IMPORTANT METEOROLOGICAL PARAMETERS FOR OZONE EPISODES EXPERIENCED IN THE TAIPEI BASIN

CHUNG-MING LIU,* CHING-YA HUANG,* SHINN-LIANG SHIEH† and CHING-CHI WU*

*Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, R.O.C. and †Central Weather Bureau, R.O.C.

(First received 12 January 1992 and in final form 28 September 1992)

Abstract—High levels of ozone occur frequently in Taipei, with the peak concentration appearing at noon. Favorable meteorological conditions are extremely important in explaining the observed episodes at stations located in central Taipei. Liu *et al.* (*Atmospheric Environment* **24A**, 1461–1472, 1990) have proposed that the existence of a simplified local land–sea breeze circulation helps to form a temporal stagnant environment during morning hours which is conducive to the photochemical production and accumulation of oxidants. In this paper, the authors focus on analysing the relationship between the morning stagnant condition and the local diurnal circulation, and hope to set up a proper procedure for episode forecast. Through a detailed comparison of the surface meteorological data observed on the ozone episode days and those collected on the low ozone days, it is found that intensified temperature increase, high percentage of low cloud cover, no precipitation, clockwise change of wind direction and a high percentage of low wind speed from sunrise to noon, are the crucial parameters accompanying the noontime high levels of ozone. These findings are further clarified through an intensive observation program during 1989. The analyses of the intensive observation data suggest that the morning stagnant condition occurs due to a transition of flow divergence after sunrise to a flow convergence at noon in the basin. The major causes of such a transition are the diabatic solar heating and an efficient city heat accumulation which is characterized by an enhanced temperature gradient between the surrounding mountains and the basin during hours of large sea–land temperature gradient, in addition to the nighttime radiative cooling. Significant convective activities are observed in the afternoon. All these findings are combined into a proposed procedure for ozone episode forecast, in which the identification of a favorable synoptic environment allowing a significant development of local circulation is the first crucial step toward a successful prediction.

Key word index: Ozone episode, local circulation, episode forecasting.

INTRODUCTION

High oxidant episodes, which were first observed during the 1950s in Los Angeles, are now a worldwide air pollution problem. A recent study by Liu *et al.* (1990) shows that high levels of ozone occur frequently in Taipei. The diurnal ozone variation is described by a single-peaked (SP) pattern, peaking near noon (1200 LT, LT is local time). Analyses of NO, NO₂ and NMHC observational data suggest that, as in other large cities, the photochemical production of ozone accounts for the observed noontime peak. Also, the frequency of occurrence of the SP ozone episode is higher in summer but lower in winter. All the air-quality stations are located near busy roads in the Taipei Basin (Fig. 1), with a typical mean [NO] / [NO₂] ratio of 1.5–3.5. Without a favorable meteorological environment, it is difficult to explain the frequent occurrences of ozone episodes.

A preliminary analysis of the surface meteorological data recorded at the Taipei station (M), which is located near the central section of the Taipei Basin (Fig. 1), for the SP days in 1986 and 1987 shows that low cloud amount, high solar insolation and low wind

speed (in the range of 0–2 m s⁻¹) in the morning are the important meteorological factors accompanying the SP ozone. Liu *et al.* (1990) suggest that a land–sea breeze circulation along the Tamshui River (Fig. 1) can lead to a stagnant environment at around 0900–1000 LT, when local traffic reaches a daily peak. Hence, accumulation of photochemically produced surface ozone is likely to occur under strong solar radiation.

The effects of land–sea breezes on the dispersion of air pollutants were studied by Keen and Lyons (1978), Ozoe *et al.* (1983) and Ohara *et al.* (1989), among others. Pollutants emitted near the shore can be confined to the closed land–sea breeze circulation region under stagnant conditions. In the daytime, air pollutants are transported inland by the sea breeze, causing high oxidant (O_x) concentrations on the ground (Ueda *et al.*, 1988). In the nighttime, Fujibe (1985) pointed out a positive correlation between the passage of the land breeze front and the appearance of high primary pollutant concentrations.

Since Taipei city is situated in a basin, other factors, such as the mountain–valley temperature difference or the urban heat island effect, can also affect the evolu-

Fig. 1. The topography of northern Taiwan with contour lines of 100 and 500 m. The air-quality monitoring stations marked as 2–5 are operated by the Environmental Protection Administration (EPA), while stations B, C, E, I and K are operated by the Bureau of Environmental Protection (EPB) of the Taipei City Government. Stations Q and M are the surface meteorological stations operated by the Central Weather Bureau (CWB). Station M also monitors the surface ozone. During intensive observation periods (IOP), a temporary ozone monitoring station was set up at the coastal station Q. Meanwhile, four pibal stations α , β , γ and δ were chosen to measure the vertical wind field in the boundary layer, along with an intensive sounding operation at stations Z and Q.

tion of the local circulation, in addition to the land–sea breeze. To understand better the meteorological environment that controls the ozone build-up, we have completed a series of analyses of the synoptic weather pattern and the surface meteorological environment. Furthermore, we have carried out a field experiment that includes intensive observations of meteorological parameters over periods predicted to be conducive for high levels of ozone. Data collected during this experiment will not only be helpful in relating the ozone build-up to the local circulation but will also improve our skill in forecasting episodes. It must be pointed out here that due to a short interval of reliable ozone monitoring data, we are more interested in setting up a primitive and qualitative approach to forecast the possible occurrence of an episode, in contrast to the use of empirical statistical models, as carried out by Cassmassi (1987).

COMPARISON OF EPISODE AND LOW OZONE SETS

In order to distinguish between the major surface weather phenomena associated with ozone episodes, two different groups of the surface meteorological data set observed during the summers of 1986–1989 have been identified. One is the episode set, defined as

days when one of the air-quality stations observed an ozone noontime (near 1200 LT) peak higher than 80 ppbv. A total of 120 days are identified. The value of 80 ppbv is chosen for increasing the number of cases and for matching the minimum standard accepted internationally. The low ozone set is defined as days when all stations observed a noontime peak lower than 40 ppbv, for which a total of 59 days are identified. The value of 40 ppbv is chosen for just being half of 80 ppbv. Another important criterion in selecting cases in these two groups is that the diurnal ozone variation at all air-quality stations matches the SP pattern defined in Liu *et al.* (1990), i.e. low ozone concentration at night, a continuous increase of ozone amount after sunrise, reaching a peak at noon and decreasing steadily to a low concentration at sunset. Therefore, even the hourly variation of the difference of mean ozone between these two groups also matches the SP pattern (Fig. 2a). The purpose of the SP criterion is to make sure that we are analysing causes which result in the differing magnitude of the noontime peak without being influenced by other phenomena.

A careful check of the daytime mean $[\text{NO}]$ and $[\text{NO}_2]$ data shows that the NO concentration observed in the episode set is in general lower than those in the low ozone set, with a maximum difference of

Fig. 2. Hourly variation of the difference of mean (a) O_3 , (b) NO and (c) NO_2 between the episode and the low ozone set.

20 ppbv at noon (Fig. 2b). Meanwhile, the $[NO_2]$ observed in the episode set is higher than that observed in the low ozone set, with a maximum difference of 30 ppbv at noon (Fig. 2c). Lower $[NO]$ accompanied with higher $[O_3]$ and $[NO_2]$ in the episode set suggests a more efficient process of photochemical production and surface accumulation of oxidants, given that the variation of the pollutant emission can be ignored after being averaged among all cases in both groups. Otherwise, if efficient dispersion of vehicle-emitted $[NO]$ was to occur during episode days, oxidants are not likely to increase

Fig. 3. The daily maximum ozone among all air-quality stations with single-peaked diurnal pattern during the summers of 1986–1989 vs the integral of the global solar radiation in the morning (0700–1200 LT) observed at the Taipei station (M) on the same day.

significantly in Taipei, thus resulting in an ozone increase in downstream suburban areas.

Since photochemical ozone production should be closely related to the intensity of solar radiation, we have plotted the daily maximum hourly average $[O_3]$ observed among all air-quality stations on SP days in the summers of 1986–1989 against the integral of the global solar radiative flux in the morning (0700–1200 LT) observed at the Taipei station (M) in Fig. 3. Besides noting that the minimum accumulation of global insolation before noon for the occurrence of ozone episode is above $4 MJ m^{-2}$, we find no positive correlation between these two parameters, which is in contrast to the findings of Edmonds and Basabe (1989) and Yoshikado and Mitzuno (1985). In other words, on days of strong morning insolation, either high or low noontime ozone concentration can be observed. A reasonable explanation lies in the differences in the local meteorological environment, e.g. the wind speed.

There are two surface weather stations in the Taipei Basin with a long record of well-calibrated data: Taipei (M) and Tamshui (Q) stations (Fig. 1). Both are operated by the Central Weather Bureau (CWB). Taipei station is located at the center of the basin, while Tamshui station is on the coast and the outer rim of the basin. A detailed analysis of the meteorological data shows that a diurnal variation of the wind, temperature and humidity fields is distinguishable at both stations on all selected days (Huang, 1992). This may be accounted for by the fact that all the days of the episode or low ozone sets were designated to be in the summer. In general, there is a rise in temperature from sunrise to noon in concert with a decrease in relative humidity. Then, the temperature drops steadily to a daily minimum at around 0600 LT the next day before sunrise, whereas the relative humidity increases

Fig. 4. (a) Hourly variation of the frequency of occurrence of the cloud cover being less than 50% in the morning of the episode days (solid line) vs that of the low ozone days (dashed line). (b) Hourly variation of the mean precipitation (mm h^{-1}) occurring on the episode days (solid line) vs that of the low ozone days (dashed line). Both sets of data were collected at the Taipei station (M, in Fig. 1).

steadily to a daily peak at the hours of the daily temperature minimum. Such a diurnal variation is quite common during the summertime in Taipei when the synoptic weather is not being controlled by a powerful system, such as a typhoon. The negative correlation between surface temperature and relative humidity indicates that the supply of water vapor by sea breeze at the surface during the daytime is incompatible with the change of the saturation vapor pressure which is increased simultaneously with the surface temperature. For the episode set, the inland Taipei station experiences an averaged increase of 7°C from sunrise to noon, which is about 3°C more than the change observed at the coastal site. At the same

time the relative humidity drops from 85% at sunrise to 60% at noon, which is about 10% drier than that observed at the coast. The noontime peak temperature of an episode day is much warmer than that of a low ozone day at both stations, with a mean difference of 2°C at Taipei station and 0.8°C at Tamshui station. Meanwhile, the episode days are characterized with drier surface air, i.e. lower relative humidity than on the low ozone days. These phenomena coincide with the observation of a higher frequency of low cloud cover (Fig. 4a) and no precipitation during morning hours (Fig. 4b) on episode days at the Taipei station. It is also noteworthy that the cloud cover increases steadily after 0800 LT and the mean precipitation reaches a peak at around 1500 LT on episode days. The high intensity and the short lifetime (3–4 h) of the afternoon rainfall matches with the characteristics of a typical summertime afternoon thunderstorm. These findings support our speculation that an intensified local circulation must occur on episode days, which is characterized with clear sky in the morning, and strong convective activity in the afternoon. This circulation is driven by the intensified solar heating and nighttime cooling.

Figures 5a and 5b show the mean hodograph of the episode and low ozone sets at the Taipei and Tamshui stations, respectively. The change of wind direction at Taipei is clockwise, i.e. in the morning south-southeasterly, in the afternoon northwesterly and then back at midnight to southeasterly. Mean wind speed is lower than 1 m s^{-1} in the morning, but is intensified in the afternoon. This kind of diurnal change of the wind field typically results from a land-sea breeze circulation (Liu *et al.*, 1990). Meanwhile, from Fig. 5a we can determine that the diurnal variation of wind direction is much stronger in the episode set than that in the low ozone set. A similar situation occurs at the coastal station (Fig. 5b) but with a much more intensified northwesterly flow (sea breeze) in the afternoon. Again we note that at the coastal site the diurnal variation is more significant in the episode set, which suggests a more intensified response of local circulation to the diabatic solar heating. Further, we observe a higher frequency of low wind speed ($< 1\text{--}2 \text{ m s}^{-1}$) and a lower frequency of strong wind speed ($> 3 \text{ m s}^{-1}$) in the morning hours (0700–1100 LT) at Taipei (Fig. 6) and Tamshui in the episode set, which can be a crucial factor for an efficient accumulation of oxidants locally. The chance of having wind speed equal to or larger than 3 m s^{-1} is below 20%.

In conclusion, strong solar insolation is a necessary but not an absolute criterion in determining the occurrence of an ozone episode in the Taipei Basin. Rather, higher frequency of low cloud cover, no precipitation, higher frequency of low wind speed and lower frequency of strong wind speed, after sunrise to noon, are the important meteorological parameters accompanying an episode. Specifically, these factors are favorable for an efficient production and accumu-

(a) Taipei

(b) Tamshui

Fig. 5. The hodograph of the mean wind field of the episode set (solid line) vs that of the low ozone set (dashed line).

lation of oxidants before noon. In addition, a significant diurnal change of wind and temperature field was observed during episode days at both the coastal and the inland station, which suggests an efficient response of local circulation, such as a land-sea breeze circulation, to the diabatic solar heating and nighttime cooling. Such a phenomenon must occur during a weak synoptic weather system, and hence can be a good indicator for episode forecasting. Meanwhile, an intensive observation program is required in order to reveal the relationship between a stagnant morning environment and a significant afternoon thunderstorm.

Fig. 6. Hourly variation of the frequency of occurrence of the wind speed in the morning (0700–1100 LT) of the episode days (solid line) vs that of the low ozone days (dashed line) at the Taipei station.

SYNOPTIC WEATHER PATTERN

In order to distinguish the favorable synoptic environment accompanying ozone episodes in the Taipei Basin, we have identified a total of 269 episode days during 1986–1989 and then carefully analysed the synoptic conditions observed during these days. Seven different weather patterns were subjectively identified after a thorough diagnosis by an experienced CWB weather forecaster. These weather patterns are described as follows:

- (I) A moving high-pressure system covering the Taiwan area (Fig. 7a): in this pattern, a continental high-pressure system with its center located south of 30°N is moving southeastward over the East China Sea.
- (II) Under the control of a subtropical high ridge (Fig. 7b): in this pattern, the Pacific subtropical high is extending westward, and Taiwan is under the control of its ridge system.
- (III) Pre-frontal warm section (Fig. 7c): in this pattern, Taiwan is located inside the pre-frontal warm section.
- (IV) In the belt of low-pressure systems (Fig. 7d): in this pattern, Taiwan is between two low-pressure systems. Usually, such conditions occur when the Intertropical Convergence Zone (ITCZ) is moving northward near Taiwan.
- (V) Return flow from a high-pressure system (Fig. 7e): in this pattern, a continental high moving eastward over the East China Sea has its center located north of 30°N.
- (VI) At the edge of an intensified high-pressure gradient (Fig. 7f): in this pattern, the center of a continental high-pressure system is located over northwestern China. The area with an intensified pressure gradient is to the north of the

Yangtze River. Taiwan is at the outer edge of the high-pressure system, with weak synoptic wind flow.

- (VII) Weak northeasterly flow (Fig. 7g): in this pattern, a moderate high-pressure system with its center located north of 30°N is stagnant. The Taiwan area is affected by a weak northeasterly flow.

In general, these weather systems are accompanied by a weak large-scale flow near Taiwan. Hence, a localized circulation driven by solar heating and nighttime radiative cooling tends to dominate local weather. The most obvious phenomena are the land breeze during nighttime and the sea breeze near noon. The low-humidity land breeze will cause a clear sky

with high insolation after sunrise, while the high-humidity sea breeze can force the formation of an afternoon convective system. During the transition of the land breeze circulation to the sea breeze circulation, which is usually between 0800 and 1000 LT, local stagnant conditions accompanied by strong solar insolation are conducive for the formation of high levels of ozone.

Table 1 lists the frequency of occurrence of these seven systems on episode days. The total 269 episode days cover every month of 1986–1989, and about 45% of these events are in summer (June–August), 13% in winter (December–February). Pattern III appears most frequently, while patterns II, III and IV are closely related to the summer episodes. Under pattern II conditions, occurrences of episodes longer than 10

(a) pattern I

(b) pattern II

(c) pattern III

(d) pattern IV

Fig. 7(a)–(d).

Fig. 7. Seven different synoptic weather patterns (I-VII) favorable for ozone build-up at Taipei.

Table 1. The monthly variation of the number of occurrences of ozone episode days with different synoptic weather patterns (I-VII, defined in Fig. 7)

Pattern	Month												Net
	1	2	3	4	5	6	7	8	9	10	11	12	
I	1		3	6	1	1			1	1		6	20
II					2	13	25	20	5	1			66
III	3		10	8	12	22	3	7	2	8	4	1	80
IV					1	5	15	7	2				30
V	6	2	9	11	5	3		3		2	7	2	50
VI	2	1	1							2	2	1	13
VII			1			3						6	10
Net	12	3	24	25	20	43	33	44	15	16	13	20	269

consecutive days are observed. Since these patterns are identified from the weather data of the 269 episode days, they can be taken as a necessary but not an absolute indicator for predicting the occurrence of an episode. For instance, just by identifying the occurrence of these seven different synoptic environments,

we have a 54.5% chance of predicting the episodes in 1989. But by further filtering out days with morning rainfall and strong wind speed ($> 5 \text{ m s}^{-1}$), the chance increases to 75%. The factors of no rainfall and low wind speed in the morning are obtained from our analyses described in the previous section.

INTENSIVE OBSERVATION

During August 1989, a team was formed to forecast the ozone episodes and to execute intensive meteorological observations. Four pilot stations, marked as α , β , γ and δ in Fig. 1, were set up. Station δ was located in the middle of Taipei city, while stations α , β and γ formed a triangle to surround the city. Also, in addition to a routine operational sounding station Z, a temporary sounding operation at Tamshui station Q was set up (Fig. 1). During selected intensive observation periods (IOPs), these stations were operated at an interval of every 3 h.

In order to compare the ozone concentrations along the coast with those in the city, a temporary ozone monitoring station was set up at station Q (Fig. 1). Air-quality data were collected at stations operated by the Environmental Protection Administration (EPA), Bureau of Environmental Protection (EPB) of the Taipei City Government, and at Taipei station M (Fig. 1) operated by the Central Weather Bureau (CWB). The total number of stations with reliable data was five, and there was no monitoring station in the southeastern area.

Three IOPs were selected based on the forecast of having two to three consecutive days of clear weather and light winds. Some of the results were reported in Liu (1990). In this section, we present the data collected during IOP1, which is from 0800 LT on 4 August to 1700 LT on 7 August 1989.

General description

During IOP1 Taiwan was between two low-pressure centers (pattern IV) with a weak large-scale prevailing wind. Taipei and Tamshui experienced significant diurnal temperature and relative humidity change (Fig. 8) just as expected, with the scale of change being larger at the inland station. It should be noted that during the maximum temperature period (around 1200 LT) at Taipei, the atmospheric stability estimated using the Turner method (Turner, 1961; Liu and Feng, 1990) indicated a very unstable condition. Meanwhile, even though the relative humidity at surface was close to 50–60% at 1200 LT, precipitation still occurred around 1400 LT on the 5th, 6th and 7th. Obviously, the convectively unstable air near the surface forced the formation of a local thunderstorm. Its lifetime was short and hence the precipitation only lasted for about 2 h each afternoon. The dry condition near the surface at noontime could have resulted from a substantial increase of the saturation vapor pressure, which is a function of air temperature, and a consistent loss of water vapor caused by the convective updraft.

The wind field during IOP1 also experienced significant diurnal change (Fig. 9). At Taipei, after sunset (about 1800 LT) to 0900 LT the next day, the surface wind was steady from the south-southeast direction with wind speed generally less than 2 m s^{-1} . After 0900 LT, the wind direction changed gradually to be northerly at noon, with wind speed about 4 m s^{-1} . A

Fig. 8. Hourly variation of the surface (a) temperature and (b) relative humidity observed at the Taipei station during 4–7 August 1989. Figures (c) and (d) are at the Tamshui station. The dated mark corresponds to 1200 LT of each day.

Fig. 9. Hourly variation of the surface (a) wind direction and (b) wind speed observed at the Taipei station during 4–7 August 1989. Figures (c) and (d) are at the Tamshui station. The dated mark corresponds to 1200 LT of each day.

similar change was also observed at Tamshui but with smoother variation. It is important to note the stagnant condition before 1100 LT at Taipei, which is suitable for chemical reactions and oxidant accumulation.

As predicted, high ozone concentrations were observed at noon over most parts of Taipei (Fig. 10). The highest concentration was above 80 ppbv and was recorded at the central Taipei station. If it were not for the lack of ozone measurements in the southeastern section of the Taipei Basin, we believe that much higher ozone concentration would have been observed at that region (Liu *et al.*, 1990). The coastal station Q also observed SP ozone but with peaks smaller than those in the central Taipei. Judging from the local air flow, the ozone build-up at the coastal area had a weak correlation with that at central Taipei, and probably resulted from local emissions or recirculation of old air in the sea breeze. Still, the ozone concentration peaked at around 1200 LT at all stations. Since the peak time correlates positively with the occurrence of maximum surface wind speed and temperature, it indicates that the dilution of pollutants by either surface wind or convective updraft is essential.

Horizontal structure

By selecting data on 6 August for detailed analysis, we have plotted the horizontal distribution of surface temperature and flow streamline over northern Taiwan in Fig. 11. To simplify the discussion, we only

compare the distribution at 0200 LT with that at 1400 LT. At 0200 LT, the colder regions were in the mountain areas, while the Taipei Basin and the coastal region had a temperature warmer than 24°C (Fig. 11a). The temperature gradient from the mountain ridge to the Taipei Basin was about 2–4°C. But at 1400 LT, substantial heating in the urban area caused the appearance of a high temperature center similar to a city heat island in the basin (Fig. 11b). Owing to a weaker warming in the mountain regions, a significant increase of the temperature gradient from the surrounding mountains to the basin of about 8°C was observed. This large temperature gradient occurred when the sea–land temperature gradient was also large, and hence must cause a significant flow convergence in the basin and alter the simplified sea breeze circulation.

At 0200 LT, land breeze was prevailing over most coastal regions, which was intensified with the descending mountain breeze over the western plain (Fig. 11c). While, in the Taipei Basin, the outflow land breeze along the Tamshui and Keelung Rivers was much stronger than the descending flow from the southern and southeastern mountain region, which led to the formation of a flow divergence area over northern Taipei. Such an area was most evident at around 0800 LT, right after sunrise. At 1400 LT, sea breeze was evident over coastal regions (Fig. 11d). But in the basin, a cyclonic flow convergence center appeared over the southeastern region, apparently caused by the inflows from the northwestern coast along the Tamshui River and from the northeastern coast along the

Fig. 10. The diurnal ozone variation during 5–7 August 1989, at stations (a) Q, (b) 2, (c) 5, (d) K, (e) 4 and (f) M (shown in Fig. 1). The dated mark corresponds to 1200 LT of each day.

Fig. 11. The surface isothermal lines over northern Taiwan at (a) 0200 LT and (b) 1400 LT on 6 August 1989, and the surface streamlines over northern Taiwan at (c) 0200 LT and (d) 1400 LT on the same day.

Keelung River, and the descending flows from the surrounding mountains. The existence of this flow convergence area was consistent with the observation of a city heat island at the same time (Fig. 11b).

In all, the transition of early morning flow divergent condition to the afternoon flow convergent situation

in the basin is in phase with the transfer of the land breeze circulation to the sea breeze circulation on the coast. The significant warming in the basin caused by both the solar heating and the city heat accumulation not only intensified the temperature gradient from mountain regions to the basin, but also the mountain

descending breeze. To quantify clearly this evolution will require a detailed dynamic flow simulation, or a more complete observation network. None the less, we suggest that a temporal stagnant condition will appear during the transition process, which matches with the observation of low wind speed before 1100 LT at Taipei and Tamshui. A stagnant condition is favorable for ozone production and accumulation. Furthermore, the convergence of flow in the basin in the afternoon is in phase with the convectively unstable condition, and hence reasonably enhances the formation of a convective storm which results in rainfall.

Vertical structure: thermodynamic system

The benefit of doing an intensive observation is having an extensive sounding and pibal data set every 3 h, which provides a good opportunity for doing detailed analyses. In this section, we intend to analyse the evolution of the thermodynamic system on a temporal-vertical profile, based on the sounding data obtained at stations Z and Q (Fig. 1). In the next section, we will analyse the vertical structure of air flow.

Since the Taiwan region has abundant moisture, the thermodynamic system of the planetary boundary layer can best be presented by the virtual potential temperature field, θ_v :

$$\theta_v = \theta(1 + 0.61q)$$

where θ is the potential temperature and q is the water vapor mixing ratio. The parameter θ_v is frequently used for studying the stability of an air parcel with abundant moisture. A vertically displacing air parcel is thermodynamically stable, neutral or unstable at regions where $\partial\theta_v/\partial z$ is larger than, equal to or smaller than zero, respectively. Figure 12 illustrates the temporal-vertical variation of θ_v at the inland station Z. Similar analyses were done for the coastal station Q, but are not shown here.

The nighttime longwave radiative cooling initiated the formation of a stable surface inversion layer which was capped at an altitude of 400 m at station Z and 300 m at coastal station Q at 0500 LT. After sunrise, the effect of surface heating resulted in a uniform θ_v in the mixing layer which reached an altitude of 1100–1400 m at station Z and 900–1200 m at station Q at around 1400 LT. Meanwhile, a diabatic unstable layer was formed closer to the ground during daytime, which maximized at an altitude of 250–400 m at station Z and about 200 m at station Q at 1400 LT. The existence of the surface unstable layer accompanied with the low-level air flow convergence would accelerate the formation of a microscale convective system and hence the thunderstorm activity. In the coastal areas, the slower response of ocean water temperature to the diurnal change of solar heating and radiative cooling apparently weakened the evolution of the local surface boundary layer.

Fig. 12. The temporal-vertical variation of the virtual potential temperature θ_v below 2 km during 5–7 August, 1989, at station Z (shown in Fig. 1).

The difference in the temperature and moisture fields between the coastal and the inland stations can be distinguished by analysing a $\Delta\theta_v$ field, which is defined as the subtraction of θ_v at station Z from that at station Q. In the evening $\Delta\theta_v$ was positive and could be up to 2.3°C at 100 m height, while at noon it was negative and could be down to -5.5°C at 600 m height. The afternoon thunderstorm helped to enhance surface moisture and to decrease surface air temperature in the basin, hence $\Delta\theta_v$ minima appeared at higher levels.

Vertical structure: air flow

From Fig. 1, we can distinguish that there are two main river valleys coming into the Taipei Basin. These two valleys intersect at a 110° angle. Even though the angle is not close to 90°, we still feel comfortable projecting the pibal and sounding data onto the two profiles in parallel to these two valleys, which are shown as two intersected lines in Fig. 1. The purpose is to analyse the air flow structure on each profile, in order to provide an approximate three-dimensional outlook. The intersected angle being larger than 90° may not be a perfect condition, but the profiles being in parallel to the river valleys do provide sufficient information in a more realistic sense. Here we select the data from 6 August for specific illustration.

Figure 13 shows the station-height profile of the wind component along the Tamshui River at 0200, 0800, 1100 and 1700 LT. Due to rainfall, we failed to obtain enough of pibal data at 1400 LT. In Fig. 13, a negative value indicates that the wind is blowing toward the sea, while a positive value is for wind heading into the basin. Similar plots were done for the profile along the Keelung River and are shown in Fig.

Fig. 13. The station-height profile of the wind component along the Tamshui river at (a) 0200 LT, (b) 0800 LT, (c) 1400 LT and (d) 1700 LT on 6 August 1989. A negative value indicates that the wind is blowing towards the sea, while a positive value is for wind heading into the basin.

14. From 0200 to 0800 LT, the prevailing wind had an inflow component along the Tamshui River and an outflow component along the Keelung River at altitudes above 800 m. This matched our observation of a prevailing southwesterly. Meanwhile, along the Tamshui River, an outflow component caused by the land and mountain breeze was from the surface to above 200 m in height, which reached 800 m at coastal station Q and 400–600 m at the southern Taipei station α . Stations β and δ , being closer to central Taipei, observed a weak outflow layer below 300 m and strong inflow above. Hence, a low-level flow divergence must occur at the central basin along the Tamshui River profile, and was strongest at 0800 LT when the difference of the outflow component between stations Q and α reached a maximum. Along the Keelung River profile, the inland station Z observed an inflow component below 200–400 m which was completely different from the outflow land breeze component observed at the northeastern Taipei station γ . Hence, a low-level flow divergence would occur at the central Taipei station δ , and was strongest at

0800 LT when the difference of the wind components between stations α and γ reached a maximum. Since a similar situation occurred on the two river profiles, it is reasonable to expect a subsidence flow from upper levels to the low-level central basin, which must be quite significant at 0800 LT when the low-level flow divergence was strongest and the nighttime inversion layer was broken due to sunrise. The existence of a morning subsidence flow can be very important in supplying upper-level oxidants and precursors to lower levels, which may assist in oxidant accumulation.

As time evolved, the development of a sea breeze at station Q was distinguishable after 0800 LT and reached a peak at 1400 LT. At 1100 LT (Fig. 13c) the inflow component reached a peak at the 580 m level and was accompanied with an outflow component above 800 m. At the same time, outflow components occurred at station δ from the surface to 450 m with a peak at the surface. Hence, a low-level flow convergence was expected at the central basin along the Tamshui River. Meanwhile, along the Keelung River

Fig. 14. As Fig. 13, but for the wind component along the Keelung River.

(Fig. 14c), the inflow wind component was strong at station γ , weak at station δ , then intensified at station α , which also led to the expectation of a low-level flow convergence at central Taipei. Therefore, an ascending flow caused by the convergence at lower levels must occur at a time when a diabatic unstable layer was also observed at lower levels. Such a condition matches our discussion based on the analyses of horizontal structure of the temperature and flow streamline, and explains the occurrence of the convective activities that followed. Most important, a smooth transition from the morning divergence of flow to the noontime convergence at lower levels requires the presence of a temporal stagnant environment, which again supports the observation of low wind speed before 1100 LT at Taipei.

The afternoon convective system penetrated above 2 km height. At 1700 LT, the downdraft in the aged system had suppressed the prevailing large-scale wind above 800 m. From the analyses of the Tamshui and Keelung River profiles (Figs 13d and 14d), the downdraft was from a southeastward direction and covered almost all regions of the basin from surface up to 2 km

high, which indicated the coverage of the convective activity.

DISCUSSION AND CONCLUSION

The major source of the surface ozone pollution is certainly through the photochemical reactions among the vehicle-emitted pollutants. However, a favorable meteorological environment is crucial to the occurrence of the ozone episode. In Taipei, most air-quality stations observe a mean $[\text{NO}]/[\text{NO}_2]$ ratio between 1.5 and 3.5, which indicates fresh emission, and a possible ozone/HC titration process. But still we have records of ozone episodes at most stations each year. Liu *et al.* (1990) illustrate the effect of land-sea breeze along the Tamshui River on the temporal and spatial variation of ozone, and suggest that during the transitional period in the morning when the land breeze circulation is gradually changing to the sea breeze circulation, there exists a stagnant condition suitable for efficient photochemical reactions and ozone accumulation. The mature sea breeze in the afternoon can

transfer ozone downstream to southeastern Taipei, while diluting the surface ozone.

In this paper, we focus on analysing the relationship between the morning stagnant environment and the local diurnal circulation, and hope to set up a proper procedure for the episode forecast. Through a comparison of the surface meteorological data of an episode and that of a low ozone set, it is found that strong solar insolation in the morning is a necessary but not an absolute criterion in forecasting ozone episode. Rather, intensified temperature increase, high percentage of low cloud cover, no precipitation, clockwise change of wind direction and high percentage of low wind speed after sunrise to noon are the crucial parameters accompanying the noontime high levels of ozone. These conditions generally indicate a stagnant environment, and are definitely in favor of an efficient chemical production and surface accumulation of oxidants under strong solar insolation. Furthermore, high cloud cover after noontime, intensified precipitation within a short time interval around 1400 LT, and strong wind flow in the afternoon, are factors found specifically on the episode days. These conditions generally indicate an intensified convective thunderstorm activity typically observed on the western side of Taiwan during summer afternoons. At this point, an intensive observation is necessary in order to understand the transition from the morning stagnant condition to the afternoon convective activity.

The data gathered during the 1989 Intensive observation periods clarify the role of local circulation in the occurrence of ozone episodes. Before sunrise, the land breeze along the coast and the mountain breeze into the basin cause a flow divergence in central Taipei (Figs 11c, 13a and 14a), which is accompanied by subsidence. However, a shallow inversion layer (below 400 m high; Fig. 12) caused by nighttime radiative cooling stops any exchange of material between the surface and upper layers. After sunrise, the break-up of the nighttime inversion is followed by swift development of a mixing layer (Fig. 12). At 0800 LT, flow divergence at lower layers is intensified (Figs 13b and 14b). The expected subsidence can help to transfer upper-layer oxidants and precursors downward to the ground to be mixed with the surface air. Meanwhile, efficient accumulation of heat in the city enhances the temperature gradient between the basin and the surrounding mountains at noontime hours when the sea-land temperature gradient is also large (Fig. 11b). This is different from the nighttime thermal distribution (Fig. 11a). Therefore, the airstream at the surface is changed from the nighttime outflow pattern (Fig. 11c) to the noontime convergence (Figs 11d, 13c and 14c) in the basin. During the transitional period in the morning, a stagnant environment characterized by low wind speed (Figs 9b and 9d), low cloud cover, no precipitation and strong solar insolation exists, which is the favorable condition for the observed noontime high levels of ozone (Fig. 10). Similar phenomena

repeated themselves during the three consecutive IOP days. In short, downward transport and mixing of higher layer oxidants and precursors after inversion break-up and the morning stagnant condition are conducive to the production and accumulation of oxidants within 4–5 h after sunrise (Fig. 10).

At noon, a diabatic unstable layer closer to the ground (Fig. 12) is accompanied by a surface flow convergence in the basin (Figs 11d, 13c and 14c). Consequently, strong uplifting of lower layer air initiates the growth of a microscale convective system which matures at around 1400 LT and causes heavy rainfall in the afternoon. At the ground level, the accumulated ozone is diluted by the thermally forced vertical mixing, the updraft lifting and later the downdraft transport. Thus, the noontime maximum ozone concentration must occur in the convergence area which is approximately at the southeastern edge of Taipei. Unfortunately, due to lack of observations, we fail to prove this point.

The data gathered during the intensive observation period have not only supported our hypothesis that the local diurnal circulation driven by the significant solar heating and nighttime cooling plays an important role in the occurrence of ozone episodes in Taipei basin, it has also provided a good opportunity to study the dynamical process of the evolution of local circulation, and to analyse the individual effects of transport and chemical reactions on the enhancement of oxidants, which shall be carried out in the future through numerical simulation.

Furthermore, the experiences gathered during the intensive forecasting and observation period also strengthen our confidence in the prediction of the ozone episode. Basically, a proper procedure to forecast next-day noontime episode is outlined below.

- (1) Based on numerical weather prediction output, check whether the coming synoptic weather system meets one of the seven favorable patterns described in Fig. 7. This procedure provides a greater than 54.5% chance to catch the event and is a very important process in filtering out unrelated cases.
- (2) A subjective forecast of clear sky, no precipitation and strong solar insolation for the next morning (from sunrise to noon), based on the overall information and past experience. This is not a perfect approach, but it provides a preliminary expectation. The no-rain criterion is most crucial to the success, because it is the only absolute criterion found so far on days of ozone episode.
- (3) An objective forecast of next-day minimum and maximum temperature, based on the CWB numerical weather prediction output. The purpose is two-fold, to estimate the difference of either the forecast minimum and maximum temperature, or the observed 0800 LT temperature and the forecast noontime maximum temperature. The former

parameter can be obtained in advance, and statistically has to be above 5°C. The latter parameter can be obtained at 0800 LT of the target day, and statistically has to be above 4°C. Both the 5 and 4°C criteria are obtained from the analyses of past episode days' data and are reliable parameters even during wintertime. The purpose of searching for a minimum temperature increase after sunrise to noon, is to look for an indirect index of the strength of the local circulation, since the circulation is driven primarily by the diabatic solar heating.

- (4) To forecast next-day mean wind speed in the morning. This is a crucial factor in determining directly the morning stagnant condition. Our analyses suggest a maximum mean speed of 1.5 m s^{-1} on episode days. However, it is not an easy task to forecast this parameter. The authors did analyse a few different approaches, but the reliability is low. However, if we can develop a certain scheme based on the observation data after sunrise of the target day, we may still catch the event beforehand. A 2–3 h warning ahead of time can still be useful information for residents in Taipei.

The above-proposed procedure for forecasting an ozone episode has ignored the possibility of a change in vehicle emissions which is very unlikely to occur in Taipei in the next 5 years.

Acknowledgements—This paper was supported by EPA R.O.C. under grant EPA-79-002-01-007 and NSC grant NSC-80-0202-M002-32. The authors wish to thank the Central Weather Bureau, the Bureau of Environmental Protection (EPB) of Taipei City Government and the Environmental Protection Administration (EPA), R.O.C., for providing assistance and data. Also, the authors would like to express sincere gratitude to Dr Shaw C. Liu for many helpful discussions. In addition, the in-depth criticism and editing provided by the anonymous reviewers is extremely appreciated. The authors thank Dr Martin Buhr and Ms A.-Y. Yang for paper editing, and Mr C.-H. Lee, Mr K.-P. Chung, Ms M.-F. Lai and Ms S.-H. Chu for data analysis, plotting, etc.

REFERENCES

- Cassmassi J. C. (1987) Development of an objective ozone forecast model for the southern coast air basin. 80th Annual Meeting of the Air Pollution Control Association, New York, 21–26 June 1987.
- Edmonds R. L. and Basabe F. A. (1989) Ozone concentrations above a Douglas-Fir forest canopy in western Washington, U.S.A. *Atmospheric Environment* **23**, 625–629.
- Fujibe F. (1985) Air pollution in the surface layer accompanying a local front at the onset of the land breeze. *J. met. Soc. Japan* **63**, 226–237.
- Huang C. Y. (1992) A study of the atmospheric environment during summertime ozone episode in Taipei region. M.S. thesis, Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, R.O.C. (in Chinese).
- Keen C. S. and Lyons W. A. (1978) Lake/land breeze circulations on the western shore of Lake Michigan. *J. appl. Met.* **17**, 1843–1855.
- Liu C. M. (1990) A study of the meteorological environment during ozone build-up in Taipei. 3rd Int. Conf. Atmospheric Science and Application to Air Quality (ASAAQ), Shanghai, China, 15–19 October.
- Liu C. M. and Feng T. S. (1990) Atmospheric turbidity over Taiwan. *Atmospheric Environment* **24A**, 1303–1312.
- Liu C. M., Liu S. C. and Shen S. H. (1990) The study of Taipei ozone pollution. *Atmospheric Environment* **24A**, 1461–1472.
- Ohara T., Uno I. and Wakamatsu S. (1989) Observed structure of a land breeze head in the Tokyo metropolitan area. *J. appl. Met.* **28**, 693–704.
- Ozoe H., Shibata T., Sayama H. and Ueda H. (1983) Characteristics of air pollution in the presence of land and sea breeze—a numerical simulation. *Atmospheric Environment* **17**, 35–42.
- Turner D. B. (1961) Relationships between 24-h mean air quality measurements and meteorological factors in Nashville, Tennessee. *J. Air Pollut. Control Ass.* **11**, 483–489.
- Ueda H., Mitsumoto S. and Kurita H. (1988) Flow mechanism for the long-range transport of air pollutants by the sea breeze causing nighttime high oxidants inland. *J. appl. Met.* **27**, 182–187.
- Yoshikado H. and Mitzuno T. (1985) Dependence of the surface ozone concentration in the Harima district on the insolation and the wind. *J. met. Soc. Japan* **63**, 1139–1146.