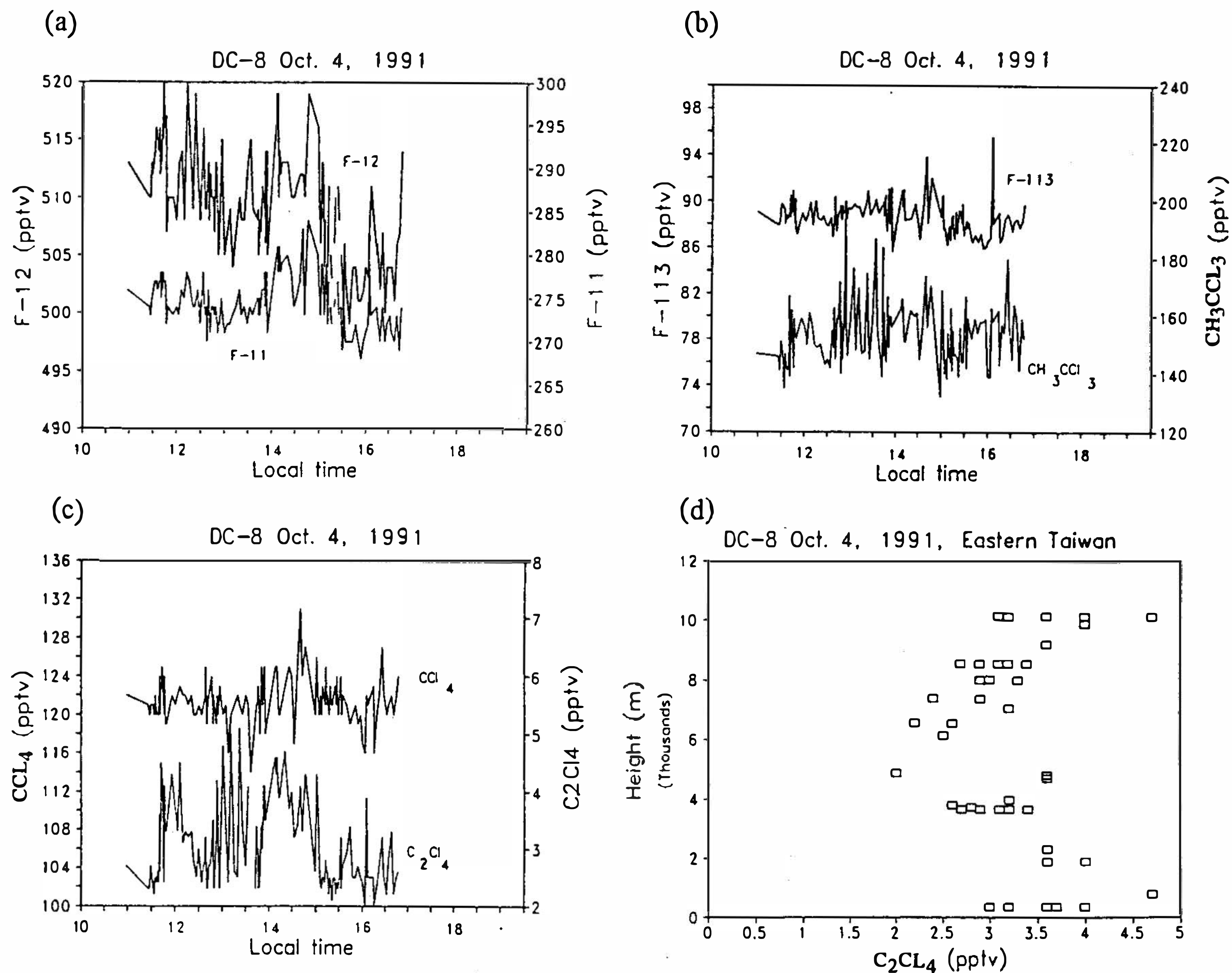


Fig. 11. Along the eastern Taiwan on October 4, the temporal variation of (a) F-11 and F-12, (b) F-113 and CH₃CCL₃, (c) CCL₄ and C₂CL₄, and (d) the vertical profile of C₂CL₄.

levels of 20-50 pptv were observed. By way of comparison, the ratios were about 3 at 10 km altitude where high ethyne levels of 200-500 pptv were observed. It is clear that the levels of ethyne (C₂H₂) also increased with altitude, but the ethane to ethyne ratios did not stay at a constant level; rather, they decreased with altitude. Both ethane and ethyne are released mainly from anthropogenic sources with a higher portion of ethane than that of ethyne in a unit volume (Liu et al., 1994), but the destruction rate of ethyne through chemical reactions is the slowest in comparison with other NMHC species. Therefore, the ratio of ethane to ethyne indicates the aging state of the air. At areas near to the emission sources, the ratio was high and when the air was transported away from the sources, the ratio was low.

The temporal variation of propane (C₃H₈) is close to that of ethane. The peak at 10 km was about 120 pptv. Below 4 km, the concentration dropped to 5 pptv. In the polluted plume at about 1 km altitude, the peak level was about 250 ppbv, which was higher than that at 10 km. Also, the ratio of propane to ethyne shows that a ratio of 2.5 occurred at 0.35 km where propane concentration was below 10 pptv, while low ratios occurred at upper altitudes. At 10 km, the ratio was about 0.5.

There were also measurements of *i*-butane, *n*-butane, and *n*-hexane, i.e. the alkane family. Their variation with respect to altitude was similar to those of ethane and propane, i.e. increasing with altitude. But the peak concentration at 10 km was smaller than the peak observed in the polluted plume at about 1 km altitude. At the upper layer, *i*-butane, *n*-butane and *n*-hexane reached 30, 70, and 11 pptv, respectively, with a low level of about 4 pptv near the surface. In contrast, in the polluted plume, the peak concentration was about 65, 120, and 10 pptv, respectively. The ratios of these species to ethyne were very similar to those of ethane and propane, i.e. high ratios at lower altitudes and low ratios at higher elevations.

There were also measurements of ethene, propene, 1-butene, 1-pentene, *i*-pentene, and *n*-pentene, i.e. the alkene family. Ethene ranged between 5-120 pptv (Figure 12c), propene 1-105 pptv, 1-butene 1-30 pptv, 1-pentene 3-28 pptv, *i*-pentene 2-60 pptv, and *n*-pentene 3-38 pptv. Measurements of benzene and toluene, i.e. the aromatic family, show that benzene ranged between 5-150 pptv and toluene 5-60 pptv. Their variations with respect to altitude were similar to those of alkanes and ethyne, i.e. they increased with respect to altitude and had similar anthropogenic sources.

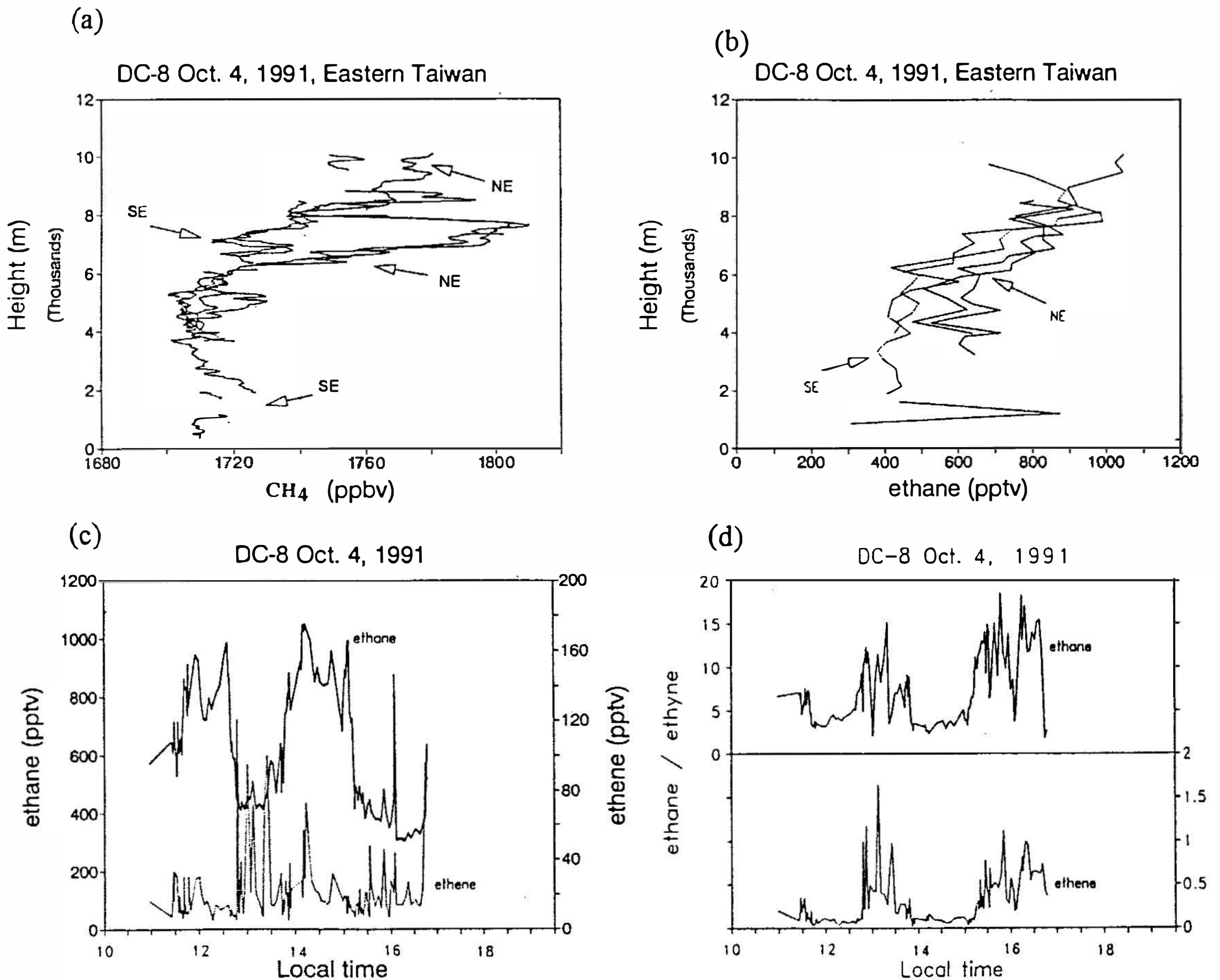


Fig. 12. Along the eastern Taiwan on October 4, the vertical profile of (a) CH₄ and (b) ethane; the temporal variation of (c) ethane and ethene, and (d) the ratio of ethane and ethene to ethyne (C₂H₂).

4.1.7 HNO₃, HCOOH, CH₃COOH and SO₂

HNO₃ (nitric acid), HCOOH (formic acid), CH₃COOH (acetic acid) and SO₂ (Figure 13a,b) were measured in a manner similar to Talbot *et al.* (1988, 1990a,b, 1992). The uncertainties of these data are listed in Table 1. High HNO₃ levels occurred at 0.35 km altitude, and the concentration reached up to 250 pptv. At other altitudes, HNO₃ remained at low values of about 25 pptv, which is close to the observed clean tropospheric data (Talbot *et al.*, 1992), but may be too low at higher altitudes to match the NO_y dataset (Figure 8c) in this case. Similar profiles were observed for HCOOH, CH₃COOH and SO₂. By comparing Figure 13b with Figure 10d, it is noted that both sets of data agree that high SO₂ levels were mainly in the boundary layer. HCOOH, CH₃COOH and SO₂ concentrations ranged between 100-650 pptv, 200-1000 pptv and 50-1000 pptv, respectively. The major enhancement occurred around 17:00 LT at southwestern Taiwan (Figure 1b) and could be attributed to local pollution sources.

The measured carboxylic acids HCOOH and CH₃COOH are ubiquitous components of the global troposphere. In remote regions, these organic acids are the principal acidity components of precipitation (Talbot *et al.*, 1990a,b). Talbot *et al.* (1992) pointed out that HCOOH and CH₃COOH are linearly correlated. Over eastern Taiwan, at altitudes above 2 km, HCOOH ranged between 100-600 pptv, while CH₃COOH varied between 200-400 pptv. These levels are close to those observed over the sub-arctic free troposphere.

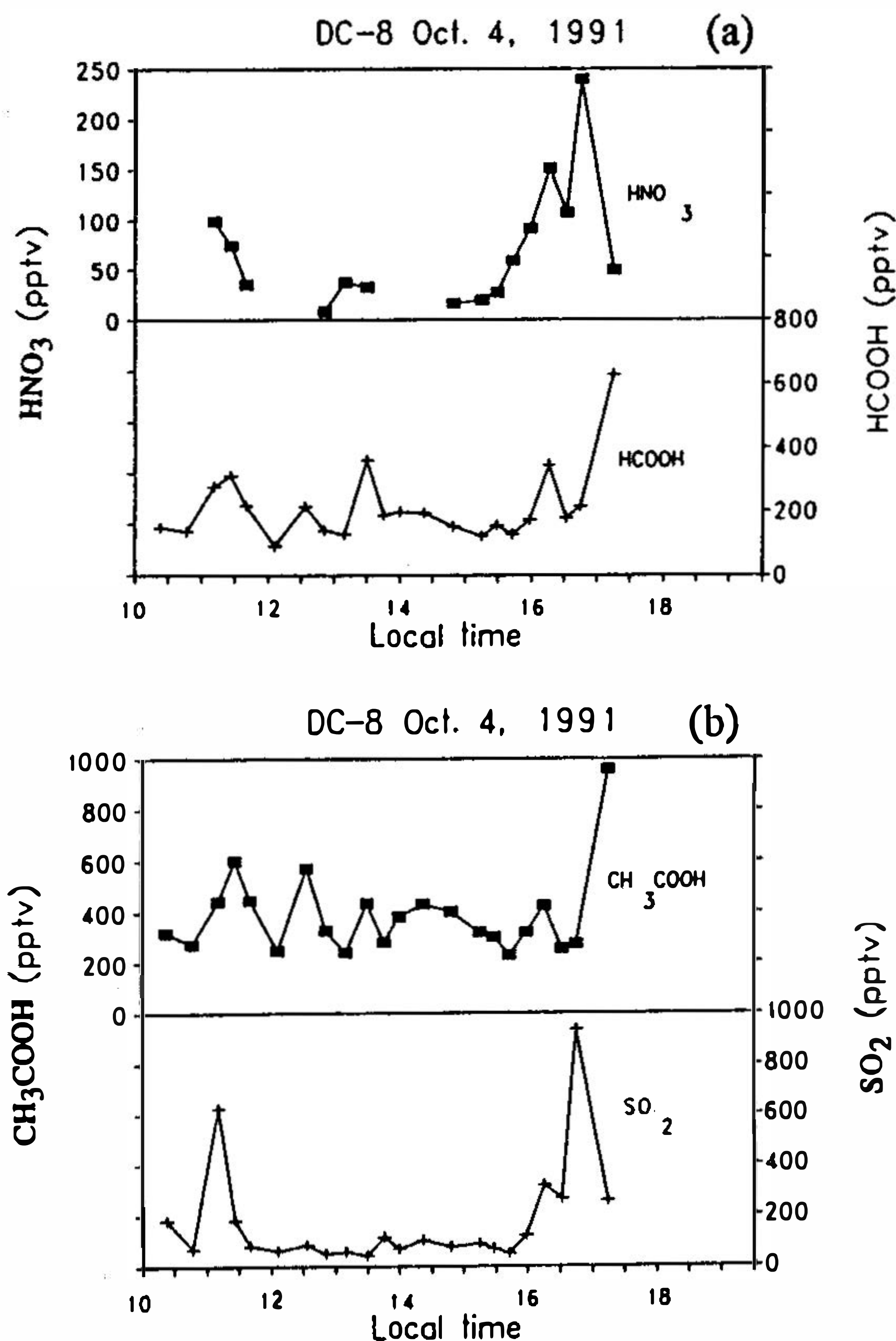


Fig. 13. Along the eastern Taiwan on October 4, the temporal variation of (a) HNO₃ and HCOOH, (b) CH₃COOH and SO₂.

4.1.8 H₂O₂, ROOH and Total Hydroperoxides

H₂O₂ (hydrogen peroxide), ROOH (organic hydroperoxides) and total hydroperoxides (Figure 14a,b,c) were measured in a manner similar to Heikes *et al.* (1987, 1988). Since measurements of OH, HO₂ and RO₂ are still not feasible at the present time, the data of H₂O₂ and ROOH are useful in estimating the potential of chemical reactions in the atmosphere. This is because hydroperoxides are reservoirs of gas phase odd-hydrogen radicals and long lived intermediates in the oxidation of hydrocarbons. Figure 14 shows that these three species all decreased significantly with respect to altitude, i.e. peak at 2 km and minimum at 10 km. For H₂O₂, concentrations below 8 km were much higher at the NE corner of Taiwan (Figure 14a), which was similar to the ozone profile. H₂O₂ and ROOH were present in concentrations of 170-2000 pptv and 50-1800 pptv. Total hydroperoxide ranged between 300-3000 pptv, consistent with the measurements done by other groups in the remote clean troposphere (Walega *et al.*, 1986; Lee and Busness, 1989).

4.2 Horizontal Distribution of Chemical Species

The DC-8 flew along five different levels during the period of the eastern Taiwan segment of the investigation. These layers were at 10 km, 8.5 km, 3.7 km, 1.9 km and 0.35 km altitude. Figure 15a shows that the variation in the ozone level was negligible with respect to latitude at layers below 3.7 km. However at 8.5 km, the ozone level increased from 30 ppbv at lower latitudes to 70 ppbv around 23.5°N, then dropped to about 50 ppbv over northern Taiwan, while at 10 km, the ozone level varied between 40-80 ppbv. These variations were associated with the large scale flow. In Figure 15a, H₂O exhibited a decreasing trend from the southern region to the northern area at 8.5 km. The H₂O levels varied between 400-1200 ppm. The inverse relationship between H₂O and ozone at this layer suggests that the air over the southern region originated from lower altitudes, while the air over the northern region was from upper layers. At 10 km altitude, H₂O concentrations were constant.

The horizontal variations of NO, NO₂ and NO_y at layers below 3.7 km (Figure 15b) were similar to that of ozone, i.e. negligible variation, while at upper layers, the variation was significant. At 10 km, high NO levels were observed between 24-25°N, which was consistent with the decrease in NO_y and the increase in ozone and suggests that the air was aged. Meanwhile, in the southern regions, high ozone was associated with high NO_y and low NO, which suggests that the air was fresh. This phenomenon was consistent with the low ozone and high H₂O level at 8.5 km. It is suspected that typhoon NAT at the upstream region provided the mechanism to transport species from the lower to upper altitudes.

PAN data show that the variation at 3.7 km was negligible (Figure 16a). At 8.5 km, the difference in PAN concentration between the northern and the southern region was about 65 pptv, which is consistent with the ozone variation (Figure 15a). At 10 km, the PAN level dropped from a peak of 240 pptv at 22°N to a minimum of 60 pptv at 24.75°N, which is consistent with the variation of NO_y.

Among the measurements of the sulfur-containing compounds, only SO₂ and CS₂ can provide useful information about the latitudinal change (Figure 16b). Again, below 3.7 km, the horizontal variation of these species was negligible. However, at 8.5 km, the SO₂ pattern was similar to those of ozone and PAN, but CS₂ exhibited negligible variation. At 10 km, high SO₂ and CS₂ levels occurred at 22°N, and at northern latitudes. This was similar to the variation of ozone.

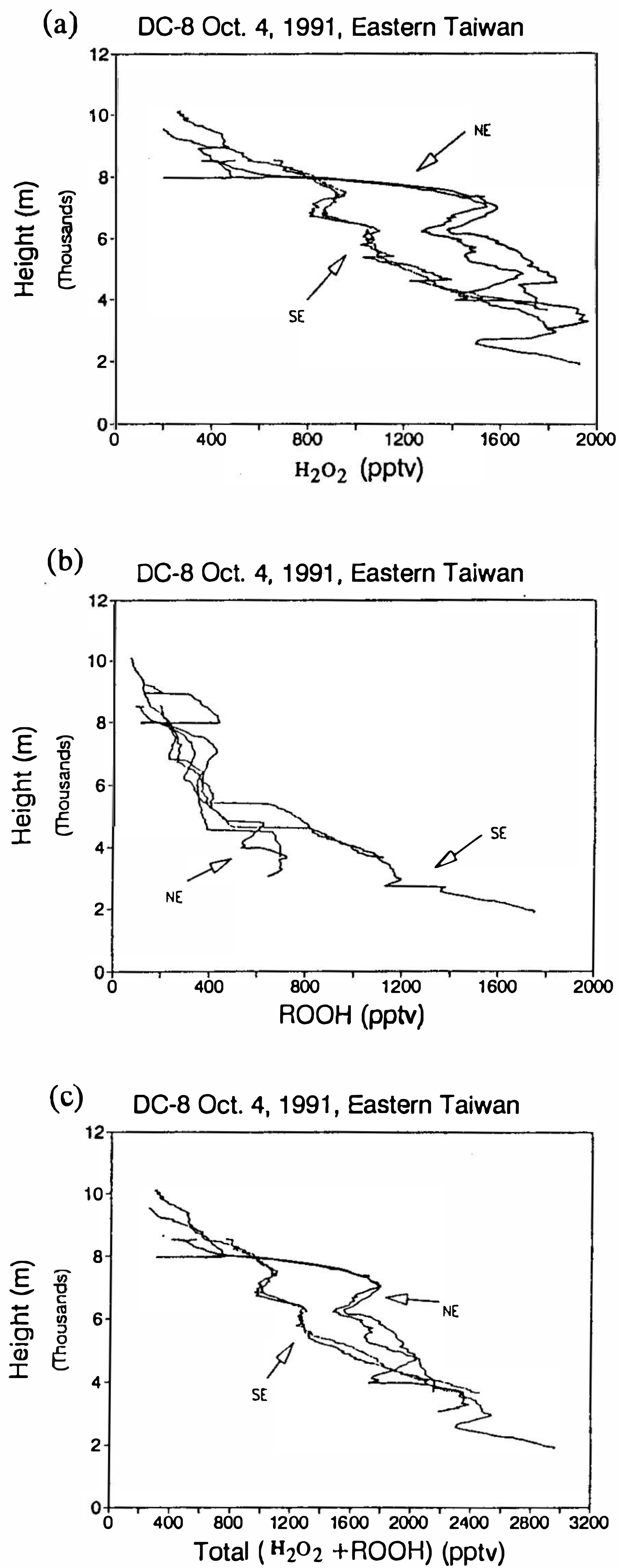


Fig. 14. Along the eastern Taiwan on October 4, the vertical profile of (a) H₂O₂, (b) ROOH, and (c) total hydroperoxide.

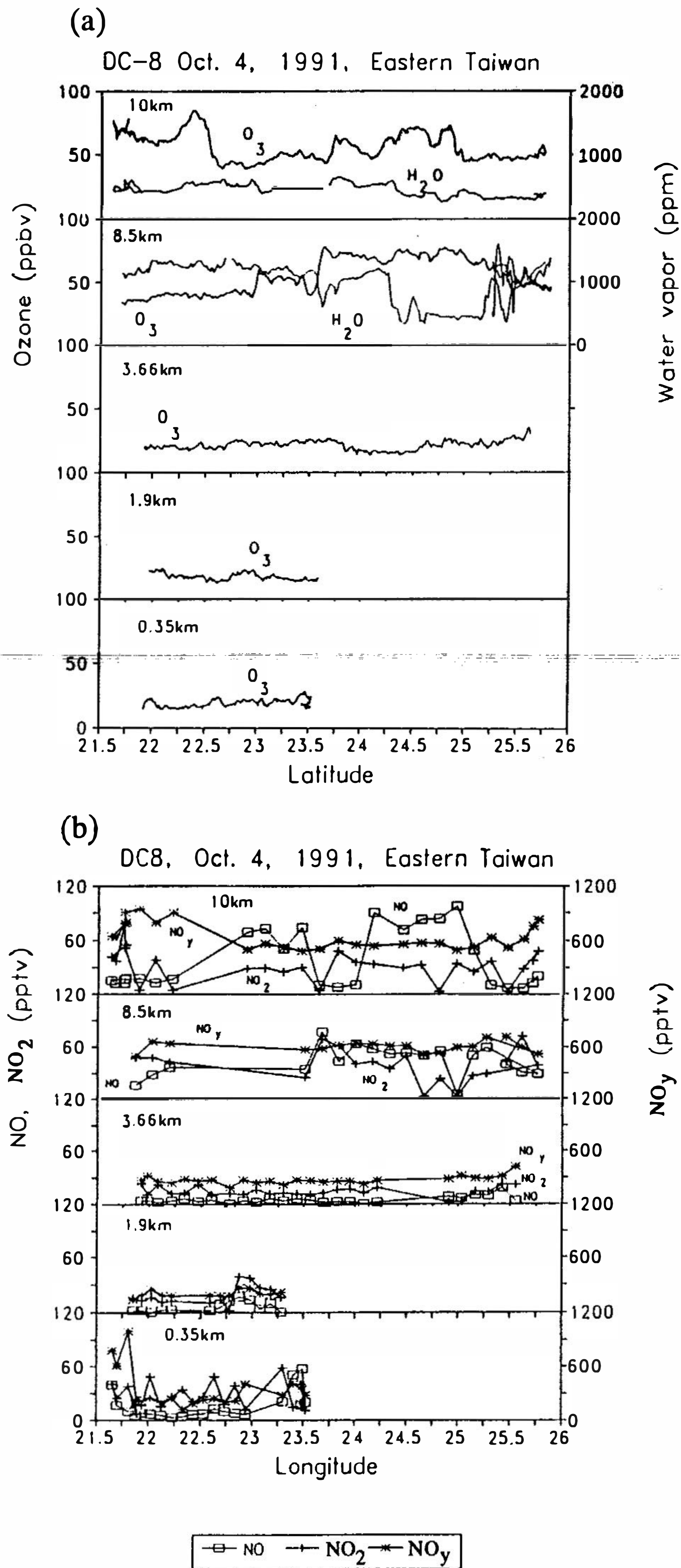


Fig. 15. Along the eastern Taiwan on October 4, the latitudinal variation of (a) ozone and water vapor, (b) NO, NO₂ and NO_y, at different altitude.

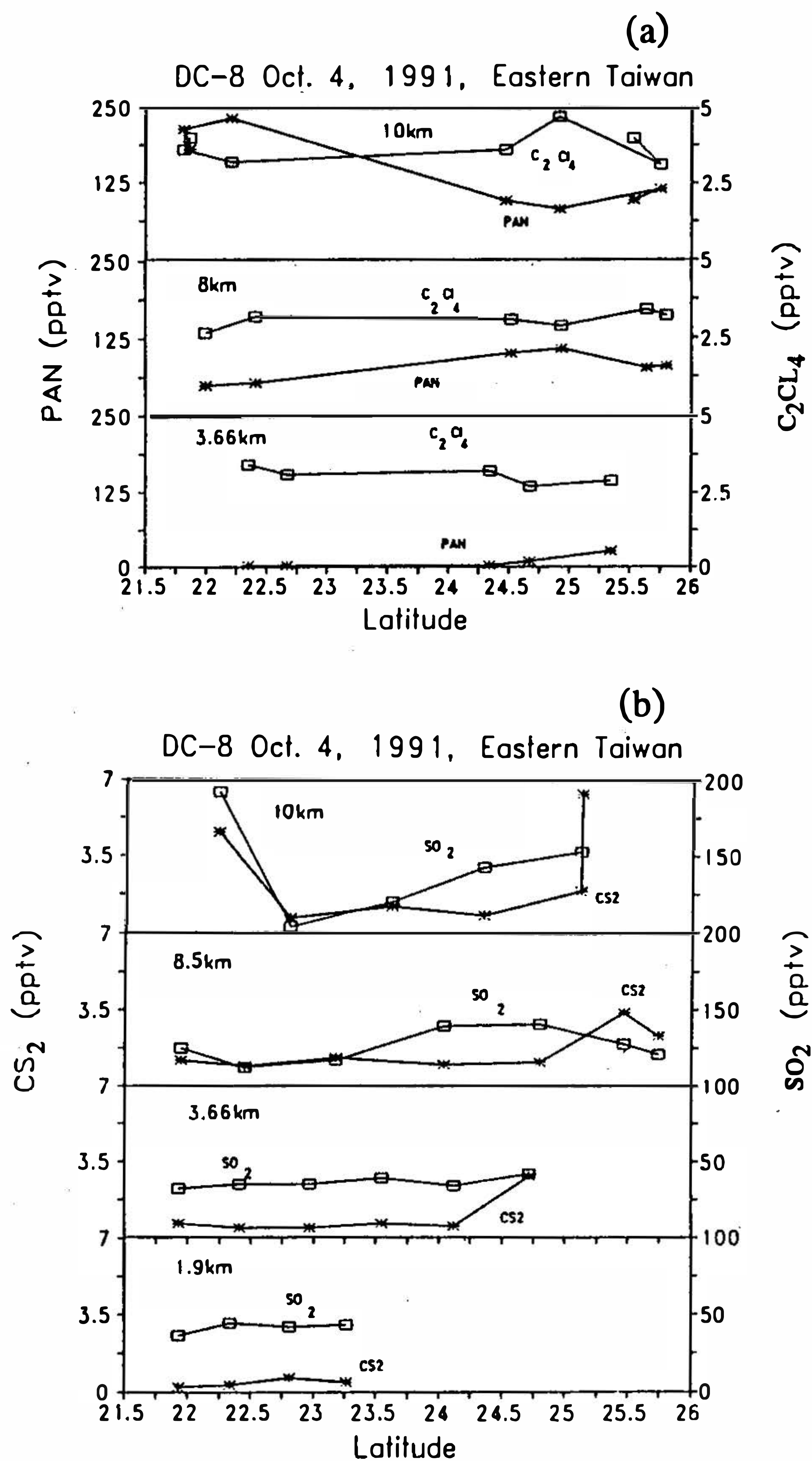


Fig. 16. Along the eastern Taiwan on October 4, the latitudinal variation of (a) PAN and C_2Cl_4 , (b) CS_2 and SO_2 , at different altitude.

The variation of CO and CH_4 is plotted in Figure 17a. In general, these two species had a negligible horizontal variation below 3.7 km. At 8.5 km, CH_4 levels were low (about 1725 ppbv) at $22^\circ N$ but increased toward the northern region. The peak value was about 1775 ppbv. This pattern was similar to that of ozone. At 10 km, both species showed an increasing trend toward higher latitudes.

Since most of the chemical species had horizontal variation patterns similar to that of ozone, it was decided that the analysis of other species could be ignored. However, H_2O_2 , ROOH and total hydroperoxides varied almost inversely to the amount of ozone at 8.5 km and 10 km altitude, i.e. high H_2O_2 , ROOH and total hydroperoxides levels corresponding to low ozone levels, and vice versa (Figure 17b).

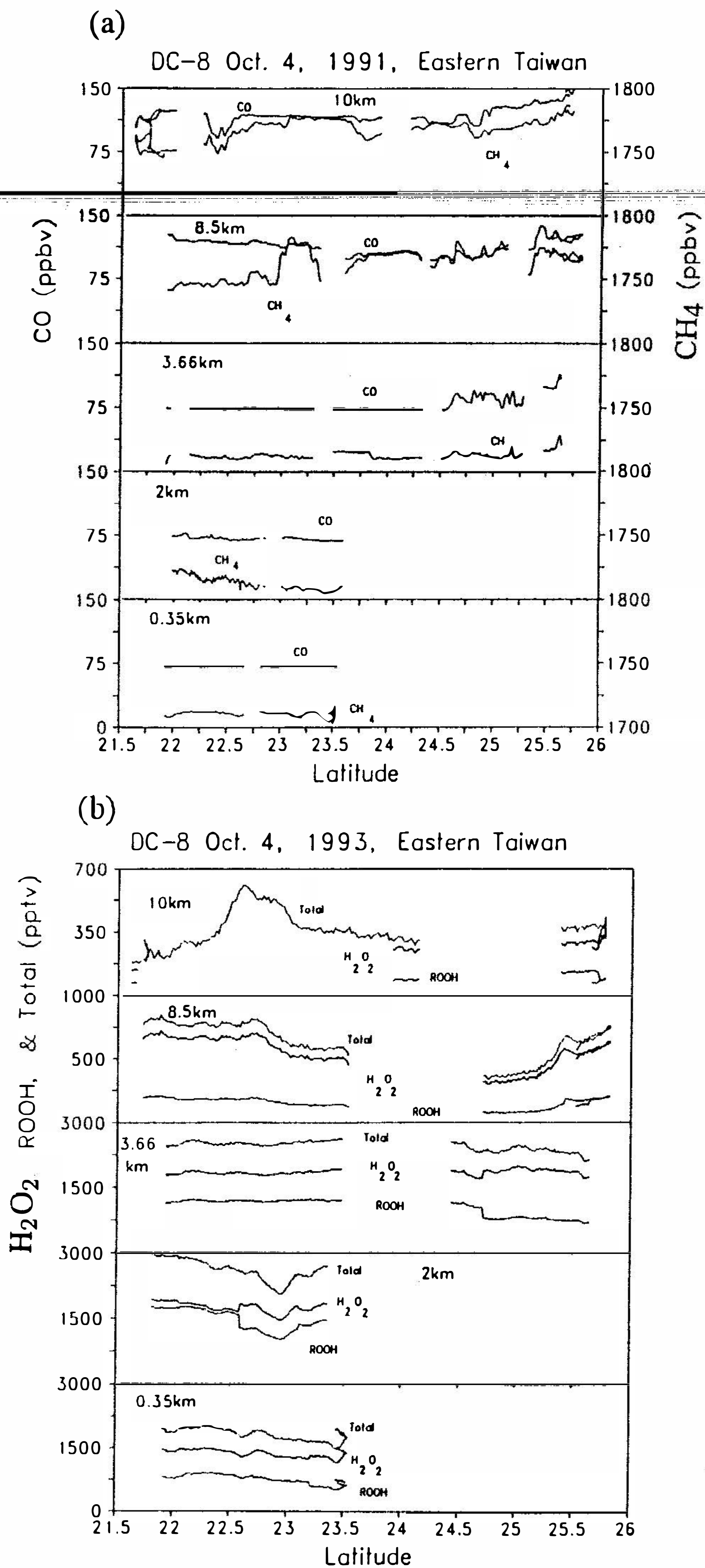


Fig. 17. Along the eastern Taiwan on October 4, the latitudinal variation of (a) CO and CH₄, (b) H₂O₂, ROOH and total hydroperoxide, at different altitude.

5. KENTING FLY-BY

The Kenting site, which was the background station operated by the CATS team during PEM-west, is at the southern tip of Taiwan. On October 4, the prevailing wind at Kenting was from a north-northeast direction with a mean wind speed of about 7 m s^{-1} (Figure 18b). The backward air-parcel trajectory suggests that the air originated from the central Pacific and moved along the outer ring of the subtropic High toward southeastern Taiwan. The relative humidity at Kenting was between 85-100%, but no rainfall was observed. The cloud coverage was about 30%. The diurnal change of temperature was significant. The surface ozone was between 4-16 ppbv, which is typical for air originating from a clean maritime source.

From 14:09-14:42 LT, the DC-8 flew at the altitude of 345 m over the sea surface, from a northeastern direction about 200 km away from Kenting (Figure 18a). The in-situ measured air flow was northeasterly with a wind speed of about 7 m s^{-1} . The DC-8 was upwind from Kenting. The in-situ ozone measurements exhibited a decreasing trend in the ozone level from 28 ppbv to 13 ppbv (Figure 18d). Meanwhile, at Kenting, an in-phase decreasing trend of the ozone level was also observed during the same period (Figure 18d). However, the surface ozone level was between 11.5-7 ppbv, which was only about half of the ozone level observed on the DC-8. According to surface wind data (Figures 18b,c) between 10:30-14:00 LT, when the air flow was from the northeast with a mean wind speed of 5 m s^{-1} , the ozone level was about 12 ppbv, which was very close to the DC-8 measurement of 13 ppbv when the aircraft was only about 1 km away from the Kenting site. After 14:00 LT, the surface wind speed started to increase while the air flow changed, now coming from the north-northeast direction. At the same time, the surface ozone also started to decrease but with some disturbance in the range of 4-6 ppbv. Because the surface wind changed, coming along the coast terrain, fluctuation in the ozone data occurred. The fluctuation may have been caused by the deposition of ozone into the forest, or the titration of ozone by NO.

Measurements of NO_x ($\text{NO}+\text{NO}_2$) were also made at Kenting. The concentration was, in general, lower than 1 ppbv. There was a negative correlation between NO_x and O_3 (Figure 19a) on October 4, i.e. levels of NO_x decreased when levels of O_3 increased. Still, there were a few disturbances embedded in the dataset. When the DC-8 approached Kenting, the surface NO_x exhibited an increasing trend, while the DC-8 in-situ measurement showed a decreasing trend. The NO level at Kenting was between 10-50 pptv (Figure 19b), while the DC-8 measured levels lower than 10 pptv. The NO_2 level at Kenting was between 60-225 pptv, while the DC-8, when it was about 20 km away from Kenting, observed 10-50 pptv of NO_2 . In all, the Kenting site was affected by emissions from local traffic.

SO_2 measurements at Kenting showed a noontime peak of 1.8 ppbv (Figure 19c). After 14:00-15:00 LT, the SO_2 concentration started to decrease steadily to about 20 pptv at 20:00 LT, which was in phase with the increase in wind speed and the change in wind direction. When the DC-8 approached Kenting, the in-situ measurement of SO_2 showed a steady decrease from 440 pptv to 100 pptv (Figure 19d). At the same time, the Kenting data maintained a value of about 1000 pptv. The difference between these two measurements was quite significant. It appears that up-stream emission sources within the lower surface layer, such as a fleet of ships, may have caused such differences. Furthermore, the emission sources might be parallel to the coast; hence, the switch in wind direction from northeast to north-northeast at Kenting with an increase in wind speed might have caused the observed decreasing trend of SO_2 after 14:00-15:00 LT.

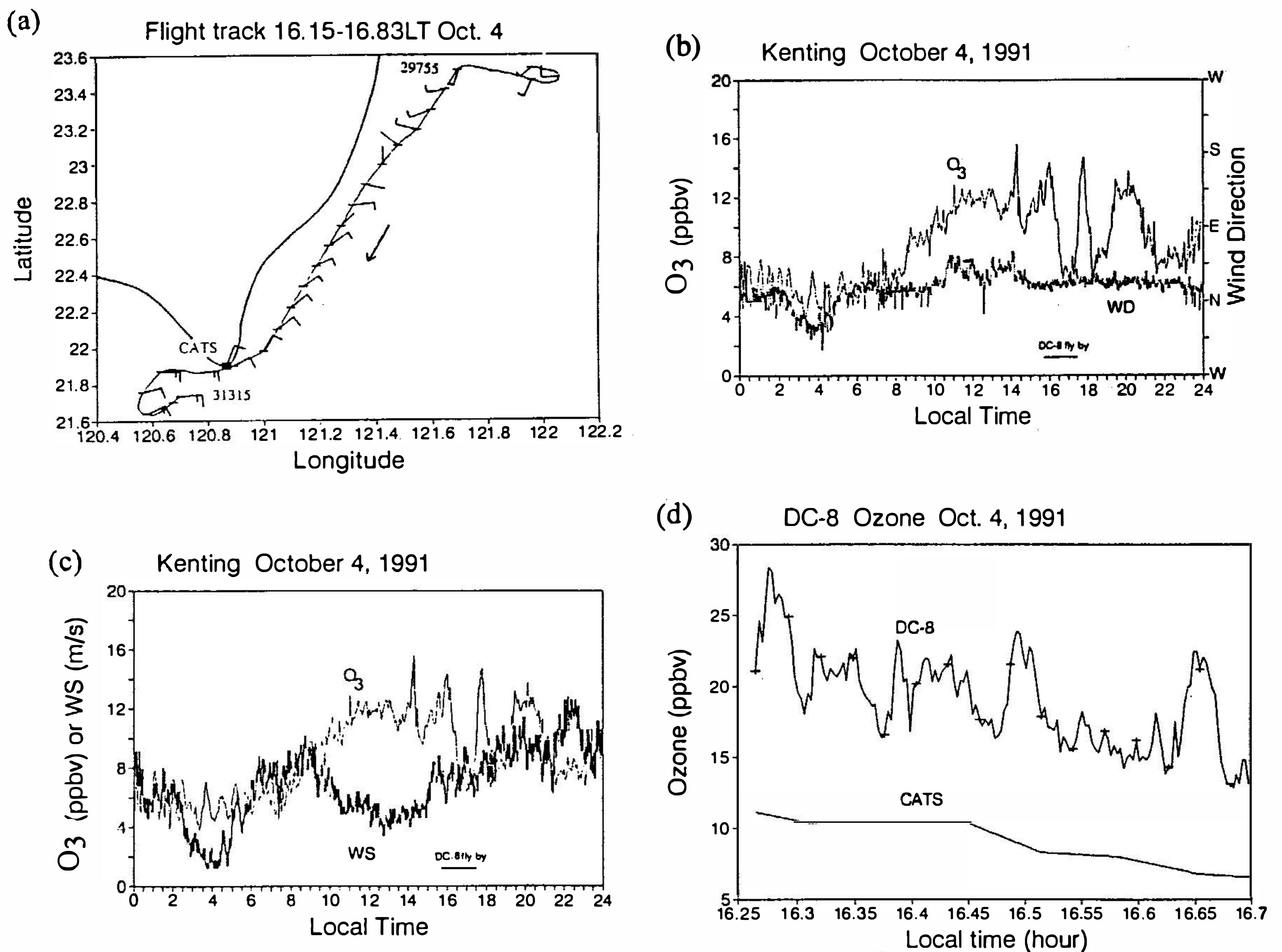


Fig. 18. (a) The flight track of DC-8 when approaching to CATS Kenting site on Oct. 4 during 16.25-16.70 local time. The temporal variation of (b) O₃ and wind speed (WS), (c) O₃ and wind direction (WD) at Kenting on the same day; (d) the temporal variation of ozone measured by DC-8 and CATS.

6. SOUTHWESTERN TAIWAN (Flight track III)

After 17:00 LT on October 4, when the DC-8 passed by the Kenting site and started to fly back to Hong Kong, it ascended gradually to 7.5 km altitude at the southwestern corner of Taiwan, then maintained the same altitude before approaching Hong Kong (Figure 20a). During the ascending period, the ozone level increased from 20 ppbv at 2 km to 50 ppbv at 7.5 km altitude (Figure 20a), levels similar to those observed over eastern Taiwan. Meanwhile, the H₂O data collected at 7.5 km showed a drop in concentration between 118-119°E appearing at the region where a transition of wind direction occurred. The level of H₂O ranged between 400-1500 ppm.

NO, NO₂ and NO_y data exhibited an increasing trend with altitude (Figure 20b). At 119°E, both NO and NO₂ levels dropped when the wind direction changed dramatically. NO_y varied in a similar way. In general, NO and NO₂ ranged between 1-80 pptv, and NO_y between 10-800 pptv. As to the peak at 120.7°E, it was most likely caused by a local pollution plume.

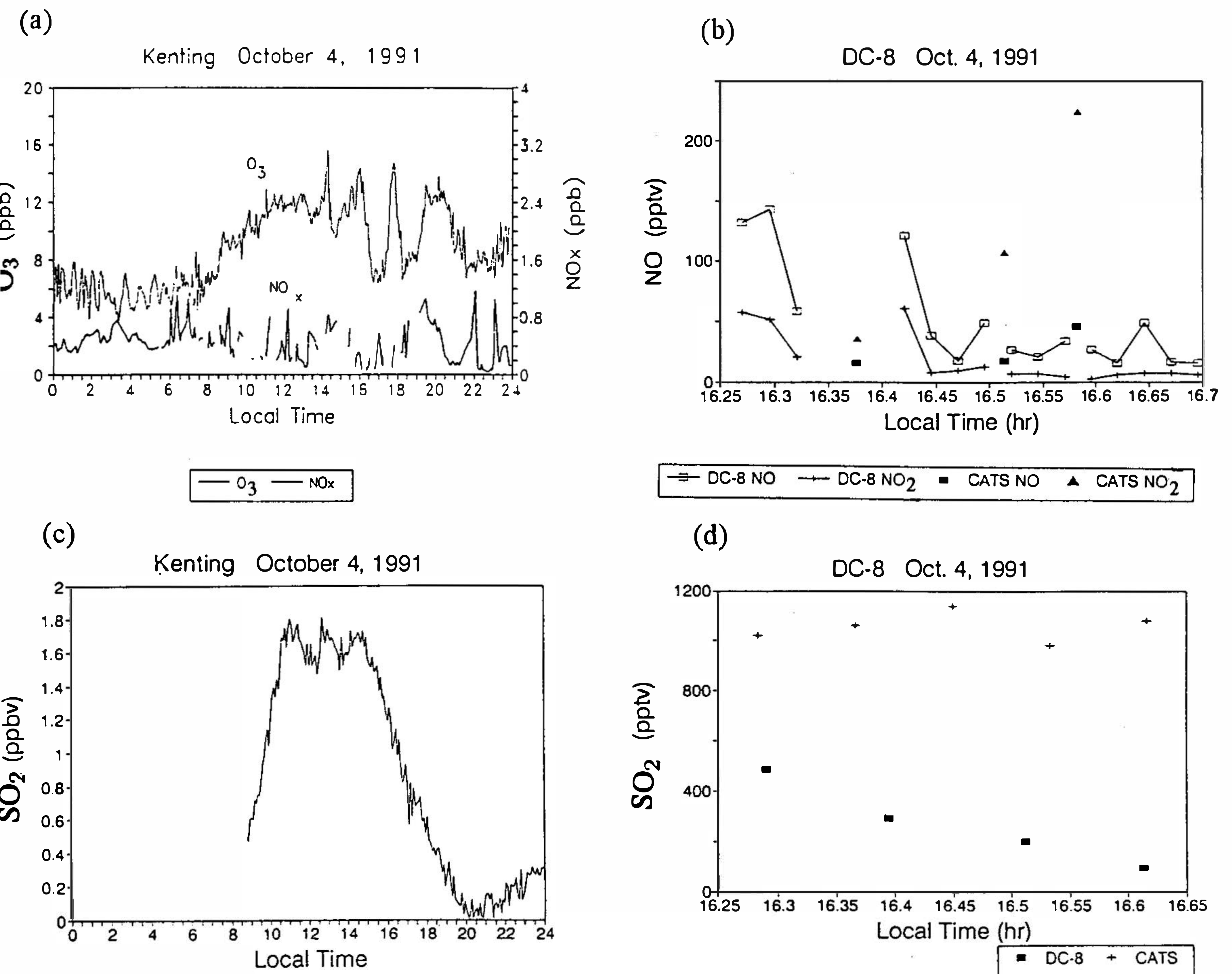


Fig. 19. The temporal variation of (a) O_3 and NO_x at Kenting, (b) NO , NO_2 during 16.25-16.70 local time, (c) SO_2 at Kenting, and (d) SO_2 during 16.25-16.70 local time on October 4.

CO_2 was about 351-353 ppm. But a peak of 357 ppm occurred near 120.5-120.70°E, which is just south of Taiwan (Figure 20c). The data of other species suggest that a polluted plume from a local region was encountered by the DC-8. This was characterized by high NO , NO_2 , alkanes, alkenes, aromatics, CO (Figure 20e) and CO_2 , but with low ozone, PAN (Figure 20d) and NO_y . Therefore, this plume must have been relatively fresh.

The vertical distributions of CH_4 , N_2O and CO were quite similar to those observed over eastern Taiwan, i.e. increasing concentration with respect to altitude (Figure 20e). Near Hong Kong, the variation was quite significant, which must have been caused by local emissions.

7. SUMMARY AND DISCUSSION

The airborne measurement of chemical species near Taiwan was conducted by a NASA DC8 aircraft on October 4, 1991 during the PEM-west Phase A mission. Since similar operations are not likely to happen frequently in Taiwan, the data collected are very valuable

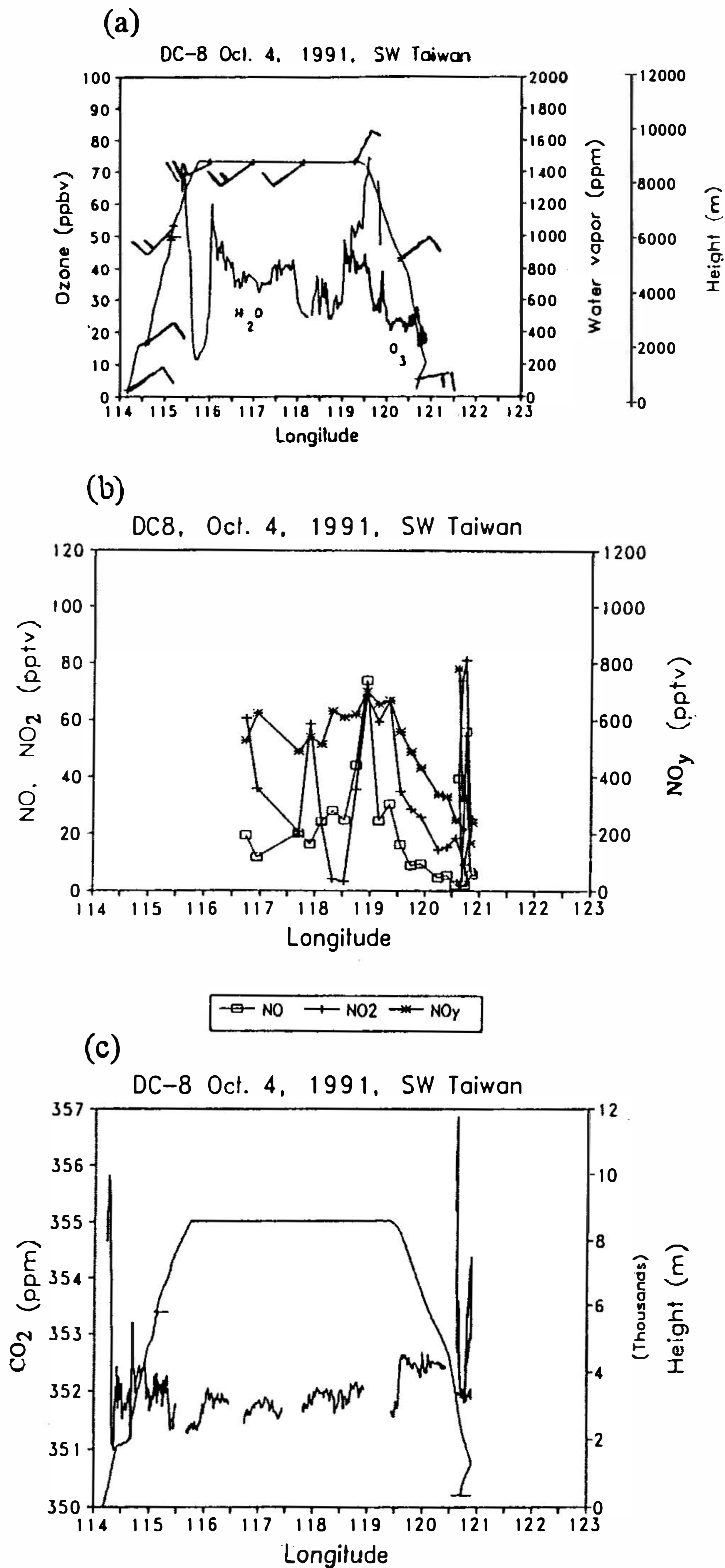


Fig. 20. Along the flight track III over the southwestern Taiwan region on Oct. 4 the longitudinal variation of (a) ozone and water vapor, (b) NO, NO₂ and NO_y, and (c) CO₂, (d) PAN and C₂CL₄, and (e) CO, CH₄ and N₂O.

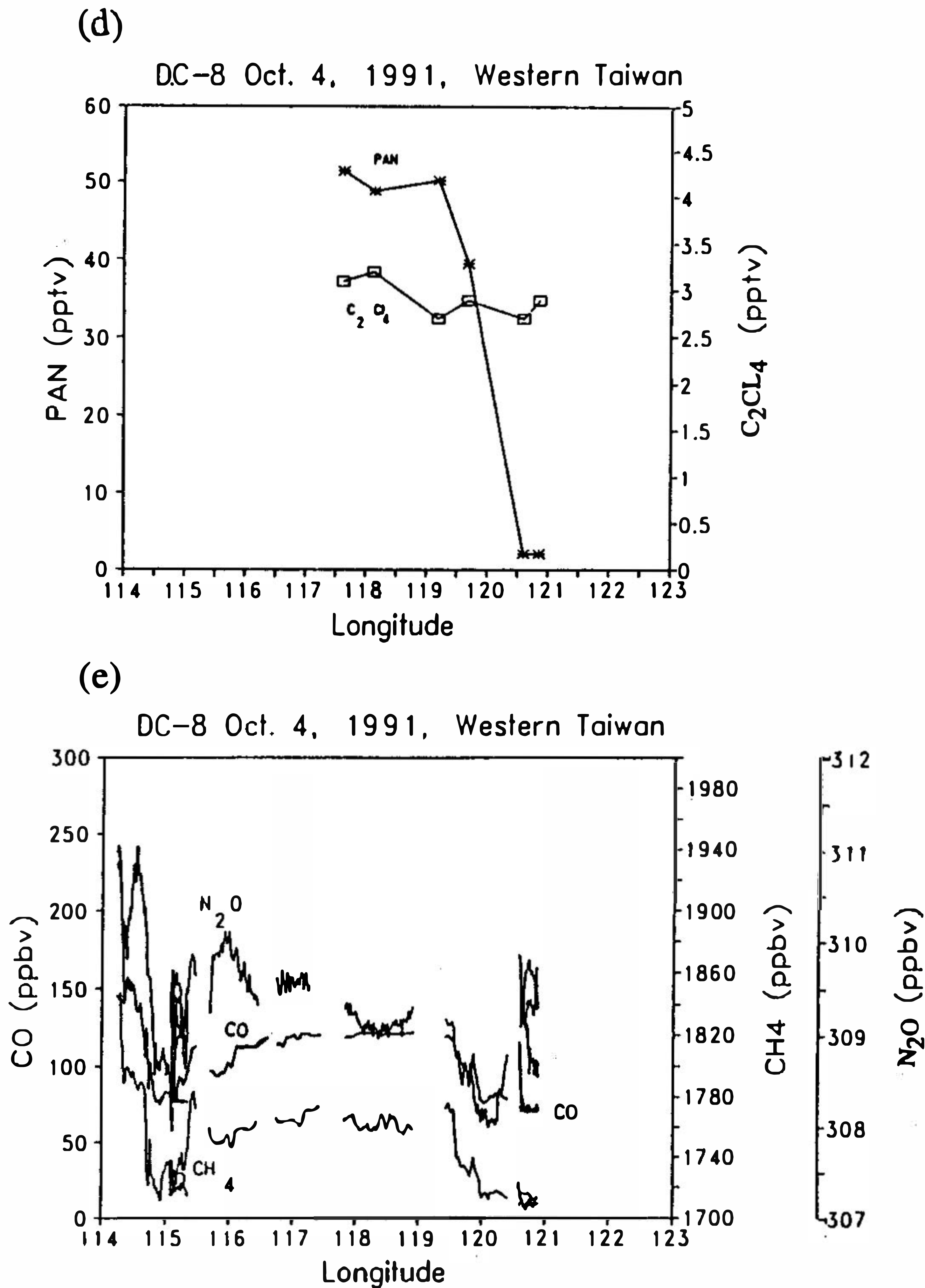


Fig. 20. (Continued)

to local scientists. In this paper, the data have been analyzed in detail in order to understand the spatial and temporal variation of different chemical species. The results are summarized in the following discussion.

From surface to upper layers, there was no dominant weather system over the Taiwan region on October 4, 1991. Below 700 mb, a slow moving front over southeastern China was heading toward Taiwan. A maritime clean airmass was on the eastern side of Taiwan. Above 700 mb, Taiwan was in a saddle region. The long-range transport of air parcels was from the central Pacific turning clockwise at 6 km altitude, and from southern China at 8-10 km altitude. Along the eastern coast, air parcels below 4 km were from the clean Pacific region. However, the DC-8 detected a few pollution plumes over northern Taipei at 3 km altitude, in the middle of the eastern coast at about 1 km altitude, over southern Taiwan at about 4 km altitude, and near the Hong Kong area.

The DC-8, after leaving Hong Kong, flew toward northern Taiwan during the morning hours, along an altitude of 6.5 km, then descended to 3 km before reaching the northeastern (NE) corner. At 6.5 km, the level of chemical species was [O₃] 20-33 ppbv, [NO] 15 pptv, [NO_y] 1000 pptv, [PAN] 20 pptv, [SO₂] 75p pptv, [CS₂] 3 pptv, [DMS] 3 pptv, [CO₂] 352

ppmv, [CH₄] 1740 ppbv, [CO] 100 ppbv. Over northern Taipei, at 3 km altitude, the DC-8 detected a polluted plume with the level of chemical species being [O₃] 60 pptv, [NO] 117 pptv, [NO_y] 4500 pptv, [PAN] 5 pptv, [SO₂] 1700 pptv, [CS₂] 40pptv, [CO₂] 360 ppmv, [CH₄] 1820 ppbv, [CO] 275 ppbv and [H₂O₂] 600 pptv. The polluted plume was likely from local metropolitan regions and was characterized by high levels of ozone, CO, SO₂, and NO_y, and low levels of PAN and hydroperoxides. Another interesting phenomenon was that over the northeastern ocean area, the level of DMS was about 11.5 pptv which is not a particularly large value, but one that does match with a fishing field over that region.

Intensive measurements were made along the eastern coast. In general, low levels of chemical species in the maritime airmass resulted in an increasing profile of concentrations with altitude. In the middle of eastern coast, a polluted plume near 1 km altitude was detected. Chemical species, such as ozone, NO, NO_y, PAN, CO, ethane, propane and most hydrocarbons, all exhibited this vertical distribution. To facilitate the discussion, the mean values are listed in 02a, 2b and 3a. These tables are useful to illustrate background atmospheric conditions. Below 4 km, the airmass had typical maritime characteristics. The ozone level was about 20 ppbv, [NO] 4-23 pptv, [NO_y] 250-450 pptv, [PAN] 2-24 pptv, [N₂O] 310 ppbv, [CO] 71-87 ppbv, [CO₂] 352 ppmv, [CH₄] 1.71 ppmv, [H₂O₂] 1378-1842 pptv, etc. Above 8 km, the air was from southern Asia. It is noted that the upward transport of chemical species, possibly by typhoon NAT in the upstream southern China region, might have caused the observed high levels of ozone and NO_y and the low level of NO at 10 km altitude, over southeastern Taiwan. Also, this process may have resulted in effective mixing of air at 4-6 km altitude.

In Table 3b, the ratios of HCs to ethyne are listed. In general, most NMHCs have similar anthropogenic sources; however, the destruction rate of ethyne through chemical reactions is the slowest. Hence, the ratio of each HC species to ethyne reflects the aging state of air, i.e. the lower the ratio, the more aged the air (Whitby and Altwicker, 1978). In Table 3b, the ratios show a clear tendency to decrease with altitude, even though the concentration of most HCs increased with altitude (Table 3a). This phenomenon suggests that most HCs are emitted mainly from ground sources and are transformed to other chemical compounds in the atmosphere. The value of each HC/ethyne ratio listed in Table 3b is useful information for comparison with the same ratios in the polluted regions.

The Kenting fly-by showed that both the DC-8 and CATS observed a steady decrease in ozone during the same observation period when the DC-8 was upwind of the Kenting site. However, CATS only observed about 7-11.5 ppbv of ozone, which was about half of the ozone level observed by the DC-8. The differences may be from deposition of ozone on the forest, titration of ozone by NO, or dilution. The observed NO and NO₂ levels at Kenting were much higher than those observed by the DC-8. Also, the level of SO₂ was higher at Kenting.

Over the southwestern corner, when the DC-8 flew from Kenting toward Hong Kong, the variations in chemical species in the vertical direction were similar to those observed over eastern Taiwan. The maritime airmass dominated the lower altitude region.

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Table 2. The mean concentration of chemical species at different altitude measured by instruments on-board DC-8 along the eastern Taiwan on Oct. 4, 1991.

(a)

Height (km)	O3 ppb	H2O ppm	NO ppt	NO2 ppt	NOy ppt	PAN ppt	HNO3 ppt	N2O ppb	SO2 ppt	DMS ppt	CS2 ppt	OCS ppt	CO ppb	CO2 ppm	CH4 ppb
10	58	455	35	33	646	145	16	310	142	3	3	504	119	352	1766
	63	607	13	39	634			310					125	353	1768
9	51	844	56	31	505	106		309					123	353	1766
	54	1019	42	35	621	78		310	127	2	2	501	115	352	1763
8	59	1198	41	26	582	109		310	111		1		113	352	1753
	42	1597	19	21	481	58		310					112	352	1763
7	40	1345	11	19	447	100		309					107	352	1749
	30	1174	10	26	411	27	27	309	63				100	352	1735
6	23		9	25	373	27		309	103		1		86	352	1717
	24		8	17	396			309					83	352	1712
5	22		7	14	338	14	9	309	65		1		84	352	1711
	21		9	18	350	8		309	51		1		81	352	1709
4	23		11	16	445	10		309					87	352	1711
	21		5	14	277	24	48	309	36		1	489	78	352	1712
3	22		13	7	360		27	309					70	352	1710
	28		4	1	227	2		310					71	352	1717
2	18		5	18	201	2	75	309	41			492	71	352	1713
	23		18	2	311			309					71	352	1716
1	25		23	32	351	10		310					82	353	1711
	19		14	28	249	3	129	309	242	5	1	491	71	352	1710

(b) (in unit of pptv)

Height (km)	F-12 ppt	F-11 ppt	F-113 ppt	CH3CCl ppt	CCl4 ppt	C2Cl4 ppt	H2O2 ppt	ROOH ppt	Total ppt
10	513	278	89	156	123	4	276	97	349
	512	279	91	166	126	4	323	108	388
9	508	276	89	161	124	4	402	161	497
	513	275	89	151	121	3	540	158	633
8	510	275	87	149	121	3	581	243	726
	512	276	90	157	123	4	1142	293	1314
7	512	276	88	149	122	3	1110	305	1289
	511	275	89	156	123	3	1151	340	1351
6	510	275	88	149	121	3	1268	348	1473
	510	274	89	151	122	3	1289	408	1529
5	511	275	89	147	121	3	1409	526	1718
	510	275	89	158	121	3	1462	714	1883
4	510	275	89	150	121	3	1572	776	2028
	509	273	89	156	120	3	1842	1033	2450
3	508	274	87	145	121	2	1815	1005	2407
	501	271	88	163	123	3	1580	1405	2407
2	503	270	87	153	120	3	1760	1484	2634
	503	272	87	139	116	2			
1	510	276	92	161	122	3			
	504	272	88	158	121	3	1378	742	1815

Table 3. Same as Table 2, but for (a) different HC_s (hydrocarbons), HCOOH and CH₃COOH (in unit of PPTV).

Height (km)	ethane	propane	i-butane	n-butane	n-hexane	ethene	propene	1-butene	i-pentene	n-pentene	1-pentene	ethyne	benzene	toluene	HCOOH	CH ₃ COOH
10	893	109	14	26	3	26	6	3	13	9		276	42	5	172	414
	920	115	14	25	5	38	10		10	13		308	59	17		
9	893	109	14	25		19	7		9	5		244	58	10		
	832	84	9	15	3	16	6	3	8	7		219	49	13	152	409
8	890	98	10	18	0	17	6		6	5		205	53	8	196	379
	801	73	11	16	10	16	8	4	42	28		215	51	24		
7	756	58	5	7		10	4	5	4			174	39	33		
	647	49	8	14	3	13	10	7	11	7	4	119	34	10	169	381
6	593	52	7	19		29	49	14	11	7	7	82	26	16		
	507	30	5	9		10	8	6	5	4		55	18	10	188	280
5	581	38	4	6		15	12	5	0	3	5	81	23	0	139	326
	479	27	7	14		19	15	7	11	6	57	53	26	15		
4	573	53	20	27	4	19	7	5	24	13		88	27	31		
	466	30	13	10	8	36	27	9	7	6	6	72	18	10	266	423
3	522	33	4	7		14	8	4				67	19	10	153	300
	435	13				9						30	16	0		
2	396	19	10	31	5	23	21	8	17	12	5	41	14	11	149	273
	440	27	11	13	3	21	18	5	10	7		51	28	21		
1	590	134	38	57	9	29	11	5	29	18		151	42	20		
	321	17	8	15		16	10	4	6	7	3	23	12	9	262	338

(b) ratios of HCs to ethyne

Height (km)	ethane	propane	i-butane	n-butane	n-hexane	ethene	propene	1-butene	i-pentene	n-pentene	1-pentene	benzene	toluene
10	3	0.6	0.10	0.19	0.03	0.09	0.03	0.02	0.11	0.07		0.5	0.06
	3	0.6	0.09	0.16	0.04	0.12	0.05		0.06	0.08		0.6	0.15
9	4	0.7	0.12	0.20		0.08	0.04		0.09	0.05		0.7	0.15
	4	0.6	0.08	0.13	0.03	0.07	0.04	0.02	0.08	0.06		0.7	0.27
8	4	0.7	0.09	0.17		0.08	0.04		0.07	0.06		0.8	0.11
	4	0.5	0.10	0.14	0.09	0.08	0.06	0.03	0.32	0.21		0.7	0.33
7	5	0.6	0.04	0.07		0.07	0.03	0.07	0.09			0.7	0.46
	6	0.6	0.09	0.16	0.04	0.12	0.09	0.08	0.15	0.09	0.07	1.0	0.39
6	8	0.9	0.13	0.39		0.30	0.68	0.25	0.26	0.17	0.18	1.0	0.51
	10	0.8	0.14	0.27		0.20	0.17	0.14	0.19	0.11		1.1	0.64
5	8	0.7	0.07	0.15		0.22	0.26	0.12		0.08	0.13	0.8	
	10	0.8	0.16	0.40		0.42	0.51	0.36	0.31	0.20		1.6	0.93
4	8	0.8	0.28	0.40	0.08	0.22	0.08	0.08	0.43	0.23		1.0	0.79
	9	0.7	0.31	0.31	0.35	0.52	0.57	0.27	0.17	0.20	0.18	0.9	0.38
3	8	0.7	0.09	0.16		0.29	0.24	0.19				0.8	0.39
	14	0.7				0.31	0.00					1.6	
2	11	0.7	0.49	1.43	0.37	0.56	0.79	0.43	1.04	0.74	0.34	1.2	0.94
	9	0.8	0.43	0.51	0.18	0.41	0.53	0.20	0.49	0.34		1.7	1.44
1	4	1.0	0.40	0.60	0.11	0.21	0.15	0.04	0.42	0.26		0.7	0.41
	14	1.2	0.71	1.40		0.73	0.66	0.39	0.67	0.79	0.42	1.6	1.42

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