PREDICTION OF URBAN AIR QUALITY BY USING VISIBILITY AS AN INDICATOR IN SOUTHERN TAIWAN

Horng-Yu Yang

Department of Civil Engineering, China Institute of Technology
245, Yen-Chiu-Yuan Road, Sec. 3rd, Taipei, Taiwan, ROC
E-mail:horngyu@cc.chit.edu.tw

Chung-Shin Yuan

Institute of Environmental Engineering, National Sun Yat-Sen University70, Lian-Hai Road, Kaohsiung, Taiwan, ROC
E-mail:ycsngi@mail.nsysu.edu.tw

ABSTRACT

This paper focused on the description and improvement of urban air quality using visibility as an indicator. Field observation of visibility were consecutively conducted to investigate the influence of pollution sources and meteorological factors on urban air quality, which can be applied to determine the control strategies for the improvement of urban air quality in Kaohsiung city. The results from regular observation of visibility from November 1998 to April 2000 indicated that most frequently observed visibility range from 2 to 8 kilometers. Approximately 79.3% of these days are with visibility less than 8 kilometers, which observed mainly during in the wintertime. However, intensive observation of visibility and measurement of scattering coefficient from January 8-16 to March 24-30 2000 indicated that atmospheric visibility had an opposite correlation with scattering coefficient for relative humidity less than 70%. The field measured scattering coefficients during two separate intensive sampling periods were 0.0928-0.5744/km and 0.0852-0.6727/km, respectively. Visibility predicted by climate-persistence (CLIPER), analog, and multiple regression models. The results from models prediction indicated that the percentage for the difference between predicted and observed visibility within 1.5 kilometers was higher than 60%. Moreover, daily observation data indicated that the worst visibility occurred in early morning at 6:00am and the best visibility occurred in the late afternoon at 1:00pm. In addition, seasonal variation of visibility indicated that the best and the worst visibility seasons were summertime and wintertime in Kaohsiung city. This study concluded that visibility might be used as indicator of ambient quality.

INTRODUCTION

The objective of this study was to develop an innovative technology to determine and to forecast the atmospheric visibility of Kaohsiung city, where atmospheric visibility has been used as an alternative ambient air quality index since 2002. The atmospheric visibility in Kaohsiung city has been regularly observed to characterize the variation of atmospheric visibility since November 1998. Three levels of atmospheric visibility were set as good (> 8 km), moderate (2-8 km), and poor (< 2 km). For investigating the development of an innovative technology to determine atmospheric visibility, the feasibility of using atmospheric visibility as ambient air quality index, and the forecasting of atmospheric visibility using climate persistence (CLIPER), analog, and multiple regression models. For this particular study, Moreover, a multiple regression model was further developed to forecast the atmospheric visibility for five weather patterns. Atmospheric visibility was forecasted at 5:00 pm with the above multiple regression model for each day. Based on 100 effective forecasted atmospheric visibility data from June 15th to October 15th, the accuracy of visibility forecasting based on three visibility levels was approximately 96.0% with root mean square of 1.79 km. The correlation coefficient of forecasted and observed atmospheric visibility was 0.80. Kaohsiung city was selected for this particular study owning to its worst ambient air quality, especially impaired atmospheric visibility, over the Taiwan island. With rapid population growth and increasing industrialization over the past three decades, poor ambient air quality has become one of the major environmental concerns of the general public in Kaohsiung city. In order to characterize the visual air quality, the atmospheric visibility has been regularly observed in Kaohsiung city since November 1998. General speaking, the atmospheric visibilities observed at Kaohsiung area are very poor and are usually lower than 10 kilometers (or 6.2 miles). The most frequently observed atmospheric visibility ranged from 2 to 4 kilometers that is much poorer than most mega cities over the world. Previous study characterize the visibility of Kaohsiung city into three levels: good (> 8 km), moderate (2-8 km), and poor (< 2 km).[1] Moreover, previous investigation also suggested that atmospheric visibility might be used as an alternative ambient air quality of Kaohsiung city.[2] Therefore, the objective of this study was to investigate the forecasting of atmospheric visibility using climate persistence (CLIPER), analog, and multiple regression models at Kaohsiung city.In order to characterize and further improve the ambient air quality of Kaohsiung city, both central government and local agency have paid many attentions on visual air quality, mainly atmospheric visibility, since 1998. This investigation studied the statistical analysis of field observed atmospheric visibility, the feasibility of using atmospheric visibility as ambient air quality index.

METHODOLOGIES

Field Observation of Atmospheric Visibility

This study was based on both regular and intensive observations of atmospheric visibility in the Kaohsiung city. Regular observation was conducted to elucidate the temporal and spatial variation of atmospheric visibility, while intensive observation was conducted to elucidate the diurnal variation of daytime atmospheric visibility. Regular observation of atmospheric visibility was performed each day at 11:00 am and 2:00 pm from November 1998 to December 2001. On the other hand, four intensive observation campaigns were conducted in January-May 1999 and January-March 2000, which were conducted each hour from 7:00 am to 5:00 pm. Concurrently, Kaohsiung aerosols were sampled in situ and meteorological data were obtained from Kaohsiung Meteorology Station for further statistical analyses. Atmospheric visibility was observed without visual aids at two observation sites, Kaohsiung Meteorology Station and Farshing Temple, as shown in Figure 1. At Kaohsiung Meteorology Station, the observations were made facing northward with an observation sector of 60^o, while those at Farshing Temple were made facing eastward with an observation sector of 120°. Hence, the field observed atmospheric visibility herein was also named as sector visibility. Objects were pre-identified prior to observation at each site for determining the atmospheric visibility. The location of each pre-identified object was mapped with global positioning system (GPS) and the GPS data was then used to determine the distance from the observation site to each object with an error lower than 50 m. In this study, eleven and seventeen objects were positioned and observed from Kaohsiung Meteorology Station and Farshing Temple, respectively.

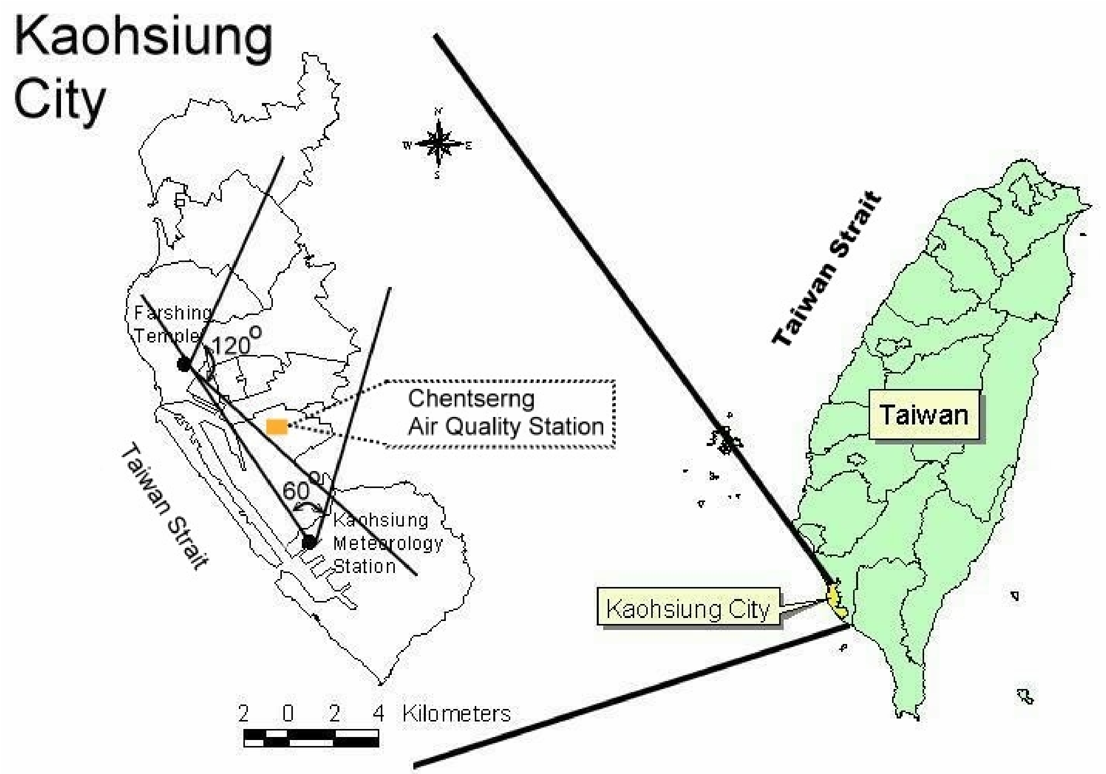

Figure 1. Location of the observation sites of atmospheric visibility and the sampling site of aerosol particles in the Kaohsiung City, Taiwan.

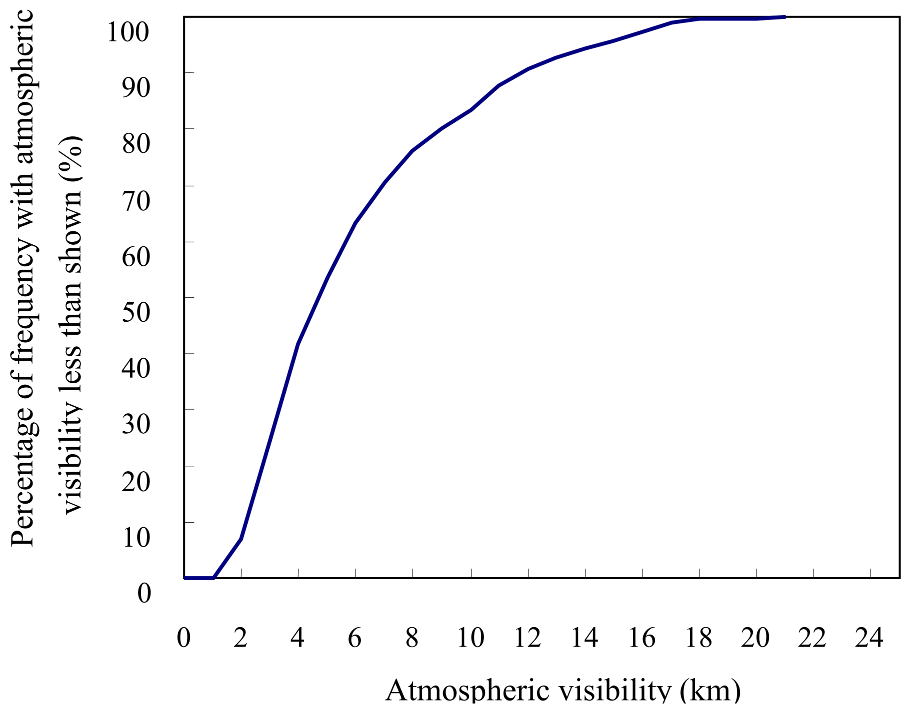

Figure 2. Cumulative distribution of daytime atmospheric visibility observed in the Kaohsiung city in the years of 1999-2001.

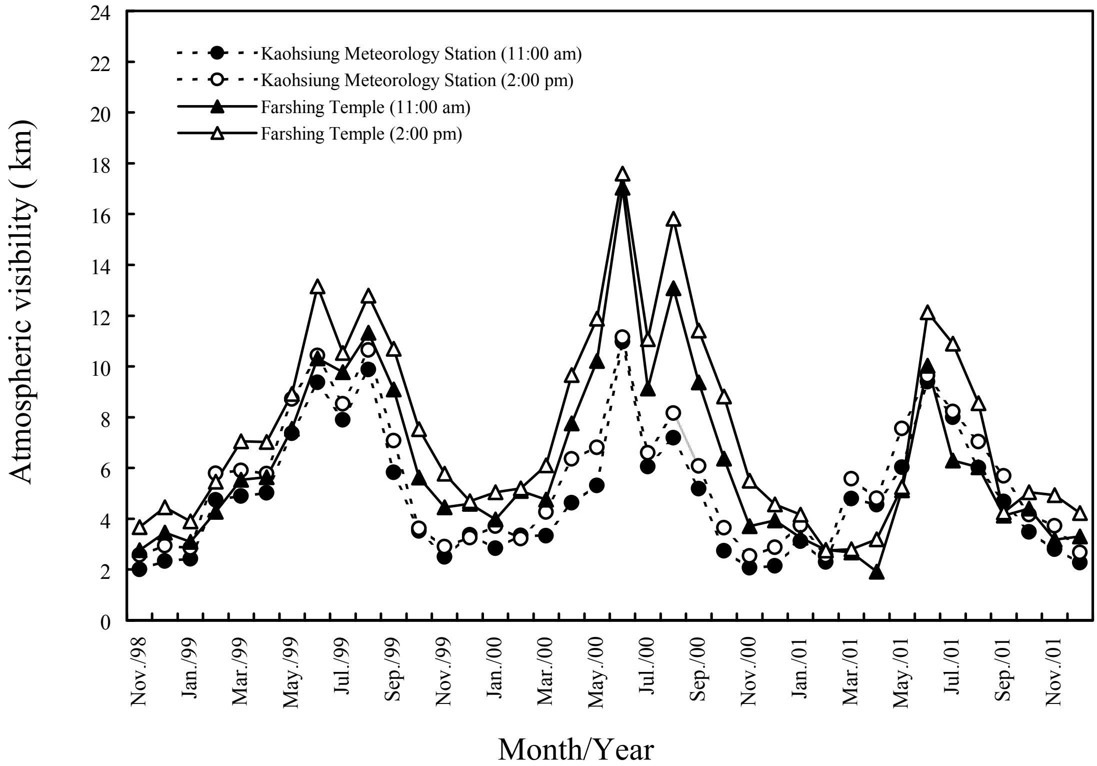

Figure 3. Seasonal variation of daytime atmospheric visibility observed in the Kaohsiung city from November 1998 to December 2001.

Forecasting Model Development

CLIPER was applied for the first guessing of a reference visibility, while analog was used to double check the low visibility during the air pollution episodes. Furthermore, a multiple regression model was further developed to forecast the atmospheric visibility based on meteorological factors and air pollutants for various weather patterns. Air pollutants included PM_{10}, NO_2, SO_2, and O_3, while meteorological parameters included relative humidity (RH), wind speed (WS), and wind direction (WD). In this study, wind direction was further divided into eight sections with 45^o of each. In addition to the aforementioned three meteorological factors, weather pattern was found to be very crucial for the forecasting of atmospheric visibility. Therefore, six multiple regression models were established for typical weather patterns dominated by cold front system, northeastern monsoon system, continental high-pressure system, oceanic high-pressure system, subtropical low-pressure system, and other systems.

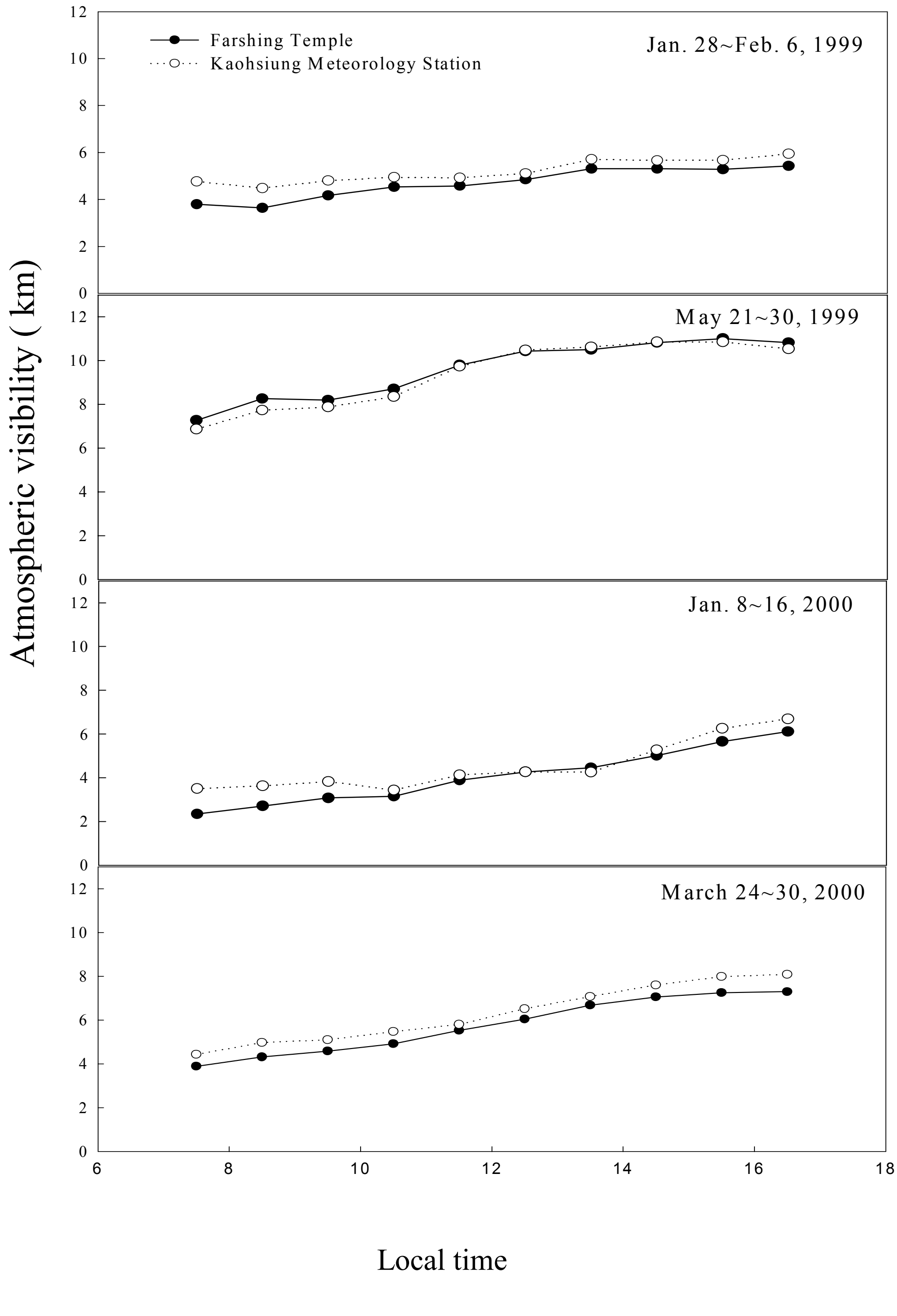

Figure 4. Diurnal variation of daytime atmospheric visibility observed in the metropolitan Kaohsiung during the intensive observation periods of 1999-2000.

RESULTS AND DISCUSSION

Temporal and Spatial Variation of Atmospheric Visibility

Regular observation of daytime atmospheric visibility was performed at 11:00 am and2:00 pm at two observation sites in metropolitan Kaohsiung. Figure 2 plots the cumulative distribution of atmospheric visibility observed from November 1998 to December 2001. It showed that the field observed atmospheric visibilities in metropolitan Kaohsiung were always lower than 21 km, ranging from 0.7 to 20.6 km. According to the levels of atmospheric visibility (i.e. 2 and 8 km) regulated by the Environmental Protection Department of Kaohsiung, the cumulative percentage of visibility less than 2 and 8 km were 7.8 and 76.2%, respectively. Approximately 50 % of the field observed atmospheric visibilities were lower than 5 km, indicating that the atmospheric visibility in metropolitan Kaohsiung has been seriously impaired. Moreover, regular observation of daytime atmospheric visibility at Kaohsiung Meteorology Station yielded an average atmospheric visibility of 6.1 and 7.2 km at 11:00 am and 2:00 pm, respectively. The results were consistent with previously reported monthly average atmospheric visibility of 7.2 km (1975-1994) with a range of 3.3-13.10 km.[(3)] Figure 3 illustrates the monthly variation of daytime atmospheric visibility during the investigation period from November 1998 to December 2001. A significant seasonal variation of atmospheric visibility was observed in the Kaohsiung city. The atmospheric visibility was generally higher in summer and lower in late autumn and winter. Moreover, the mean seasonal atmospheric visibilities in spring, summer, fall, and winter were 5.4, 9.1, 8.2, and 3.4 km, respectively. Low atmospheric visibility observed in late autumn and winter was mainly due to the high frequency of fog formation, resulting from the radiation inversion occurred in the early morning.During the intensive observation periods, daytime atmospheric visibility was observed at two observation sites each hour from 7:00 am to 5:00 pm. Figure 4 illustrates the diurnal variation of daytime atmospheric visibility and compares the atmospheric visibility observed at two sites. The atmospheric visibilities observed at Kaohsiung Meteorology Station (northward) were slightly higher than those at Farshing Temple (eastward). Atmospheric visibility tended to increase in the morning and then leveled off at 2:00-3:00 pm in the afternoon. During four intensive observation periods, the atmospheric visibilities in three winter periods were markedly higher than those in the early summer period. On average, the lowest mean atmospheric visibilities at 7:00 am were 5.7 and 4.8 km at Kaohsiung Meteorology Station and Farshing Temple, respectively. While, the highest mean atmospheric visibilities at 3:00-5:00 pm were 7.9 km and 7.5 km at Kaohsiung Meteorology Station and Farshing Temple, respectively. It is quite consistent with previously reported diurnal variation of atmospheric visibility observed for the past two decades[(4)]. In that study, the lowest atmospheric visibility observed at 7:00 am were around 5 km at Kaohsiung Meteorology Station, while the highest atmospheric visibility observed at 3:00-5:00 pm were around 8 km. The phenomenon was attributed to the following two reasons. First of all, relative humidity was usually higher in the early morning, causing fog formation, which scattered visible light and hence impaired atmospheric visibility. Secondly, the primary fine particles emitted from motor vehicles in rush hours would enhance the effects of light scattering and absorption, and thus reduced the atmospheric visibility due to the condensation and nucleation of moisture onto the fine particles in the early morning.

Light Scattering Coefficient

Results from the measurements of nephelometry indicated that, during the first intensive measuring period (January 8~16, 2000), an hourly average b_{sp} (dried) of 330/km with a range of 0.0928-0.5744/km was recorded. During the second intensive measuring period (March 24~30, 2000), the hourly average b_{sp} (dried) was 290/km with a range of 0.0852-0.6727/km. For comparison, they are of similar magnitude to values recorded in metropolitan areas in the Yangtze delta region of South China [5].

Validation for Atmospheric Visibility Forecasting

A multiple regression model was established to correlate atmospheric visibility with air pollutants and meteorological factors is shown below. Among them, NO_2 and SO_2 are the precursors of secondary nitrate and sulfate aerosols. Relative humidity represents the moisture content of aerosol particles. Although fine particles (0.26μ m < dp <0.9μ m) were thought as the most efficient aerosols to scatter visible light,[6] PM_{10} was used as the input variable since it was routinely measured in situ. The correlation coefficients of the regression models for various weather patterns are listed in Table 1.

Weather Pattern	Correlation Coefficient (R)
Cold Front System	0.90
Northwestern Monsoon System	0.78
Continental High-Pressure System	0.92
Subtropical High-Pressure System	0.93
Low-Pressure System	NA
Other Systems	0.91

NA: data is not enough to correlate visibility with air pollutants and meteorological parameters

Table 1. Correlation coefficients of multiple regression models for various weather patterns.

$$\log(L_v) = a_1PM_{10} + a_2NO_2 + a_3SO_2 + a_4O_3 + a_5RH + a_6WS + a_7WD_1 + a_8WD_2 + a_9WD_3 + a_{10}WD_4 + a_{11}WD_5 + a_{12}WD_6 + a_{13}WD_7 + a_{14}WD_8 + a_{15} \quad (1)$$

where L_v: atmospheric visibility (km); PM_{10}: particulate matter with dp≦ 10μ m (μ g/m^3); SO_2, NO_2, O_3: concentration of gaseous pollutants (ppbv); RH ：relative humidity (%); WS: wind speed (m/s); $WD_{1\text{-}8}$ ：wind direction (clockwise, “1” for the northeast and “8” for the north).

Equation (1) was then used to determine the atmospheric visibility with known input variables and could be further compared with the observed atmospheric visibility. Figure 5 illustrates the comparison of estimated and observed atmospheric visibility. During this investigation period, the accuracy of atmospheric visibility forecasting based on three visibility levels was approximately 86.7% with root mean square of 1.84 km. The correlation coefficient of forecasted and observed atmospheric

visibility was 0.75.
Approximately 92.0% of the forecasted atmospheric visibility was within an error of 3.0 km, while about 77.9% of the forecasted atmospheric visibility was within an error of 2.0 km. Moreover, around 41.6% of the forecasted atmospheric visibility lied within an error less than 1.0 km. These results implied that the forecasting of atmospheric visibility was feasible that can be achieved by approximately 70.0% for an error of 1.84 km.

Forecasting of Atmospheric Visibility

Atmospheric visibility was forecasted at 5:00 pm each day with the aforementioned multiple regression model. Based on one hundred effective forecasted atmospheric visibility data from June 15th to October 15th, the accuracy for the forecasting of atmospheric visibility based on three visibility levels was approximately 96.0% with the root mean square of 1.79 km (see Figure 5). The correlation coefficient of the forecasted and the observed atmospheric visibility was 0.80 (see Figure 6). In general, the variation of forecasted atmospheric visibility was quite consistent with the observed atmospheric visibility although the root mean square went up to 1.79 km. However, several opposite trends for visibility forecasting were also observed on August 21st-22nd and on September 5th-8th. By further reviewing of both air pollutant concentrations and meteorological factors, this study concluded that the opposite trend

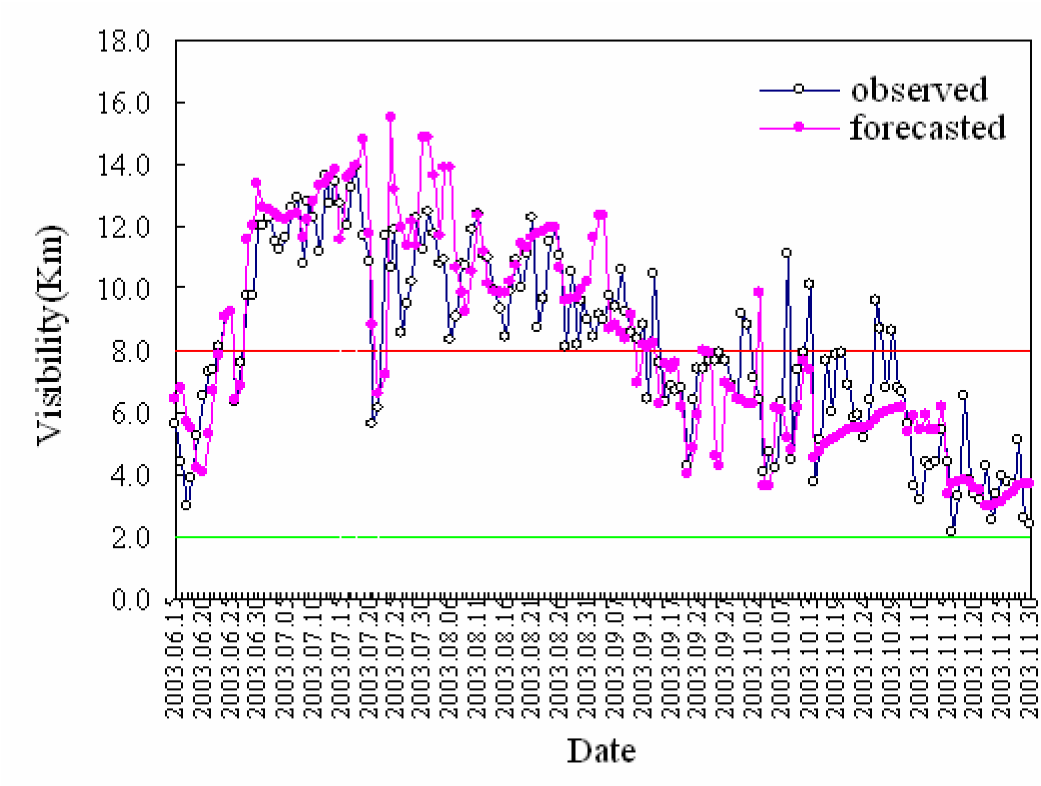

Figure 5. Comparison of forecasted and observed atmospheric visibility.

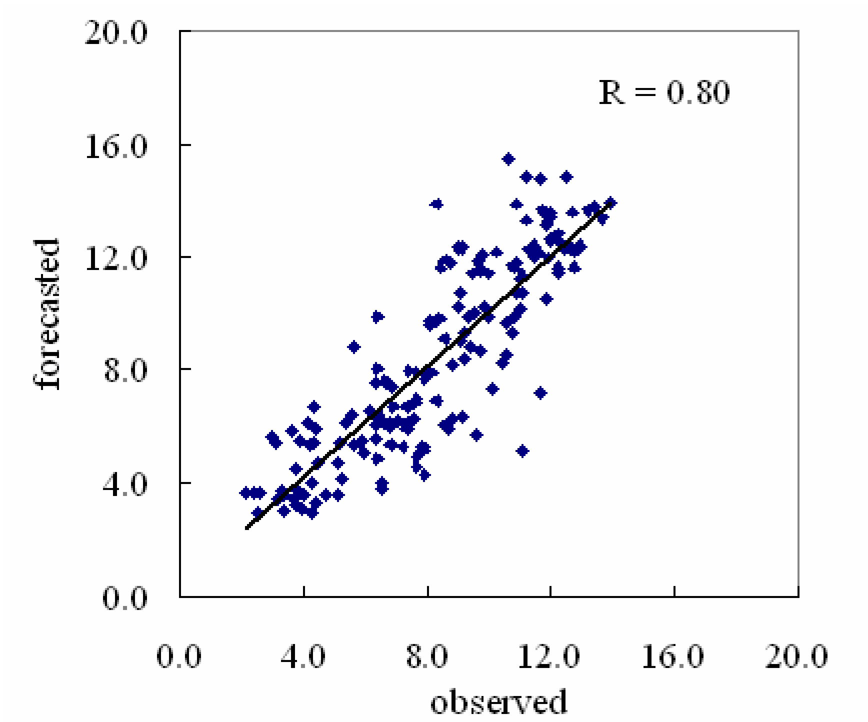

Figure 6. Correlation of forecasted and observed atmospheric visibility
for the forecasting of atmospheric visibility were mainly attributed to incorrect judgment of either weather patterns or wind directions.

SUMMARY

Moreover, a multiple regression model considering both ambient air pollutants (PM_{10}, NO_2, SO_2, and O_3) and meteorological parameters (relative humidity, wind speed, and wind direction) was successfully developed to forecast the atmospheric visibility for various weather patterns. The atmospheric visibility was then forecasted with the multiple regression models at 5:00 pm each day. Based on a hundred of effective atmospheric visibility data forecasted from June 15th to October 15th, 2003, the accuracy was approximately 96.0% with a root mean square of 1.79 km on the basis of visibility levels (i.e. good, moderate, and poor). The correlation coefficient of the forecasted and the observed atmospheric visibility was 0.80.

REFERENCES

[1] Yuan, C.S.; Lin, Y.C.; Lee, C.G.; Lo, C.C. The 14th IUAPPA International Conference on Air Quality – Assessment and Policy at Local, Regional, and Global Scales, Dubrovnik, Croatia, Oct. 6-10, 2003.

[2] Won, C.H; Yuan, C.; Yuan, C.S. Alternative Air Quality Index, Final Report, Department of Environmental Protection, Kaohsiung Municipal Government.

[3] Yuan, C.S., Lee, C.G., Liu, S.H., Yuan, C., Yang, H.Y., Chen, C.T., 2002. Developing Strategies for Improving Urban Visual Air Quality. Aerosol and Air Quality Research, 2, 9-22.

[4] Yuan C. S., Chang J. C., Yuan J. S., Lin Z. T., Yuan C. and Yang H. Y., 1998. A field Study on the Relationship of Visibility with Suspended Particles and Meteorological Factors in Kaohsiung city. The 90th A&WMA Annual Meeting, San Diego, California.

[5] Xu J., Bergin M., Yu X., Zhao J., Carrico C., Beaumann K., 2002. Measurement of Aerosol Chemical, Physical and Radioactive Properties in the Yangtze Delta

Region of China. Atmos. Env. 36: 161-173.
[6] Luo, C.H., Liu, S.H., and Yuan, C.S. Aerosol and Air Quality Research, 2002, 2(1), 23-29.

Key Words
atmospheric visibility
visibility forecasting technology
multiple regression model