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# Characteristics of near-surface ozone distribution

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This study presents an analysis of the characteristics of vertical ozone distribution near the surface using ozonesonde data(1995 to 1998), plus surface ozone and meteorological data from the Pohang region. These features were examined in detail using three case studies. The first related to episodes of high surface ozone concentrations during the Spring season when the frontogenesis between the high and low pressure associated with the upper-level jet stream was found to be located near the surface. The second was a 5-day winter period(13 ~ 17 December, 1997) in the Pohang province when the hourly concentrations exceeded 90 ppb on several occasions owing to low-level jets(LLJs) induced by a nocturnal stable layer. Accordingly, this explains why the high surface ozone concentrations occurred at night as the ozone was transported across the zone by a strong wind speed(over 12.5 $ms^{-1}$). The third case study was ozone enhancement due to photochemical reactions. In this case, the maximum concentration of ozone exceeded 60 ppb in the summer(23 ~ 28 August, 1997). When an ozone peak appeared within the boundary layer, the occurrence frequency of a low-level jet due to the nocturnal stable layer was about 77%, similarly the occurrence frequency of a near-surface ozone peak relative to the appearance of an LLJ was about 76%. Accordingly, there is clearly a close correlation between the occurrence of LLJs and near-surface ozone peaks.

Key words : high concentration episode, frontogenesis, high-low pressure system, low-level jet, nocturnal stable layer

## 1. Introduction

Surface ozone observations in the mid-latitudes of the Northern Hemisphere show maximum concentrations in the spring and summer seasons. However, the marked increase in ozone precursor emissions, especially since the 1950s, has caused the annual surface ozone concentration cycle in industrialized regions to be characterized by a broad summer(approximately April to August) maximum due to photochemical reactions. This broad summer maximum in ozone concentrations has even extended up to mid- troposphere levels(Logan, 1985[1]; Austin and Follows[2], 1991) and in a few remote regions in the Northern Hemisphere (Mukammal *et al.*[3], 1985; Angle and Sandhu[4], 1989).

The flux of ozone across the tropopause has been already parametrized and modeled by Austin and Follows(1991). These parametrizations and models consider the chemical reactions, deposition, and sink of ozone and are based on the exchange that occurs in the upper-level frontogenesis and tropopause folding regions. Andreae *et al.*[5](1994) proposed that the peak ozone photochemical production originates as a stratospheric intrusion related to the biomass burning over West Africa or South America.

A low-level jet(LLJ) is an important element of low-level atmospheric transports associated with surface ozone peaks in the winter season. In previous studies on LLJ, Uccellini[6](1980), Chen and Kpaeyeh[7](1993) investigated the role of upper troposphere jet streaks and leeside cyclogenesis in the development of low-level jets over the Great Plains in North America. LLJ studies by Wu and Raman[8](1998) suggested that LLJ cores are either near or below the tops of nocturnal inversions and that the life cycles of LLJs and nocturnal inversions are almost the same. Over the Great Plains, the formation of LLJs begins after the formation of inversions, then the LLJs disappear after the inversions become weaker. LLJ formation regularly appears east of the Rocky Mountains when a developing baroclinic wave occurs with an upper-level in a warm sector of the extratropical cyclones of the Great Plains during the winter months(Djuric and Ladwig[9], 1983; Michell *et al.*[10], 1995), plus LLJs usually have a weak diurnal variation in their frequency of occurrence and wind speed.

No specific studies on the ozone production mechanism associated with upper-level troughs, surface high pressure systems, and LLJs have been performed in relation to Korea. Accordingly, the objective of this study is to analyze ozone distribution associated with three near-surface case studies using meteorological elements, ozonesonde, and surface ozone data observed at Pohang in Korea.

## 2. Case studies on vertical ozone distribution near the surface

To study the vertical ozone distribution near the surface, three specific cases were investigated. The distribution of the surface ozone concentration was analyzed using the following mechanisms. In addition, surface ozone data, meteorological data of the surface and upper-level observed at Pohang meteorological station were used.

### 2.1 Upper-level trough and surface high pressure system

To examine the relationship between surface ozone concentrations and pressure patterns, Fig. 1 shows a conceptual model(Danielsen[11], 1980) of the trajectories of ozone-rich air from a tropopause folding region to lower levels, behind a cold front and in the forward site of a new surface anticyclone. There is also observational evidence available to support this model. Intrusions into the troposphere can produce very high ozone concentrations in the middle troposphere(Buzzi *et al.*[12], 1984). A review of ozone data, as observed in relation to stratospheric ozone intrusions down to ground level, can be found in Viezee *et al.*[13](1983). Fig. 2 shows the features of a synoptic weather map from 3, 4, and 6 March, 1997. As in the mechanism of Fig. 1, Figs. 2(a) and (b) show a pressure pattern including a trough and ridge system, which maintains similarly from 200 and 700 hPa to a height of 850 hPa. That is, this pressure pattern indicates the transport of ozone-rich air into the upper troposphere behind a cold front, along with a gradual downward movement (including penetration to near the surface). Moreover, high surface ozone concentrations in the forward site of a surface anticyclone can be seen in the surface weather chart of Fig. 2(b). In this case, the ozone-rich air is concentrated in the Pohang region, which is the forward site of a surface anticyclone through divergence and convergence.

Unlike Figs. 2(a) and (b), the weather chart in Fig. 2(c) shows no penetration into the middle troposphere towards the surface. In relation to the above analysis, Liu and Liu[14](1991) noted increased surface ozone concentrations in the Tapai Basin(in a region of complex topography in northern Taiwan) after the passage of a cold front. Derwent *et al.*[15](1978) also reported on episodes of elevated ozone concentrations in rural locations of the U. K. with stratospheric intrusions in association with vigorous cold fronts.

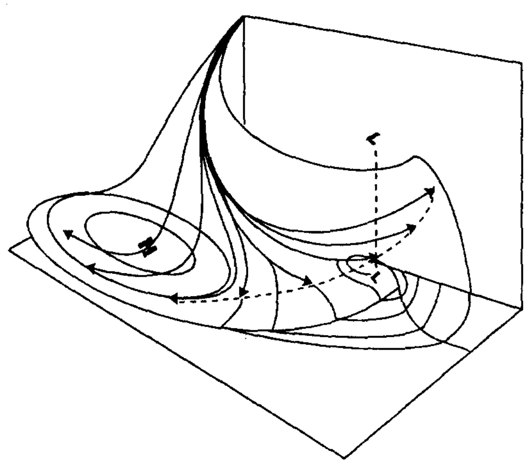

Fig. 1. Conceptual model(after Danielsen, 1980) of trajectories of ozone-rich air from tropopause fold region in upper-level trough behind a cold front and forward site of anticyclone. L, low pressure; H, high pressure.

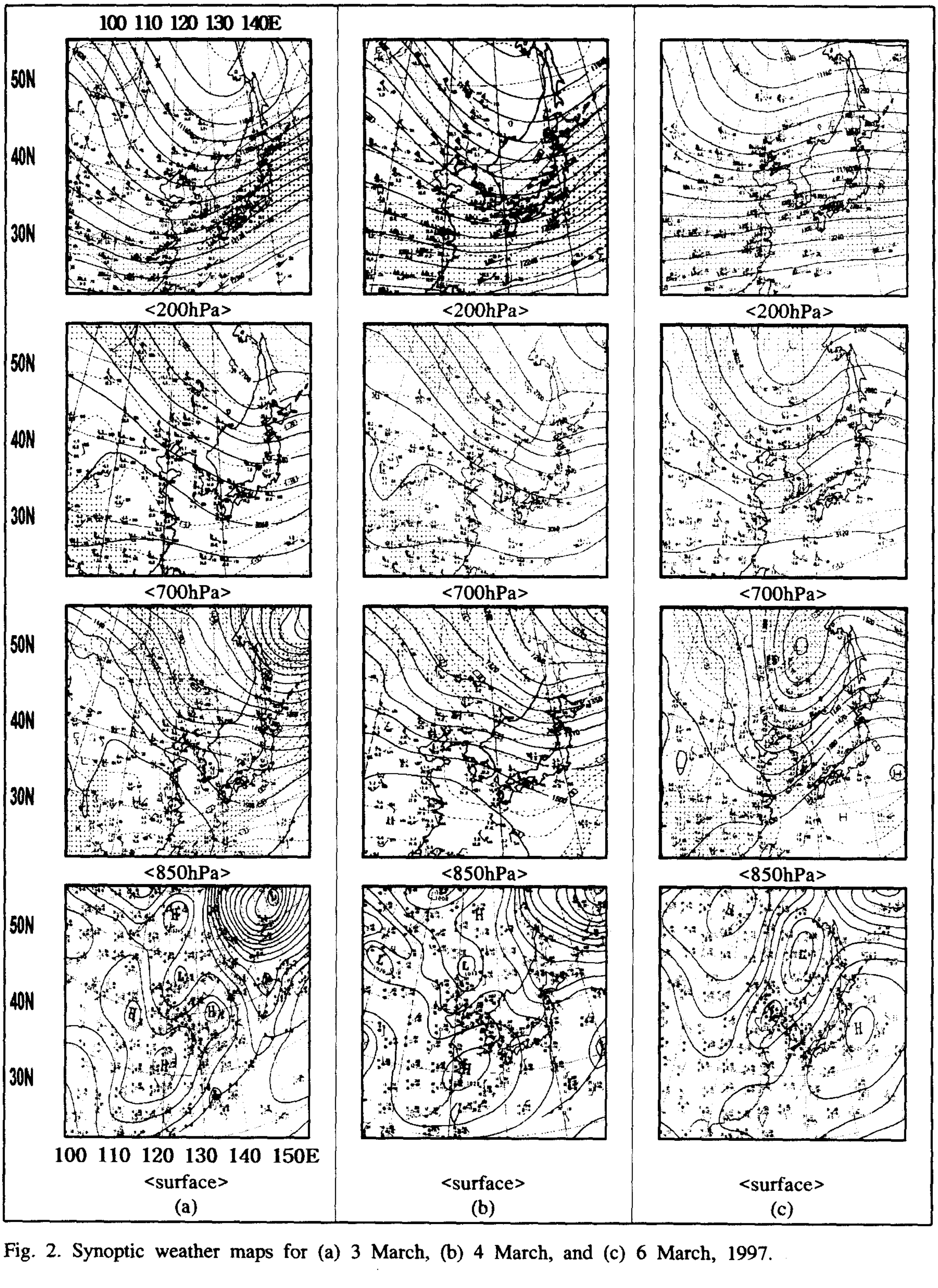


Fig. 2. Synoptic weather maps for (a) 3 March, (b) 4 March, and (c) 6 March, 1997.

To substantiate the relationship between peak surface ozone concentrations and high pressure following an upper trough and cold front, the variations in the surface ozone concentrations in the Pohang region were virtually analyzed, as shown in Fig. 3. This figure shows the hourly surface ozone concentrations in the Pohang region from 1 to 8 March, 1997. When Fig. 2 is compared with Fig. 3, the surface ozone concentrations were found to be particularly high on 4 and 5 March when they almost exceeded 45 ppb. The maximum value on March 4 was 62 ppb and a higher value of around 50 ppb was also recorded at night. That is, these values were higher than the concentrations(around 30 ppb) recorded on other days in Pohang in early spring. The surface ozone concentration in the Pusan region was also compared to that in Pohang to verify the ozone enhancement more accurately. In early spring, it was found that the ozone concentration in the Pusan region was quite low at around 30 ppb. In particular, the concentrations at Yeonsan-dong in the Pusan region, which is located near Pohang were between 20 and 40 ppb, as shown in Fig. 4, and the pattern of the ozone peak was similar between Pohang and Pusan. Therefore, it would appear that ozone-

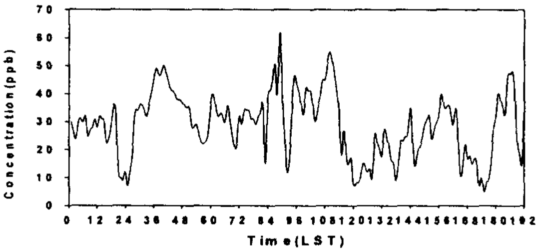


Fig. 3. Hourly surface ozone concentrations at Pohang from 1 to 8 March, 1997.

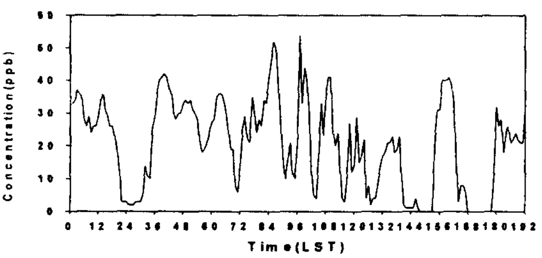


Fig. 4. Hourly surface ozone concentrations at Younsan-dong in Pusan from 1 to 8 March, 1997.

rich air penetrates to the ground-level in the Pohang region, which is the forward site of a surface anticyclone through divergence and convergence.

## 2.2. Near surface ozone concentrations relative to low-level jets

A low-level jet(LLJ), which is a strong wind zone(over 12.5 $ms^{-1}$, Chen and Yu[16], 1988) that occurs at a height of around 700～1000 hPa in the lower atmosphere. It is very important that a LLJ produces moisture transport, horizontal divergence, and a rising zone. In addition, a heavy downpour zone is also commonly formed in the shear zone of an LLJ.

An LLJ will often occur when the stability of the low-level is changed and the convection is quite active. For example, after sunset on a clear evening when the atmosphere cools down, if the conditions are calm, a stable temperature "inversion" starts up where the cool air aloft, which is heavier than the warm air, sinks to the ground and any left over warm air sits on top of it. As a result, high ozone concentrations will occur in the vicinity of a low-level jet with a strong wind speed of more than 12.5 $ms^{-1}$, due to the stable layer in the lower troposphere.

### 2.2.1. Analyses of ozone peak in lower troposphere

The distribution of the ozone concentrations in the lower troposphere was analyzed using data observed at the Pohang Weather Station, including surface and upper-air ozone data, surface meteorological data, and weather charts. The study periods were specially selected days in 1997 and 1998(13 to 15 December 1997, and 19 March 1998). A comparison of the distribution of the ozone partial pressure with the real wind speed relative to altitude is shown in Fig. 5. On 13 December 1997(see Fig. 5(a)) LLJs(Davis and Schuepbach[17], 1994) due to the nocturnal stable layer were present, and a high ozone concentration was also recorded during the night. The real wind speed on 2100 LST was higher than 13 $ms^{-1}$. The findings of 19 March 1998, shown in Fig. 5(b), were also similar to those in Fig. 5(a) and the wind speed was recorded at about 18 $ms^{-1}$ at an elevation of around 1 km. Accordingly, it would appear that the above results were due to the ozone transport associated with the LLJs occurring as a result of nocturnal inversions in a stable atmosphere.

Thereafter, the weather charts for 13, 14, and 15 December, 1997 were compared with those of Fig. 2 to analyze the synoptic pressure pattern. Unlike the pattern shown in Fig. 2, Figs. 6((a), (b), and (c)) showed that an upper-level trough and ridge system occurred at a height of 200 hPa, yet there was no downward transport from heights of 700 and 850 hPa. As such, this pressure pattern indicates no transport of ozone-rich air into the upper troposphere and a negligible downward movement.

Regardless of the synoptic pattern in the upper-level, nocturnal ozone enhancement occurred frequently in the winter of 1997 due to the strong wind speed of the low-level jets and several other mechanisms.

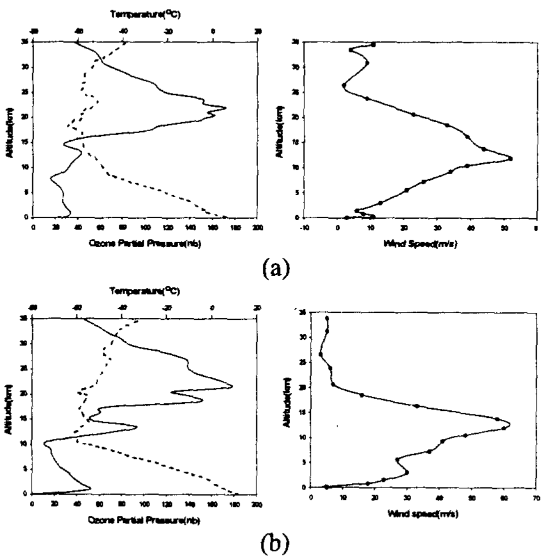


Fig. 5. Vertical profile of ozone partial pressure and wind speed at Pohang on (a) 13 December, 1997 and (b) 19 March, 1998.

### 2.2.2. Analyses of meteorological parameters

As seen in Fig. 5, the concentrations on 13 December, 1997 and 19 March, 1998 were recorded at about 40 and 50 nb, respectively. Also, the meteorological conditions were automatically analyzed when the surface ozone concentrations were found to be higher than 90 ppb. Therefore, to precisely analyze the meteorological parameters in relation to the LLJs, 13~17 December 1997 was selected as the study period. Fig. 7 shows the frequency of the ozone concentrations and meteorological parameters at Pohang from 13 to 17 December in 1997.

In summary, the surface ozone maximum corresponded with the ozone partial pressure pattern due to the LLJs and transports. Even though the meteorological conditions appeared to have a negative correlation when compared based on the daytime, the high concentration ozone occurred at night due to the vertical mixing resulting from the strong wind speed. That is, the ozone produced by photochemical reactions during the daytime reached the upper atmosphere through the development of the mixing height. Owing to the formation of temperature inversions in the lower atmosphere, despite a reduction in the surface ozone concentration, the ozone concentration above the inversion layer will still be high relatively(Cvitas *et al.*[18)], 1985; Pisano *et al.*[19)], 1997). Accordingly, if a powerful vertical circulation with a strong wind speed develops, or convective mixing occurs due to the breaking of the temperature inversions as a result of a rising temperature in the low level, the air in the upper planetary boundary layer containing rich ozone moves down to the ground-level, thereby increasing the surface ozone concentration. This is the main reason for the occurrence of an ozone peak on a low level. Therefore, since a nocturnal peak on the ground-level is formed by a strong wind speed, this is also connected to the occurrence of an LLJ(more than 12.5 $ms^{-1}$).

Consequently, the occurrence frequency of ozone peaks appearing near the surface were identified using ozonesondes data observed at Pohang Weather Station, see Table 1. Apart from the winter period, which showed a high frequency, the frequencies in the other months remained quite low with a slightly higher occurrence of ozone peaks in the summer season. Tables 2 and 3 show the occurrence of low level ozone peaks in Pohang over a 4-year period in relation to the occurrence frequency(%, percentage) of LLJs. When ozone peaks appeared, the frequency of LLJs due to a nocturnal stable layer was about 77%(50/65 days × 100 = 76.92%, for 4 years).

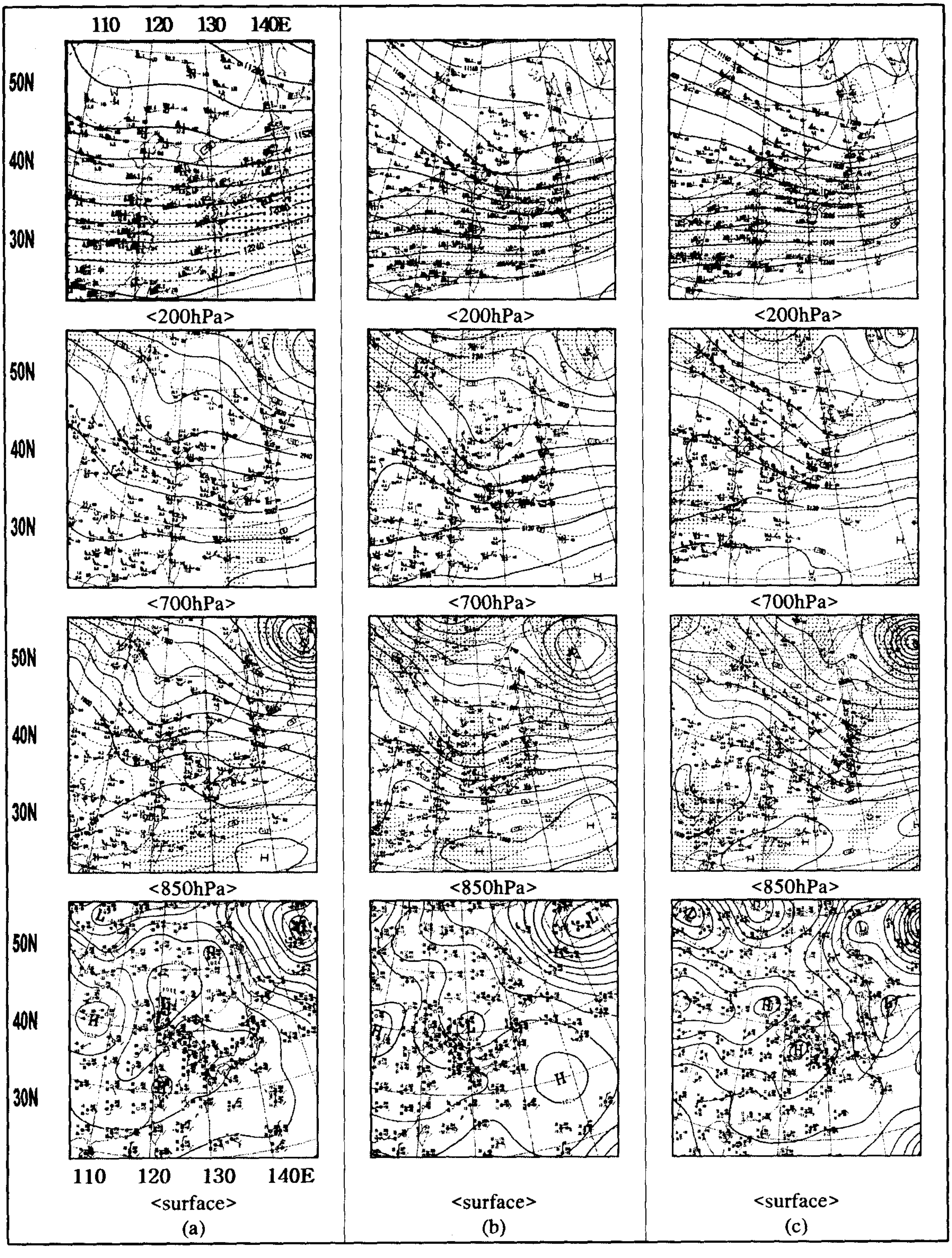


Fig. 6. Synoptic weather maps for (a) 13, (b) 14, and (c) 15 December 1997.

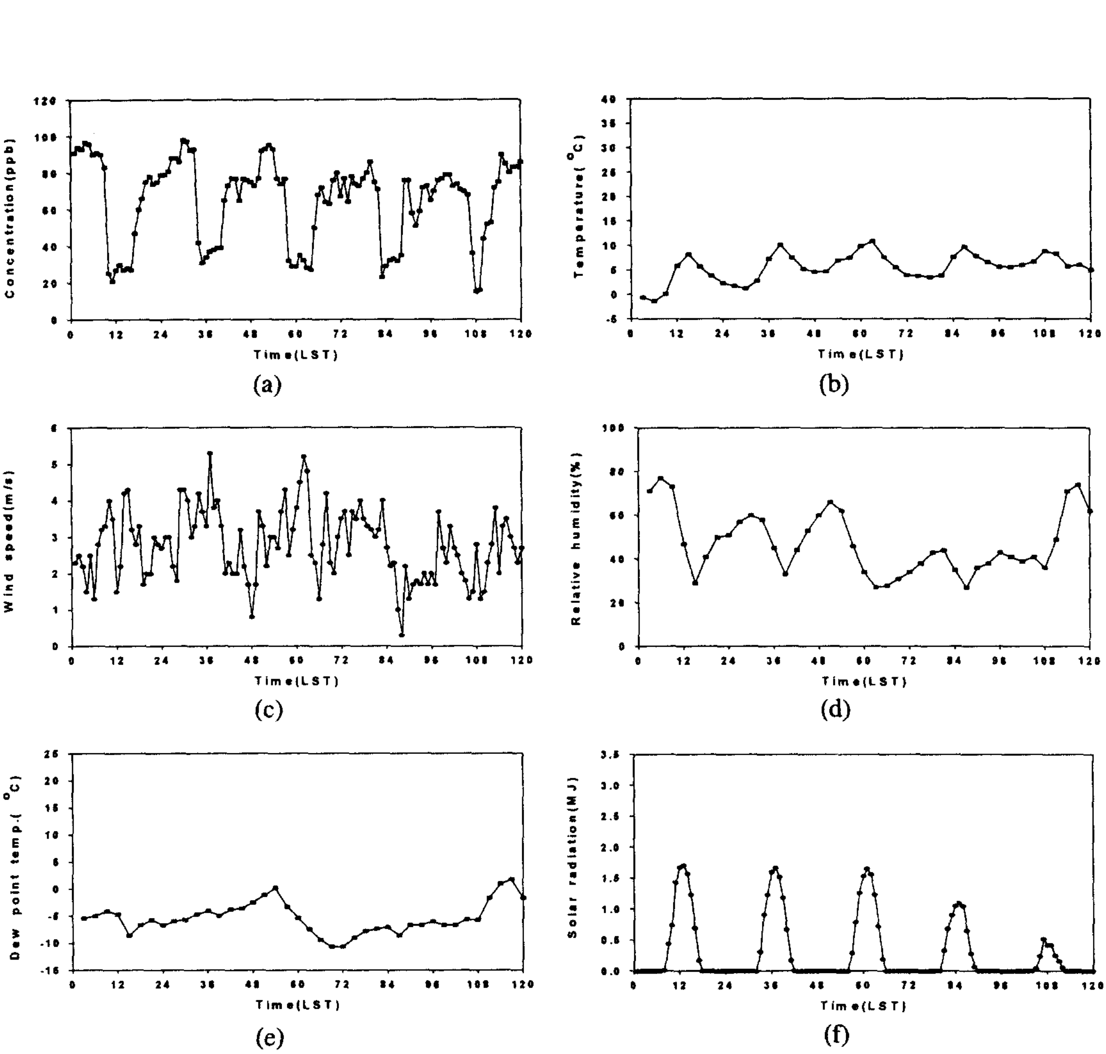


Fig. 7. Frequency of ozone concentration and meteorological parameters at Pohang from 13 to 17 December in 1997. (a) ozone concentration, (b) temperature, (c) wind speed, (d) relative humidity, (e) dew point temperature, and (f) solar radiation.

Table 1. Occurrence frequency of ozone peaks relative to low-level jets at Pohang over 4-year period(1995, 1996, 1997, and 1998)

| Year \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1995 | 2 | 1 | 1 | 1 | 3 | - | 2 | 2 | - | 1 | 2 | 1 | 16(2) |
| 1996 | 4 | 2 | 2 | 2 | 1 | - | 1 | - | - | - | 2 | 2 | 16(4) |
| 1997 | 3 | - | - | 1 | 3 | - | 1 | 1 | 1 | 1 | 2 | 5 | 18(8) |
| 1998 | 2 | 1 | 2 | - | 1 | 2 | - | 2 | 1 | - | 1 | 3 | 15(4) |
| Total | 11 | 4 | 5 | 4 | 8 | 2 | 4 | 5 | 2 | 2 | 7 | 11 | 65(18) |

※ Missing data is presented as parenthesis.

Table 2. Percentage of low-level jet appearance with low level peak occurrence at Pohang over 4-year period(1995, 1996, 1997, and 1998)

| Year | Percentages |
|---|---|
| 1995 | 11days ÷ 16days × 100 = 68.75 |
| 1996 | 13days ÷ 16days × 100 = 81.25 |
| 1997 | 14days ÷ 18days × 100 = 77.78 |
| 1998 | 12days ÷ 15days × 100 = 80.00 |
| Average | 76.92 |

Table 3. Percentage of ozone peak occurrence with appearance of low-level jet at Pohang over 4-year period (1995, 1996, 1997, and 1998).

| Year | Percentages |
|---|---|
| 1995 | 12days ÷ 17days × 100 = 70.59 |
| 1996 | 13days ÷ 18days × 100 = 72.22 |
| 1997 | 14days ÷ 18days × 100 = 77.78 |
| 1998 | 12days ÷ 14days × 100 = 85.71 |
| Average | 76.12 |

The occurrence frequency of ozone peaks near the surface relative to the appearance of LLJs was also about 76%(51/67 days × 100 = 76.12%, for 4 years). As such, there is clearly a very close correlation between low level ozone peaks and the occurrence of LLJs.

Consequently, a further analysis of how LLJs relate to high surface ozone concentrations was performed using the above results from the study period 13 to 17 December 1997.

## 2.3 Photochemical reaction and transport

Based on various previous studies on surface ozone variations, photochemical reactions have been established as a very important source inducing high concentrations. Accordingly, a comparison was made between the 13 ~ 17 December 1997 period and an earlier period, 23 ~ 28 August 1997, which included a high ozone episode day(more than 60 ppb), as recorded in the surface ozone data from the Pohang Weather Station. Furthermore, the parameters for the typical high ozone episode days were used to compare the meteorological parameters during two periods, plus weather charts for the same periods were analyzed to determine whether the pressure patterns were similar to that in Fig. 2.

Unlike the patterns in Figs. 2 and 6, Fig. 8 showed almost no occurrence of trough and ridge systems in the upper-level, and no downward vertical motion. As confirmed by previous studies, the surface ozone enhancement could be explained by photochemical reactions, regardless of the vertical transport and advection in the upper-level, plus all pressure patterns on the surface showed typical meteorological conditions inducing photochemical reactions(see Fig. 9). That is, a clear day without cloud, thereby inducing a high surface ozone concentration with a high pressure pattern over Pohang.

As a result, it would appear that phenomenon of a high concentration ozone in the third case study indicates the local transport of trace gases including ozone and the production of photochemical reactions.

As illustrated in Fig. 9, the relationship between surface ozone concentrations and meteorological parameters is very clear. The surface ozone concentrations were more than 60 ppb(see Fig. 9(a)) at all sites monitored by the Pohang Weather Station. The meteorological conditions that induced active photochemical reactions on the episode day are shown in Figs. 9(b) ~ (f). The temperature, wind speed, and solar radiation were more than 25℃, around 3 $ms^{-1}$, and about 3 $MJ/m^2 \cdot h$, respectively. In addition, it was found that most of the high ozone concentrations occurred on a clear day without precipitation.

In conclusion, it would appear that there is a close correlation between three mechanisms (pressure patterns, LLJs, and photochemical reactions) and near surface ozone peaks.

# 3. Conclusions

The vertical ozone distribution over Korea centering around Pohang was analyzed using ozonesonde and rawinsonde data(1995 to 1998), NCEP(1997), and TOMS(1997) data. Particular

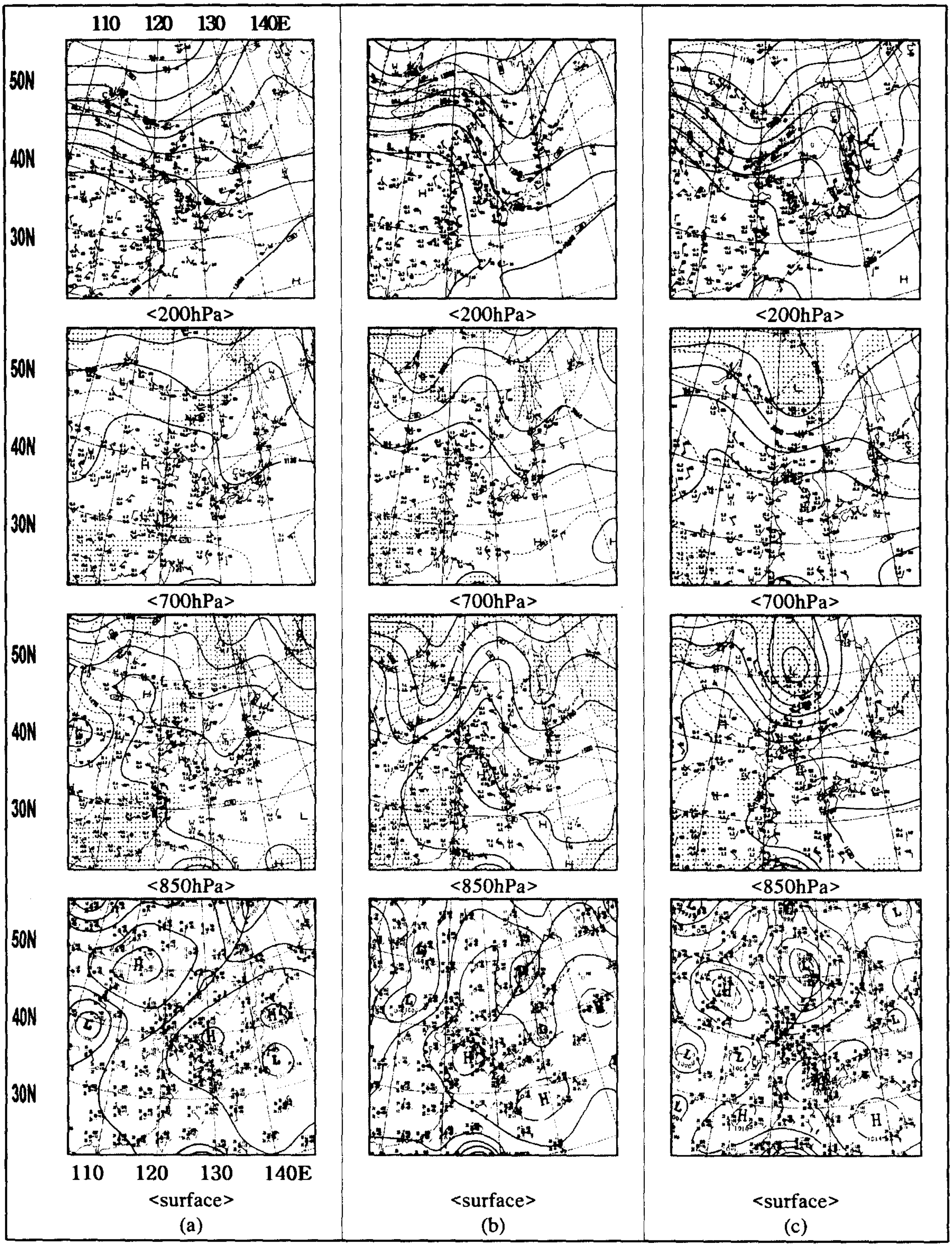


Fig. 8. Synoptic weather maps for (a) 26, (b) 27, and (c) 28 August, 1997.

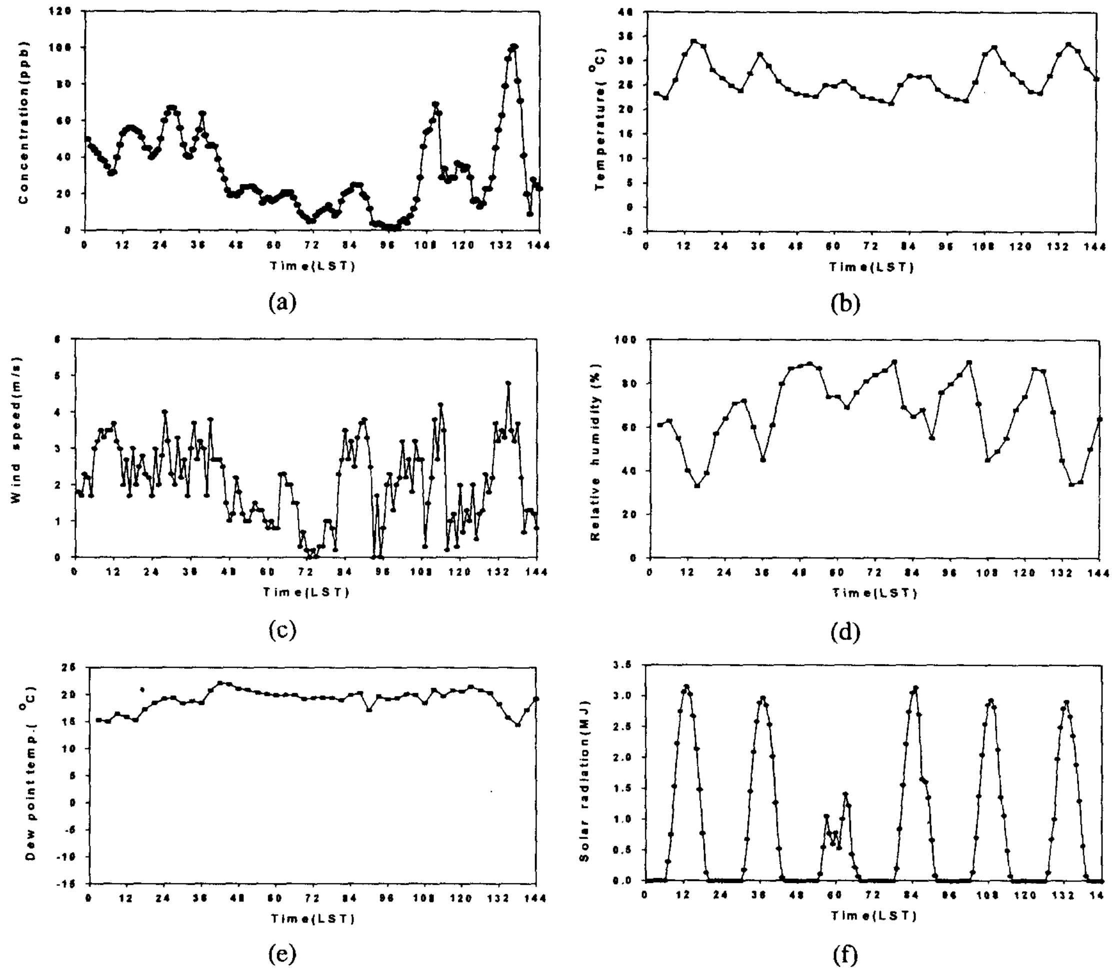


Fig. 9. Same as Fig. 7 except for 23 to 28 August 1997.

case studies were performed to examine the relationship between the vertical ozone distribution and the upper/lower jet caused by the synoptic pattern and temperature gradients associated with stratosphere-troposphere exchange mechanisms.

In the case studies on the vertical ozone distribution near the surface, the frontogenesis between the high and low pressure associated with an upper-level jet stream was shown near the surface in the spring season. Whereas, low-level jets associated with nocturnal inversions induced strong wind speeds(more than 12.5 $ms^{-1}$), which would thus explain why high surface ozone concentrations(above 90 ppb) were recorded at night as the ozone is transported by this wind speed.

When ozone peaks appeared, the related appearance of a low-level jet due to the nocturnal stable layer was about 77%. Similarly, the occurrence frequency of near surface ozone peaks with the appearance of LLJs was about 76%. Accordingly, there is clearly a close correlation between the occurrence of LLJs and near surface ozone peaks.

A high concentration of surface ozone associated with photochemical reactions was recorded at Pohang in the summer season when the temperature, wind speed, and solar radiation were more than 25℃, around 3 $ms^{-1}$, and 3 $MJ/m^2 \cdot h$, respectively, on a clear day without precipitation.

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