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Spatial Correlation of Satellite-Derived $PM_{2.5}$ with Hospital Admissions for Respiratory Diseases

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Abstract: Respiratory diseases, particularly allergic rhinitis, are spatially and temporally correlated with the ground $PM_{2.5}$ level. A study of the correlation between the two factors should therefore account for spatiotemporal variations. Satellite observation has the advantage of wide spatial coverage over pin-point style ground-based in situ monitoring stations. Therefore, the current study used both ground measurement and satellite data sets to investigate the spatial and temporal correlation of satellite-derived $PM_{2.5}$ with respiratory diseases. This study used 4-year satellite data and $PM_{2.5}$ levels of the period at eight stations in Taiwan to obtain the spatial and temporal relationship between aerosol optical depth (AOD) and $PM_{2.5}$. The AOD-$PM_{2.5}$ model was further examined using the cross-validation (CV) technique and was found to have high reliability compared with similar models. The model was used to obtain satellite-derived $PM_{2.5}$ levels and to analyze the hospital admissions for allergic rhinitis in 2008. The results suggest that adults (18–65 years) and children (3–18 years) are the most vulnerable groups to the effect of $PM_{2.5}$ compared with infants and elderly people. This result may be because the two affected age groups spend longer time outdoors. This result may also be attributed to the long-range $PM_{2.5}$ transport from upper stream locations and the atmospheric circulation patterns, which are significant in spring and fall. The results of the current study suggest that additional environmental factors that might be associated with respiratory diseases should be considered in future studies.

Keywords: $PM_{2.5}$; aerosol optical depth; allergic rhinitis

1. Introduction

Many epidemiologic studies have reported associations between particulate matter (PM) air pollution and cardiorespiratory hospital admissions over the past two decades (e.g., [1–4]). These studies have shown that PM with a fine aerodynamic diameter of $\leq$2.5 µm ($PM_{2.5}$) is associated with increased respiratory and cardiovascular morbidity and mortality [5,6]. With rapid economic growth and industrial development, $PM_{2.5}$ pollution has become one of the most severe environmental problems and has been extensively studied [7]. The $PM_{2.5}$ level also significantly influences sustainable development and the ecological balance of Earth, which directly affects human health (e.g., [8–10]). Therefore, it is critical to understand the correlation between epidemiological diseases and environmental factors such as the $PM_{2.5}$ level.

Epidemiologic studies of $PM_{2.5}$ require long-term and accurate $PM_{2.5}$ exposure information, which is generally collected through ground monitoring networks. However, ground-based in situ observation stations are typically located in the center of downtown areas or in highly polluted industrial parks. The lack of information on the spatial distribution of environmental variables may lead to considerable bias when applying and comparing the stationary data set directly against the corresponding hospital admissions. Moreover, in situ observation stations are set up to monitor the environment at fixed locations, whereas the population is widely distributed in the affected regions. Consequently, the pin-point style of measurement may not represent the overall population variation spatially.

Recently, the use of satellite remote sensing observation in air quality studies has evolved greatly [11]. Because space-borne remote sensing provides comprehensive spatial and temporal coverage, estimating $PM_{2.5}$ from space data can complement the ground $PM_{2.5}$ monitoring network [12,13]. The National Aeronautics and Space Administration (NASA) had launched two Earth Observing System (EOS) satellites, Terra and Aqua, in 1999 and 2002, respectively. The follow-up Suomi National Polar-Orbiting Partnership (S-NPP) satellite was launched in October 2011. Moderate Resolution Imaging Spectroradiometer (MODIS) on board both Terra and Aqua and Visible Infrared Imager Radiometer Suite on board S-NPP provide measurements of the aerosol optical depth (AOD). The data are retrieved from spectral observation at visible and near-infrared wavelengths. The corresponding particle sizes of AOD range from 0.1 to 2 μm, which is similar to the size of $PM_{2.5}$ particles. Recent studies have examined the relationship between $PM_{2.5}$ and satellite-derived AOD by using various techniques and have developed several adequate models (e.g., [14,15]). However, few studies have analyzed satellite-derived $PM_{2.5}$ and its association with epidemiologic diseases, such as upper respiratory tract infection. This study utilized satellite-derived AOD to retrieve the $PM_{2.5}$ level in Taiwan in order to determine whether the relationship between the ground-level measured $PM_{2.5}$ level and AOD is a strong predictor of high temporal variation in $PM_{2.5}$.

The purpose of this study was three-fold: (a) to develop the optimal localized $PM_{2.5}$ estimation model for Taiwan from space-borne satellite observation; (b) to explore the effect of satellite-derived $PM_{2.5}$ on hospital admissions for respiratory diseases; and (c) to investigate the effect of $PM_{2.5}$ on the occurrence of respiratory diseases in different age groups.

2. Materials and Methods

2.1. Study Area

Taiwan is located in East Asia between 22°01′–25°12′N latitude and 119°25′–122°48′E longitude (Figure 1). Taiwan is situated in the tropical climate zone with four distinct seasons. However, the typical climate leads to a slight difference between the northern and southern regions of Taiwan. The northern region lies in the subtropical climate zone, whereas the southern region lies in the tropical climate zone. Hence, the average daily temperatures in these regions range from 15.1 °C to 30.2 °C throughout the year. With urbanization and industrialization in recent decades, the growing population, industrial manufacturing, and dense vehicle traffic have greatly contributed to air pollution, which is currently considered the most noticeable environmental issue in Taiwan. Through the Taiwanese government's efforts and regulations, air pollution emission and $PM_{2.5}$ production have been controlled to steady levels. However, the ground-level $PM_{2.5}$ monitoring data show huge seasonal variation. Long-term observation indicates that this seasonal variation is mostly caused by the long-range transport of air pollution from regions surrounding Taiwan [16]. In fall and winter, atmospheric circulation transports air from China to Taiwan, whereas in spring and summer, the prevailing wind drives the passage of the monsoon from Southeast Asia to Taiwan [17]. Hence, numerous cases of strong seasonal repeated infections of the upper respiratory tract in the Taiwanese population may be caused by this long-range transport of air pollution. Taiwan is an ideal region for studying the relationship between $PM_{2.5}$ and respiratory diseases, because data on island-wide in situ observation and satellite-derived $PM_{2.5}$ levels and hospital admission for respiratory diseases are all comprehensively recorded.

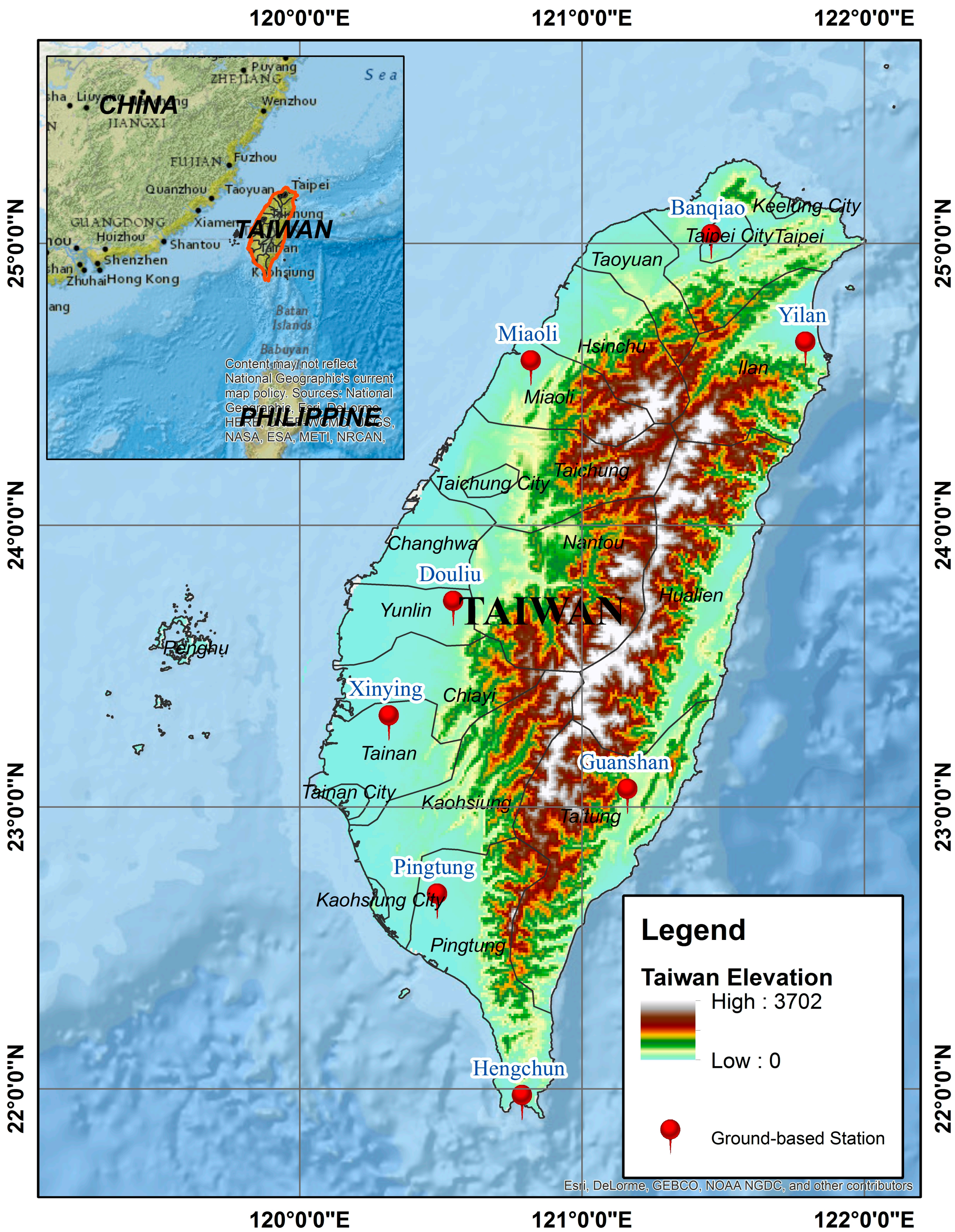

Figure 1. Map of Taiwan with the altitude overlaid in color scale. Grey lines denote the boundary of each individual city. The distribution of ground-based $PM_{2.5}$ measurement stations was acquired from the Taiwan Air Quality Monitoring Network (TAQMN). The eight pin-point locations on the map, Banqiao, Maoli, Douliu, Xinying, Yilan, Guanshan, Hengchun, and Pingtung, indicate the $PM_{2.5}$ measurement stations included in this study. The elevation data were obtained from Advanced Spaceborne Thermal Emission and Reflection Radiometer/Global Digital Elevation Model (ASTER GDEM) Version 2 at https://asterweb.jpl.nasa.gov/gdem.asp.

2.2. Satellite Data

The satellite data used in this study and their associated AOD products were retrieved from NASA/EOS Terra MODIS observation. The Terra satellite has an approximate equatorial crossing time at 10:30 a.m. (PM) locally for the ascending (descending) orbit, and the MODIS scans at a swath of 2330 km globally. The MODIS has 36 spectral channels with wavelengths including the visible, near-infrared, and infrared regions. The MODIS data have been used and their benefits have been demonstrated for environmental applications such as monitoring and predicting weather and climate (e.g., [18–21]). Abundant MODIS-derived products are available for atmospheric, oceanic, and land applications, among which AOD is the most relevant to air quality studies. The MODIS-retrieved AOD data were obtained at 10-km spatial resolution at nadir. It is a dimensionless measure of the scattering and absorption of sunlight by aerosols in the atmospheric vertical column [22]. The collection 6 MODIS aerosol product data (MOD04) in Taiwan and the surrounding regions were processed and downloaded from the Level 1 and Atmospheric Archive and Distribution System (LAADS Web; http://ladsweb.nascom.nasa.gov).

2.3. Ground In Situ $PM_{2.5}$ Data

We selected eight ground stations from the Taiwan Air Quality Monitoring Network (TAQMN): Banqiao, Maoli, Douliu, Xinying, Yilan, Guanshan, Hengchun, and Pingtung (Figure 1). These stations have recorded long-term historical observation data. Their installed instruments are calibrated periodically. Their distribution is almost uniform across the northern and south regions of Western Taiwan. These stations provide a favorable representation of various levels of $PM_{2.5}$ in one MODIS swath (i.e., one MODIS "granule" data) when the study area has a concentration gradient due to the long-range transport of air pollution from the upper stream. Yilan and Taitung are two counties in Eastern Taiwan that are less affected by atmospheric circulation, industrial activities, population, and traffic. These two sites served as the reference for background information. This configuration increases the reliability of the AOD-$PM_{2.5}$ model introduced in Section 2.4.

2.4. Hospital Admission Data

We collected data on island-wide hospital admissions for respiratory diseases in Taiwan from January to December 2008. The hospitals included in the compiled data were publicly and privately funded hospitals that provide regular outpatient services. Patient data were captured from the computerized medical record system of the National Health Insurance Research Database of Taiwan at a temporal resolution of one day. Data on age, date of admission, source of admission, hospital, residential address, and principal diagnosis on discharge were retrieved using International Statistical Classification on Diseases and Related Problems, Ninth Revision (ICD-9) codes [23]. We selected hospital admissions for diseases of the upper respiratory tract system through both outpatient and accident/emergency services (ICD-9 codes 470–478). In this study, we specifically selected allergic rhinitis (ICD-9 codes 477.0–477.9), because previous studies have demonstrated a high correlation between allergic rhinitis and environmental air pollution [24,25]. We also compiled data on hospital admissions among patients who are residents of the three major cities of Taiwan, namely Taoyuan, Taichung and Tainan, to evaluate the potential influence of exposure.

3. Preliminary Results

3.1. AOD-$PM_{2.5}$ Model

As indicated in previous studies, Taiwan has strong seasonal $PM_{2.5}$ variability because of its atmospheric circulation patterns (e.g., [16]). The biomass-burning pollution at high altitudes from Indochina is transported to the surface during spring and summer, whereas upper stream pollution in China is driven by the subsidence of a cold surge anticyclone to the island. Therefore, we collected both satellite-derived AOD data and ground TAQMN in situ $PM_{2.5}$ measurements from January 2007 to December 2010 in the study regions, as described in Sections 2.1–2.3. Because the NASA EOS Terra satellite is polar orbiting, and MOD04 data are only available in the daytime, one MODIS granule covers Taiwan per day. We followed a precise collocation technique, which considered the criteria spatially and temporally at 10 km and 1 h, respectively, as used in [21] and [26], to obtain the matched AOD-$PM_{2.5}$ data set. Among the collected satellite and ground measurement data, 399 data sets were matched successfully. Other data sets were excluded because of cloud presentation (i.e., "Cloud Fraction" is not equal to 0 in MOD04) or the unavailability of ground measurement data for matching. Cloud presentation of complex or strong cloud scattering leads to reflected solar irradiance not only from aerosols but also from clouds. The unavailability of ground-based $PM_{2.5}$ data from TAQMN may be attributed to instruments under maintenance, calibration, or other uncontrollable factors.

Two studies have investigated the correlation between MODIS-derived AOD and air pollutant levels over Italy [12] and Hong Kong [27]. The results of both studies suggested a linear relationship between these two variables when the local weather is dominated by synoptic scale circulation. Chudnovsky et al. (2013) [28] used the linear regression method to examine the correlation between AOD and surface $PM_{2.5}$ in metropolitan Boston and obtained a similar result. Therefore, we evaluated the possibility using an empirical statistical method and developed an advanced spatial statistical $PM_{2.5}$ estimation model. Because our study area (Taiwan) has considerable $PM_{2.5}$ variability and gradient, comprehensive historical data records are essential for the empirical statistical method. We used the matched data set to develop the optimal localized $PM_{2.5}$ estimation model from space-borne satellite observation. A least square method was applied to generate continuous surface $PM_{2.5}$ values by using the wide spatial coverage of satellite observation. In this study, an empirical statistical AOD-$PM_{2.5}$ model was created using the following general structure:

$$PM_{2.5}^{sat} = \beta_1 \times AOD^{sat} + \beta_0 \quad (1)$$

where $PM_{2.5}^{sat}$ is the ground-level $PM_{2.5}$ from satellite estimation in the unit of $\mu g \cdot m^{-3}$, and β_1 and β_0 denote the study area-specific slope and -intercept of satellite AOD product (AOD^{sat}), respectively. The in situ $PM_{2.5}$ measurements are used as initial $PM_{2.5}^{sat}$ and matched to NASA EOS Terra MODIS AOD^{sat} to obtain both β_1 and β_0 by using the least square method. The cross-validation (CV) technique was applied to test for potential model overfitting. This ensured that the model had improved predictive performance in the applied data set in model fitting than that from the rest of the study area. We used the model in Equation (1) as reference and one standard deviation of the matched data set to quantify the applicability of this model in the current study. Furthermore, mean prediction error (MPE) and root mean squared prediction error (RMSE) were adopted to evaluate the model prediction accuracy for model fitting and CV result.

Figure 2 shows the scatter plots for model fitting and CV of the empirical statistical model in Equation (1). For model fitting, the Pearson correlation coefficient was 0.69 when the CV technique was applied. Our results showed that the CV RMSE was 18.27 $\mu g \cdot m^{-3}$, and the CV relative prediction error of the model was 40.5% (RPE, defined as RMSE divided by the observed mean ground $PM_{2.5}$). These statistics are approximately 25% higher than those reported in a previous study in the United States [29]. One possible reason is that our model tends to underestimate $PM_{2.5}$ when ground $PM_{2.5}$ levels are higher than approximately 40 $\mu g \cdot m^{-3}$ (Figure 2). A previous study in Eastern United States also reported similar results, in which $PM_{2.5}$ was substantially underestimated at higher levels (>40 $\mu g \cdot m^{-3}$) [11]. A sublinear relationship between $PM_{2.5}$ and AOD at high particle loadings has also been posited [30]. Another possible reason is that these high $PM_{2.5}$ levels might be a local phenomenon and thus cannot be favorably represented in a relatively large satellite footprint or data grid. Our model could explain more than 73.7% of data within half of CV RMSE (dashed red curve) and 78.3% of data within one CV RMSE (dotted magenta curves in Figure 2). Both proportions would be much higher than 38.2% and 68.2% if data were normally distributed away from the evaluated values with the same criteria applied. Reasonable differences were observed in the median (Q2) and interquartile range (IQR) between observed and predicted $PM_{2.5}$ levels (Table 1). Although the inclusion of the atmospheric thermodynamic state or aerosol size distribution in multivariable regression (e.g., [31,32]) may improve model performance, the additional input factors and the correlation among them require further examination. Such examination is beyond the scope of this study. The aforementioned statistics clearly indicate that the empirical model is comparable with or even more effective than previous models (e.g., [14,30]).

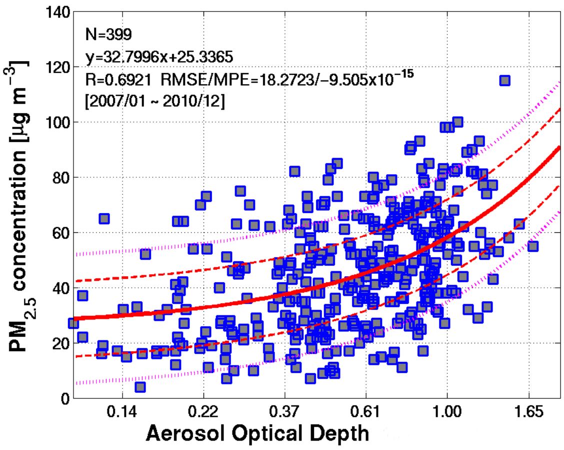

Figure 2. Scatter plot of collocated National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Terra MODIS-derived aerosol optical depth (AOD) at the wavelength of 0.55 μm (*x*-axis) against ground-based $PM_{2.5}$ levels (*y*-axis). Both data sets were processed from 2007 to 2010 in the study area. Please refer to the text for the detailed collocation procedure. The *x*-axis and *y*-axis are represented in logarithmic and linear scales, respectively. The cross-validation statistic results of the empirical statistical model (solid red curve) are shown in the upper left corner. The dashed red and dotted magenta curve each represents half and one standard deviation away from the evaluated values, individually.

Table 1. Summary statistics of satellite-derived aerosol optical depth (AOD) and observed and estimated $PM_{2.5}$ obtained using the cross-validation (CV) technique in Taiwan for the period from 2007 to 2010. Interquartile range (IQR) is defined as the range between Q1 and Q3 in a sorted percentile. The minimum (min) and maximum (max) are the lowest and the highest value, respectively, of the given variable. The ratios between IQR and the full range are listed in the right-most column.

Variable	Mean ± Std. Dev.	Percentile			IQR/(Max-Min)
		Q1 (25th)	Q2 (50th)	Q3 (75th)	
Satellite-derived AOD	0.6029 ± 0.3195	0.378	0.581	0.842	27.7%
Observed $PM_{2.5}$ ($\mu g \cdot m^{-3}$)	45.1108 ± 21.4385	27.0	44.0	62.0	23.8%
Estimated $PM_{2.5}$ ($\mu g \cdot m^{-3}$)	44.9092 ± 10.4801	37.7	44.4	53.0	27.1%

3.2. Satellite-Derived $PM_{2.5}$ and Hospital Admissions for Allergic Rhinitis

We explored the effect of satellite-derived $PM_{2.5}$, which has spatial and reliable features, on hospital admissions for respiratory diseases. In particular, we focused on the correlation between hospital admissions for allergic rhinitis in the three cities of Taiwan (Section 2.3) and satellite-derived daily $PM_{2.5}$ levels (Section 3.1). Figure 3 shows the time-series curves of satellite-derived $PM_{2.5}$ (blue curves) and hospital admissions for allergic rhinitis (orange curves) in Taoyuan (top panel), Taichung (middle panel), and Tainan (bottom panel) from the 45th to 140th days of the year (DOY) in 2008 (mid-February to mid-May is denoted as spring time). Initial analysis of hospital admissions revealed zero or very low admissions periodically. The zero admissions were because no outpatient clinic was open over the weekend or on national holidays. Therefore, the number of outpatients decreased significantly. Moreover, there is a limitation that satellite-derived $PM_{2.5}$ is only available under cloud-free scenarios. Therefore, when less than 50% of cloud-free data coverage was obtained for the city, including overcast, we excluded both $PM_{2.5}$ and the number of admissions in the figure to ensure comparable comparisons between the two examined factors. The panels in Figure 3 illustrate a coherent pattern for the time-series curves of hospital admissions for allergic rhinitis and $PM_{2.5}$. The results demonstrated that higher $PM_{2.5}$ levels were associated with higher hospital admissions for allergic rhinitis. Overall, Taichung City has a relatively higher number of hospital admissions than Taoyan and Tainan, because of higher population (Table 2). A plausible explanation for the finding is that Taichung City has higher satellite-derived $PM_{2.5}$ levels and a higher frequency of $PM_{2.5}$ over 40 $\mu g \cdot m^{-3}$ than do the other two cities.

Figure 3. Time-series curves of satellite-derived $PM_{2.5}$ levels (blue curves) and hospital admissions for allergic rhinitis (orange curves) in Julian day from 40 to 145 of the year 2008 for Taoyuan (**a**), Taichung (**b**), and Tainan (**c**).

Similar time-series curves are provided in Figure 4 for DOYs of 245–335 (early September to late November, denoted as winter time). In general, the hospital admissions in this period were slightly higher than those in spring. The same results were obtained for satellite-derive $PM_{2.5}$ levels in Figure 3, except for Tainan. A positive correlation between the two factors was confirmed by a reduced $PM_{2.5}$ level, attributed to synoptic atmospheric circulation, and lower hospital admissions in Tainan, a city located Southern Taiwan.

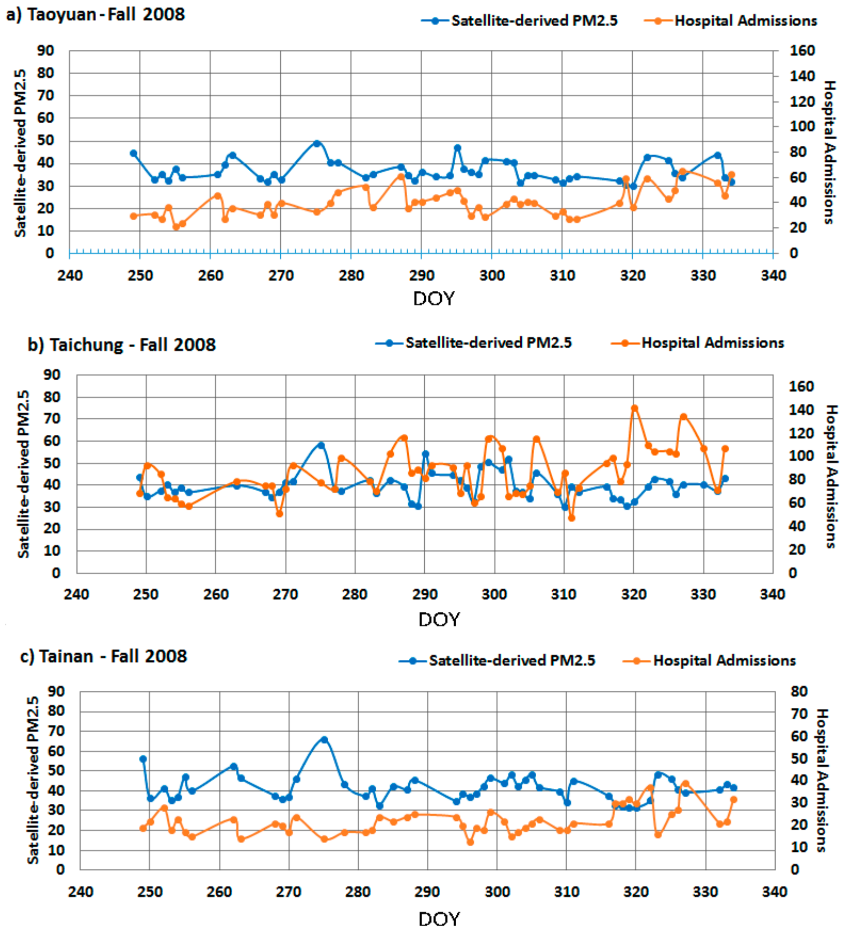

Figure 4. Time-series curves of satellite-derived $PM_{2.5}$ levels (blue curves) and hospital admissions for allergic rhinitis (orange curves) in Julian day from 245 to 335 of the year 2008 for Taoyuan (**a**), Taichung (**b**), and Tainan (**c**).

The time-lag effect was examined throughout the whole-year data sets. The coefficients of 1-day and 2-day time-lag were both slightly higher than those of 3-day or more time-lag, although the difference was not significant. Hospital admissions for allergic rhinitis may be increased on the day of and 1 or 2 days after the occurrence of high $PM_{2.5}$ levels. This observation was not significant for Taoyan, a city located in Northern Taiwan, with lower temperature and more rainy days (Table 2). Other environmental factors (e.g., temperature and precipitation downwash) and exposure duration should be considered in future studies.

Table 2. Summary of city area, population, climatological temperature, and relative humidity (RH) in Taoyuan, Taichung, and Tainan. The area and population data were obtained from the Ministry of Interior of Taiwan. The population census was taken in December 2012. The spring season is defined as the period from February to March, and the fall season is defined as the period from September to November, to match the temporal window in our study. The climatological temperature and RH data were based on the data collected in 1981–2010 from the Central Weather Bureau of Taiwan.

City	Area (km^2)	Population (Thousand)	Temperature (°C) (Spring/Fall)	RH (%) (Spring/Fall)
Taoyuan	1221	2106	19.9/24.1	81.1/76.7
Taichung	2215	2744	21.5/24.8	77.0/73.7
Tainan	2192	1885	22.9/25.7	77.0/76.3

To further investigate the effect of $PM_{2.5}$ on hospital admissions among different age groups, the sample populations of the hospital admissions were categorized into four age groups: (i) ≤3 years; (ii) 3–18 years; (iii) 18–65 years; and (iv) >65 years. The scatter plots in Figure 5 show the relationship between hospital admissions and satellite-derived $PM_{2.5}$. The results demonstrated that the number of hospital admissions was 5 or more at any $PM_{2.5}$ level. This finding suggests a threshold exists for the background outpatient number. From the statistics of $PM_{2.5}$ and hospital admissions above this threshold, age groups (iii) and (ii) (red and blue dots, respectively, in Figure 5) were ranked as the first and second groups. The numbers for allergic rhinitis patients in age groups (i) and (iv) were almost the same, although those in age group (iv) were slightly higher.

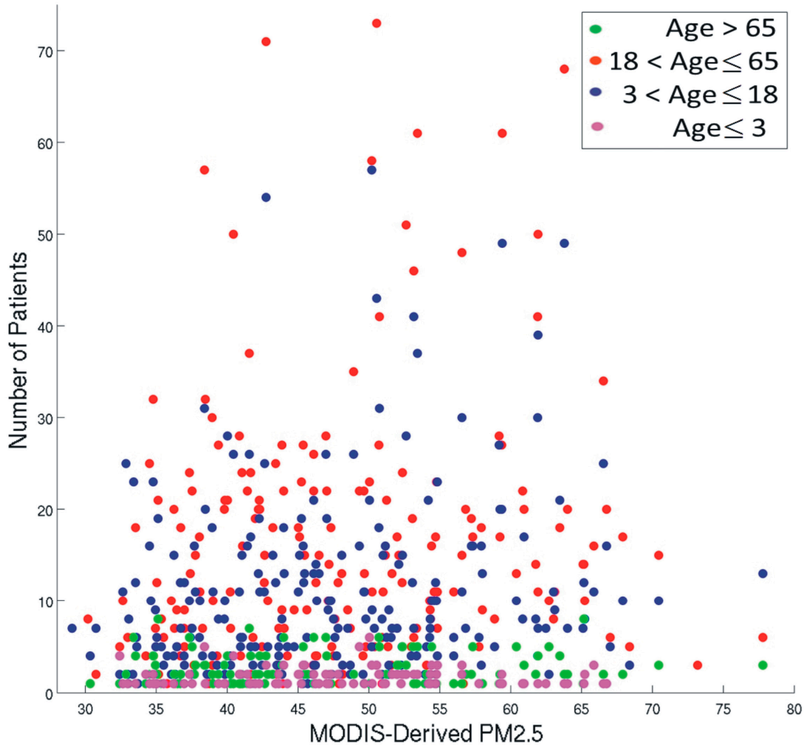

Figure 5. Scatter plot of satellite-derived $PM_{2.5}$ (*x*-axis) against daily numbers of allergic rhinitis patients among four age groups for the year of 2008.

According to an advisory from the United States Environmental Protection Agency (US/EPA), air quality is considered good when the $PM_{2.5}$ level is lower than 12.0 $\mu g \cdot m^{-3}$. However, $PM_{2.5}$ levels above this threshold are considered to exert various effects, from moderate to very unhealthy, on daily activities, as shown in Table 3. $PM_{2.5}$ levels higher than 35.5 $\mu g \cdot m^{-3}$ negatively affect older adults and children. Figure 6 illustrates the numbers of hospital admissions for the four age groups under the different air quality scenarios in Table 3. The results clearly demonstrated that $PM_{2.5}$ levels exerted almost no effect on infants or toddlers and elderly people (age groups (i) and (iv)). However, a higher $PM_{2.5}$ level was associated with increased admission numbers in children and adults (age groups (ii) and (iii)). At $PM_{2.5}$ levels higher than 35.5 $\mu g \cdot m^{-3}$, satellite-derived $PM_{2.5}$ particularly exerted more impact on adults (age group (iii)) than on children (age group (ii)). It can be assumed that age groups (i) and (iv), representing infants or toddlers and elderly people, respectively, are more susceptible to allergic rhinitis because of their relatively weaker immune system. However, our results did not follow this assumption. Presumably, people in these two age groups mainly stay indoors. Even if they perform outdoor activities, they do not stay outside for long hours. Our results showed that adults and children (age groups (iii) and (ii)) were significantly affected by the $PM_{2.5}$ level and were the groups most vulnerable to air pollution.

Table 3. Air quality index for particle pollution.

$PM_{2.5}$ Concentration ($\mu g \cdot m^{-3}$)	Air Quality Scenarios	Health Advisory
0.0~12.0	Good	None
12.1~35.4	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion
35.5~55.4	Unhealthy for Sensitive Groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion
55.5~150.4	Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion.
150.5~500.0	Very Unhealthy	People with heart or lung disease, older adults, and children should avoid physical activity outdoors. Everyone else avoid prolonged or heavy exertion.

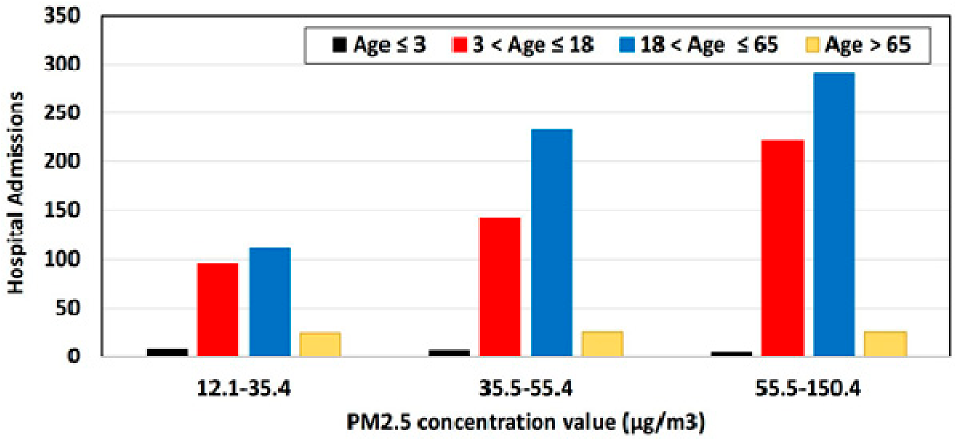

Figure 6. Bar graph of hospital admissions for four age groups against the $PM_{2.5}$ level under three air quality scenarios. The lower and upper limits of these three scenarios are based on the United States Environmental Protection Agency (US/EPA) health advisory in Table 3.

4. Discussion

The study of the relationship between respiratory diseases and the ground $PM_{2.5}$ level must include spatiotemporal considerations. It is crucial to use space-borne satellite observation for $PM_{2.5}$ estimation because of the advantage of its wide spatial coverage. The in situ $PM_{2.5}$ monitoring network conducts sampling work on the basis of pin-point measurement, which overlooks spatial consideration. The current study takes the advantage of ground measurement and strengthens it with the spatial and temporal collocated satellite data sets to develop an empirical statistical AOD-$PM_{2.5}$ model by using the least square method synergistically. The initial statistics suggests that a high-spatial and temporal resolution map of $PM_{2.5}$ for Taiwan was obtained using satellite-derived AOD data. The CV technique was applied to quantify both accuracy and uncertainty of this AOD-$PM_{2.5}$ model in Equation (1). Therefore, it is reasonable to study the spatial correlation between satellite-derived $PM_{2.5}$ and allergic rhinitis. The Figure 7a illustrates one particular example on 27 March 2008. Satellite-derived $PM_{2.5}$ data revealed almost island-wide coverage for $PM_{2.5}$ in Taiwan on that day. The satellite-derived $PM_{2.5}$ data are only available under cloud-free scenarios and at AOD 10-km spatial resolution grid. A high $PM_{2.5}$ level was observed in regions extending from Taiwan Strait to Central Taiwan. A marginally high $PM_{2.5}$ level was also observed in Southern Taiwan. This observation is attributed to the synoptic atmospheric circulation that transports air pollution from Southeast Asia and across South China Sea to Taiwan. The north part of Taiwan was less impacted by air pollution from mainland China because of different atmospheric circulation on that day. Clearly, the impact of gradient of $PM_{2.5}$ levels was relatively high in the west coast of Taiwan, compared with that in the east coast. The relatively low impact in the east coast is attributed to the natural terrain effect of the Central Mountain Ridge.

With an altitude of more than 3500 m, the Central Mountain Ridge may block air pollution from the west coast (Figure 1). As shown in Figure 7a, five ground stations, denoted by filled labeled in circles, took measurements simultaneously when the satellite passed over each time. The pin-point in situ $PM_{2.5}$ levels are color-filled within the circles. They are identical in the color scale with satellite-derived $PM_{2.5}$ values. We examined the backward trajectories at 0000 UTC of 27 March 2008, i.e., 08:00 a.m. local time on the same day, in Taichung. The 96-h backward trajectories of the air parcels at the surface, 100 m, and 1000 m can be tracked from the middle, south, and northwest parts of China, respectively (Figure 8). Some stations showed higher $PM_{2.5}$ levels than those in the satellite-derived data, which might be attributed to local pollution. The stationary measurement cannot be favorably represented in a relative large satellite footprint or data grid. Thus, the model in the current study not only spatially estimates the $PM_{2.5}$ level gradient but also provides high reliability and accuracy.

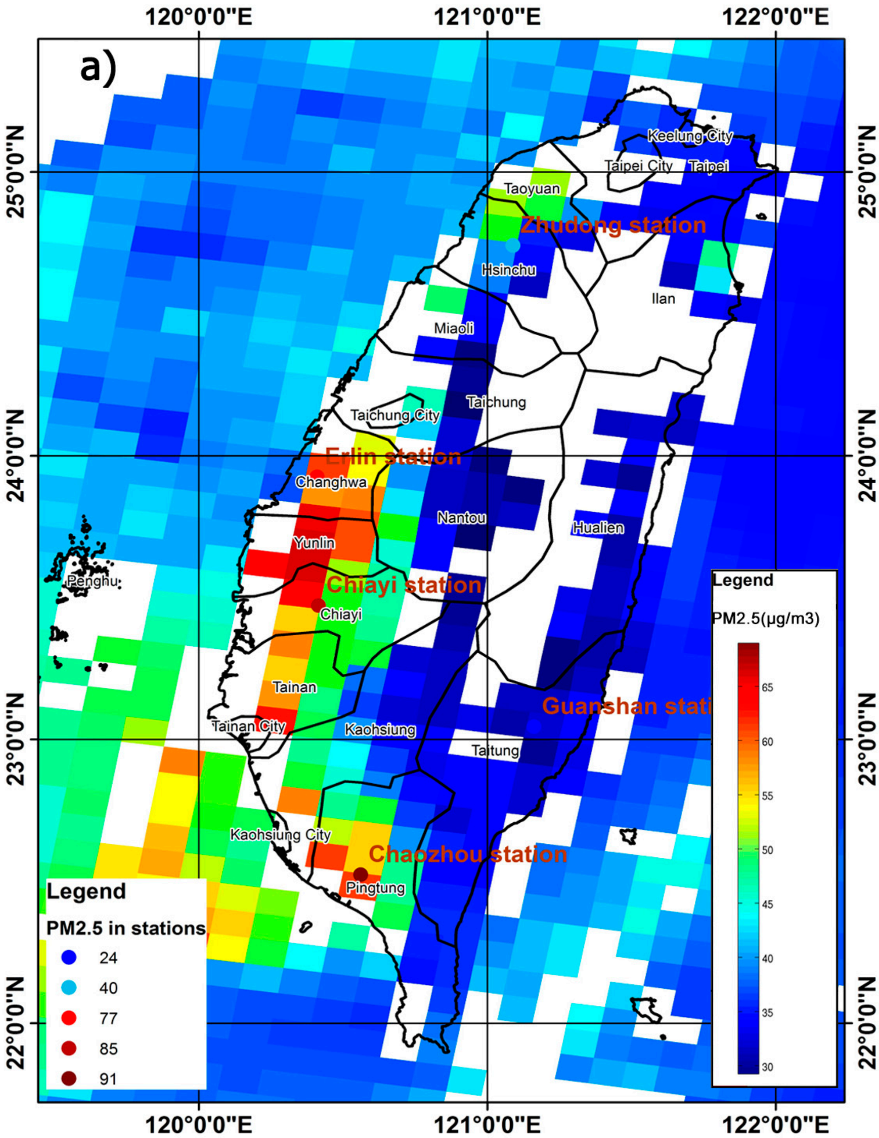

Figure 7. *Cont.*

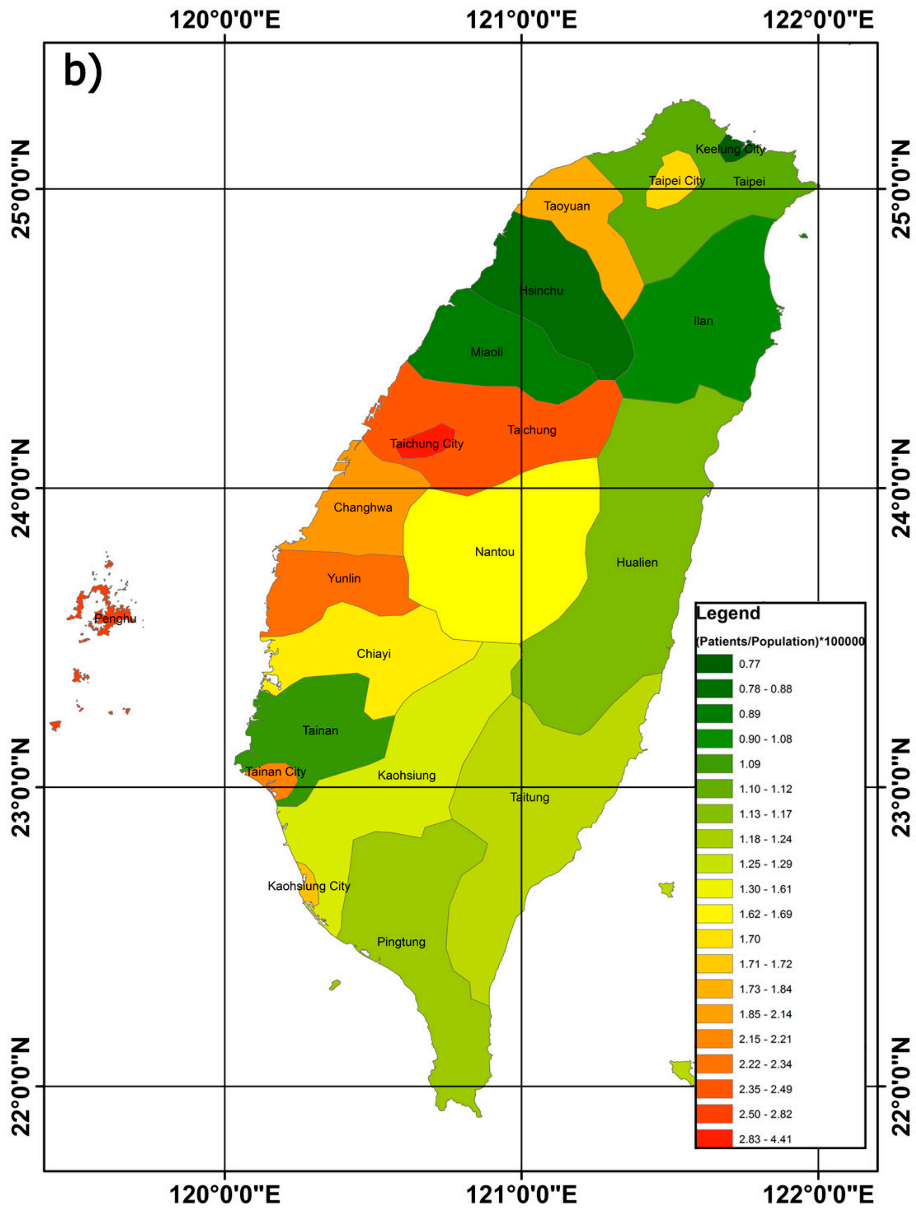

Figure 7. Schematic of satellite-derived $PM_{2.5}$ level (**a**) and the ratio of hospital admission for allergic rhinitis to the total population of each individual city in Taiwan (**b**) on 27 March 2008. The $PM_{2.5}$ level from ground station measurements are overlaid with color-filled circles in (**a**).

The association between satellite-derived $PM_{2.5}$ and respiratory diseases, in particular hospital admissions for allergic rhinitis, was examined in the current study to investigate the potential spatial correlation. We found a high correlation between these two factors in Taiwan, particularly in spring and fall. This correlation was more prominent in the middle (Taichung) and south (Tainan) parts of Taiwan than in the north part (Taoyuan). A spatiotemporal filter with the criteria of both city area and 7-day was applied for whole-year data set for the year of 2008. The results confirmed that a high correlation between the satellite-derived $PM_{2.5}$ level and allergic rhinitis in a relatively dry and warm area. The Figure 7b indicates the hospital admission rate of each individual city of Taiwan on 27 March 2008. The hospital admission rate is defined as the number of outpatients with allergic rhinitis out of the total population in that city. Therefore, a higher ratio implies that the $PM_{2.5}$ level exerts a stronger impact on the hospital admission rate for allergic rhinitis. Taoyuan, Taichung, Yulin, and Tainan were found to have a higher hospital admission rate for allergic rhinitis. These results were consistent with those accordingly observed in the left panel, indicating higher satellite-derived $PM_{2.5}$ levels. Evaluation of the sensitivity of the $PM_{2.5}$ level on age group was also conducted in this study. The $PM_{2.5}$ level exerted a stronger effect on adults (18–65 years) and preschoolers or teenagers (3–18 years) than on infants (age $\leq$ 3 years) and elderly people (age > 65 years), because the age groups of 18–65 and 3–18 years spend a relative longer time outdoors. This finding reflects the importance of $PM_{2.5}$ monitoring. It also implies the work should be conducted in temporal and spatial aspects continuously. The satellite observation covers both features and has been proven to provide valuable information to highlight the potential high-risk regions of air pollution.

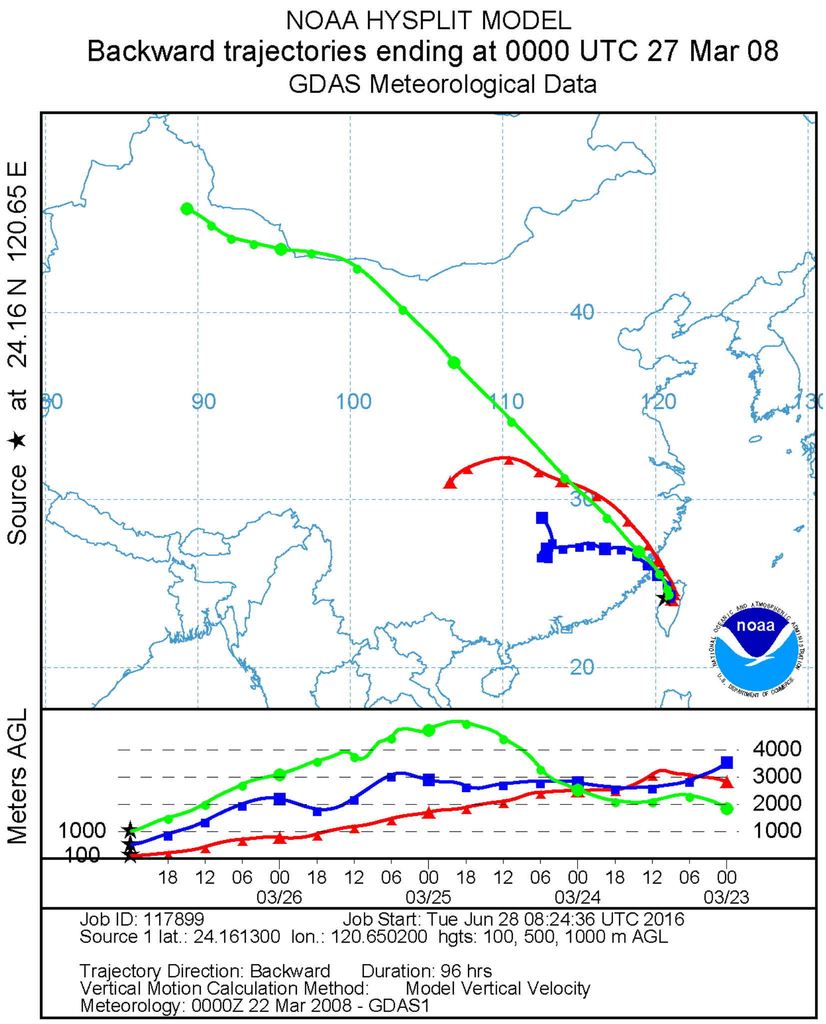

Figure 8. The 96-h backward trajectories of the air parcels in Taichung at 0000 UTC March 2008. The red, blue, and green curves represent the air parcels at the surface, 100 m, and 1000 m, respectively.

5. Conclusions

Our AOD-$PM_{2.5}$ model exhibits high reliability and accuracy for long-range transported air pollution and can be used to study the spatial correlation with allergic rhinitis study in Taiwan. However, the polar-orbiting satellite data only cover Taiwan one morning per day and may lack the temporal resolving capability. With the launch of advanced satellites in geostationary orbit, such as the Japanese Himawari-8/-9, high temporal resolution AOD data are expected in the near future. These data can be used to investigate the effect of exposure time according to the same $PM_{2.5}$ level. Finer spatial resolution down to the county or village scale, as illustrated in Figure 7, can also be reevaluated when high spatial resolution AOD data are available.

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References

1. Lipsett, M.; Hurley, S.; Ostro, B. Air pollution and emergency room visits for asthma in Santa Clara County, California. *Environ. Health Perspect.* **1997**, *105*, 216–222. [CrossRef] [PubMed]
2. Ilabaca, M.; Olaeta, I.; Campos, E.; Villaire, J.; Tellez-Rojo, M.M.; Romieu, I. Association between levels of fine particulate and emergency visits for pneumonia and other respiratory illnesses among children in Santiago, Chile. *J. Air Waste Manag. Assoc.* **1999**, *49*, 154–163. [CrossRef] [PubMed]
3. Slaughter, J.C.; Kim, E.; Sheppard, L.; Sullivan, J.H.; Larson, T.V.; Claiborn, C. Association between particulate matter and emergency room visits, hospital admissions and mortality in Spokane, Washington. *J. Expo. Anal. Environ. Epidemiol.* **2005**, *15*, 153–159. [CrossRef] [PubMed]
4. Bell, M.; Ebisu, K.; Peng, R. Community-level spatial heterogeneity of chemical constituent levels of fine particulates and implications for epidemiological research. *J. Expo. Sci. Environ. Epidemiol.* **2011**, *21*, 372–384. [CrossRef] [PubMed]
5. Pope, C.A.; Burnett, R.T.; Thun, M.J.; Calle, E.E.; Krewski, D.; Ito, K.; Thurston, G.D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J. Am. Med. Assoc.* **2002**, *287*, 1132–1141. [CrossRef]
6. Dominici, F.; Peng, R.D.; Bell, M.L.; Pham, L.; McDermott, A.; Zeger, S.L.; Samet, J.M. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *J. Am. Med. Assoc.* **2006**, *295*, 1127–1134. [CrossRef] [PubMed]
7. Yuan, Y.; Liu, S.; Castro, R.; Pan, X. $PM_{2.5}$ monitoring and mitigation in the cities of China. *Environ. Sci. Technol.* **2012**, *46*, 3627–3628. [CrossRef] [PubMed]
8. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* **2008**, *151*, 362–367. [CrossRef] [PubMed]
9. Perez, L.; Grize, L.; Infanger, D.; Künzli, N.; Sommer, H.; Alt, G.M.; Schindler, C. Associations of daily levels of PM10 and NO2 with emergency hospital admissions and mortality in Switzerland: Trends and missed prevention potential over the last decade. *Environ. Res.* **2015**, *140*, 554–561. [CrossRef] [PubMed]
10. Hosono, T.; Su, C.C.; Siringan, F.; Amano, A.; Onodera, S.I. Effects of environmental regulations on heavy metal pollution decline in core sediments from Manila Bay. *Mar. Pollut. Bull.* **2010**, *60*, 780–785. [CrossRef] [PubMed]
11. Hoff, R.M.; Christopher, S.A. Remote sensing of particulate pollution from space: Have we reached the promised land? *J. Air Waste Manag. Assoc.* **2009**, *59*, 645–675. [PubMed]
12. Chu, D.; Kaufman, Y.; Zibordi, G.; Chern, J.; Mao, J.; Li, C.; Holben, B. Global Monitoring of Air Pollution Over Land from the Earth Observing System-Terra Moderate Resolution Imaging Spectroradiometer (MODIS). *J. Geophys. Res. Atmos.* **2003**, *108*. [CrossRef]
13. Kumar, N.; Liang, D.; Comellas, A.; Chu, A.; Abrams, T. Satellite-Based PM Concentrations and Their Application to Copd in Cleveland, OH. *J. Expo. Sci. Environ. Epidemiol.* **2013**, *23*, 637–646. [CrossRef] [PubMed]
14. Ma, Z.; Hu, X.; Huang, L.; Bi, J.; Liu, Y. Estimating Ground-Level $PM_{2.5}$ in China Using Satellite Remote Sensing. *Environ. Sci. Technol.* **2014**, *48*, 7436–7444. [CrossRef] [PubMed]

15. Chu, D.; Ferrare, R.; Szykman, J.; Lewis, J.; Scarino, A.; Hains, J.; Burton, S.; Chen, G.; Tsai, T.; Hostetler, C.; et al. Regional Characteristics of the Relationship Between Columnar AOD and Surface $PM_{2.5}$: Application of Lidar Aerosol Extinction Profiles Over Baltimore-Washington Corridor during Discover-AQ. *Atmos. Environ.* **2015**, *101*, 338–349. [CrossRef]
16. Lin, C.-Y.; Liu, S.C.; Chou, C.C.-K.; Liu, T.H.; Lee, C.-T.; Yuan, C.-S.; Shiu, C.-J.; Young, C.-Y. Long-Range Transport of Asian Dust and Air Pollutants to Taiwan. *Terr. Atmos. Ocean. Sci.* **2004**, *15*, 759–784.
17. Liu, C.-Y.; Kuo, S.-Z.; Lim, A.H.N.; Hsu, S.-C.; Tseng, K.-H.; Yeh, N.-C.; Yang, Y.-C. Optimal Use of Space-Borne Advanced Infrared and Microwave Soundings for Regional Numerical Prediction. *Remote Sens.* **2016**, *8*, 816. [CrossRef]
18. Li, J.; Liu, C.-Y.; Huang, H.-L.; Schmit, T.J.; Wu, X.; Menzel, W.P.; Gurka, J.J. Optimal Cloud-Clearing for AIRS Radiances Using MODIS. *IEEE Trans. Geosci. Remote Sens.* **2005**, *43*, 1266–1278.
19. Liu, C.-Y.; Li, J.; Weisz, E.; Schmit, T.J.; Ackerman, S.A.; Huang, H.-L. Synergistic use of AIRS and MODIS radiance measurements for atmospheric profiling. *Geophys. Res. Lett.* **2008**, *35*, L21802. [CrossRef]
20. Li, J.; Liu, C.-Y.; Zhang, P.; Schmit, T.J. Applications of Full Spatial Resolution Space-Based Advanced Infrared Soundings in the Preconvection Environment. *Weather Forecast.* **2012**, *27*, 515–524. [CrossRef]
21. Liu, C.-Y.; Li, J.; Ho, S.-P.; Liu, G.-R.; Lin, T.-H.; Young, C.-C. Retrieval of Atmospheric Thermodynamic State from Synergistic Use of Radio Occultation and Hyperspectral Infrared Radiances Observations. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2016**, *9*, 744–756. [CrossRef]
22. Tsai, T.C.; Jeng, Y.J.; Chu, D.A.; Chen, J.P.; Chang, S.C. Analysis of the relationship between MODIS aerosol optical depth and particulate matter from 2006 to 2008. *Atmos. Environ.* **2011**, *45*, 4777–4788. [CrossRef]
23. World Health Organization. *International Statistical Classification of Diseases, Injuries, and Causes of Death*, 9th ed.; World Health Organization: Geneva, Switzerland, 1975.
24. Fuertes, E.; Brauer, M.; MacIntyre, E.; Bauer, M.; Bellander, T.; von Berg, A.; Berdel, D.; Brunekreef, B.; Chan-Yeung, M.; Gehring, U.; et al. Childhood allergic rhinitis, traffic-related air pollution, and variability in the GSTP1, TNF, TLR2, and TLR4 genes: Results from the TAG Study. *J. Allergy Clin. Immunol.* **2013**, *132*, 342–352. [CrossRef] [PubMed]
25. Zhang, Q.; Qiu, Z.; Chung, K.F.; Huang, S.-K. Link between environmental air pollution and allergic asthma: East meets West. *J. Thorac. Dis.* **2015**, *7*, 14–22. [PubMed]
26. Liu, C.-Y.; Liu, G.-R.; Lin, T.-H.; Liu, C.-C.; Ren, H.; Young, C.-C. Using Surface Stations to Improve Sounding Retrievals from Hyperspectral Infrared Instruments. *IEEE Trans. Geosci. Remote Sens.* **2014**, *52*, 6957–6963.
27. Li, C.; Lau, A.; Mao, J.; Chu, D. Retrieval, Validation, and Application of the 1-km Aerosol Optical Depth from MODIS Measurements over Hong Kong. *IEEE Trans. Geosci. Remote Sens.* **2005**, *43*, 2650–2658.
28. Chudnovsky, A.A.; Kostinski, A.; Lyapustin, A.; Koutrakis, P. Spatial scales of pollution from variable resolution satellite imaging. *Environ. Pollut.* **2013**, *172*, 131–138. [CrossRef] [PubMed]
29. Liu, Y.; Franklin, M.; Kahn, R.; Koutrakis, P. Using aerosol optical thickness to predict ground-level $PM_{2.5}$ concentrations in the St. Louis area: A comparison between MISR and MODIS. *Remote Sens. Environ.* **2007**, *107*, 33–44. [CrossRef]
30. Liu, Y.; Sarnat, J.A.; Kilaru, V.; Jacob, D.J.; Koutrakis, P. Estimating ground-level $PM_{2.5}$ in the eastern United States using satellite remote sensing. *Environ. Sci. Technol.* **2005**, *39*, 3269–3278. [CrossRef] [PubMed]
31. Cordero, L.; Malakar, N.; Wu, Y.; Gross, B.; Moshary, F. Assessing surface $PM_{2.5}$ estimates using data fusion of active and passive remote sensing methods. *Br. J. Environ. Clim. Chang.* **2013**, *3*, 547–565. [CrossRef] [PubMed]
32. Gupta, P.; Christopher, S.A. Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: Multiple regression approach. *J. Geophys. Res.* **2009**, *114*, D14205. [CrossRef]

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