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The Impact of Long-Range Transport of Biomass Burning Emissions in Southeast Asia on Southern China

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Abstract: The long-range transport of biomass burning pollutants from Southeast Asia has a significant impact on air quality in China. In this study, the Moderate Resolution Imaging Spectroradiometer (MODIS) fire data and aerosol optical depth (AOD) products and the Tropospheric Monitoring Instrument (TROPOMI) carbon monoxide (CO) data were used to analyze the impact of air pollution caused by biomass burning in Southeast Asia on southern China. Results showed that Yunnan, Guangdong and Guangxi were deeply affected by biomass burning emissions from March to April during 2016–2020. Comparing the data for fires on the Indochinese Peninsula and southern provinces of China, it is obvious that the contribution of pollutants emitted by local biomass burning in China to air pollution is only a small possibility. The distribution of CO showed that the overall emissions increased greatly from March to April, and there was an obvious transmission process. In addition, the MODIS AOD in areas close to the national boundary of China is at a high level (>0.6), and the AOD in the southwest of Guangxi province and the southeast of Yunnan Province is above 0.8. Combined with a typical air pollution event in southern China, the UVAI combined with wind direction and other meteorological data showed that the pollutants were transferred from the Indochinese Peninsula to southern China under the southwest monsoon. The $PM_{2.5}$ data from ground-based measurements and backward tracking were used to verify the pollutant source of the pollution event, and it was concluded that the degree of pollution in Yunnan, Guangxi and Guangdong provinces was related to the distance from the Indochinese Peninsula. Results indicate that it is necessary to carry out in-depth research on the impact of cross-border air pollution transport on domestic air quality as soon as possible and to actively cooperate with foreign countries to carry out pollution source research and control.

Keywords: biomass burning emissions; satellite; carbon monoxide; aerosol optical depth

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Citation: Zhang, L.; Ding, S.; Qian, W.; Zhao, A.; Zhao, S.; Yang, Y.; Weng, G.; Tao, M.; Chen, H.; Zhao, S.; et al. The Impact of Long-Range Transport of Biomass Burning Emissions in Southeast Asia on Southern China. *Atmosphere* **2022**, *13*, 1029. https://doi.org/10.3390/atmos13071029

Academic Editor: Rajasekhar Balasubramanian

Received: 19 May 2022
Accepted: 23 June 2022
Published: 28 June 2022

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1. Introduction

Biomass burning refers to the burning of agricultural and forestry wastes or forests in order to increase land fertilizer and exploit land [1–3]. March to April is the peak time for biomass burning in countries on the Indochinese Peninsula every year. Biomass burning produces a large number of greenhouse gases, trace gases and atmospheric particles, which can seriously pollute a region or even the world [4]. It is estimated that organic carbon (OC) and black carbon (BC) emitted by biomass burning emissions account for about 50–80% of total global emissions [5], carbon monoxide (CO) accounts for about 30–40% of the total emissions and carbon dioxide (CO_2) accounts for 18% of total anthropogenic emissions [6].

In addition, biomass burning emissions contribute significantly to the increase in gaseous pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_X) and volatile and semi-volatile organic compounds (VOC_S/$SVOC_S$) [7].

Pollutants from biomass burning in Southeast Asia affect the southern part of China through the southwest monsoon [8–11], resulting in more severe air pollution in China. Data show that biomass burning in Southeast Asia contributes to 26–62% of the spring optical thickness in southern China, the South China Sea and the Taiwan Strait [8]. Numerical models can be used to simulate the biomass burning in Southeast Asia to the $PM_{2.5}$ mass concentration in Yunnan in March, and its contribution can be as high as 20 [9] and its impact on the air quality in southwest China in spring cannot be ignored. In addition, Zhu et al. [11] showed that biomass burning aerosols in Southeast Asia can be transported to the Kunming site on the Yunnan–Guizhou Plateau in southwest of China. Therefore, strengthening our research on the changes in aerosol characteristics during the process of biomass-burning aerosol pollution has important scientific significance for understanding the climate and environmental impact of biomass burning pollutants and their transportation process.

Biomass combustion is one of the important emission sources of some gases and aerosols in the atmosphere, and it has a significant impact on the regional atmospheric environment and global climate [12]. For some important air pollutants, such as BC, CO and NO_X, biomass burning is one of the most important sources in the world [13–15]. Biomass burning also emits some greenhouse gases, such as CO_2, methane (CH_4) and N_2O, affecting the carbon budget of the global atmosphere and climate [16]. In addition, CO, VOCs and NO_X emitted by biomass combustion carry out oxidative photochemical reactions in the atmosphere, leading to the generation of ozone and other secondary pollutants, thus affecting the health of humans and animals by inhibiting the growth of plants, promoting the formation of acid rain and reducing the visibility of the atmosphere [17–20]. Atmospheric aerosols are solid and liquid particles generated by natural processes and human activities that are stably suspended and dispersed in other media [21]. Primary organic aerosols (POA) generated by biomass combustion account for about 85% of the total emissions. These aerosols alter the ratio of direct and indirect solar radiation through intense and complex interactions with solar radiation and clouds [22]. They also affect primary productivity and thus forest growth and agricultural production.

In addition, the level of fine particulate pollution exposure is closely and strongly correlated with the increase in the incidence and mortality of undesirable infectious diseases [23]. Long-term exposure to combustion-related fine particulate matter pollution is an important environmental risk factor for cardiopulmonary and lung cancer mortality. For example, high levels of organic aerosols can cause eye and throat irritation in humans [24], and inhalation of wood [25] can induce cardiovascular disease, respiratory disease and asthma. Biomass burning under poor combustion conditions produces polycyclic aromatic hydrocarbons (PAHs), which have the serious consequence of causing at least 40,000 premature deaths per year in Europe [26]. Therefore, understanding the transnational pollution process of Southeast Asian biomass burning is beneficial for protecting people's personal safety and maintaining our quality of life.

In this study, we present comprehensive insight into the long-range transport of pollution from biomass burning in southeast Asia. We used MODIS satellite data to analyze fire and aerosol data and sentinel 5 TROPOMI carbon monoxide (CO) data to comprehensively analyze the emission process of biomass burning pollutants in the Indochinese Peninsula. In addition, we focus on a typical pollution event in southern China in 2021, analyze air pollution sources using continuous Ultraviolet Aerosol Index (UVAI) and wind direction maps and verify the analysis using ground-based $PM_{2.5}$ data and backward trajectory maps from cities in southern China. Finally, the impacts of biomass burning emissions from Southeast Asia on the air quality in China are summarized, and corresponding policy suggestions for transnational transport control of air pollution are put forward according to the complex characteristics of air pollution in China and the severe situation of the control task.

2. Data and Methods

2.1. Description of the Study Area

The Indochinese Peninsula is a peninsula located in Southeast Asia between China and the South Asian subcontinent, bordering Yunnan and Guangxi in China, as shown in Figure 1. The climate on the peninsula is hot and humid with lush vegetation. The countries on the peninsula are agricultural countries, rich in rubber, rice and oil palm. During the annual harvest season, agricultural waste is burned in large quantities to quickly clear the land. In order to study the impact of biomass burning on the Indochinese Peninsula on air quality in southern China, we chose the range of about 90–120° E and 5–30° N as the research area.

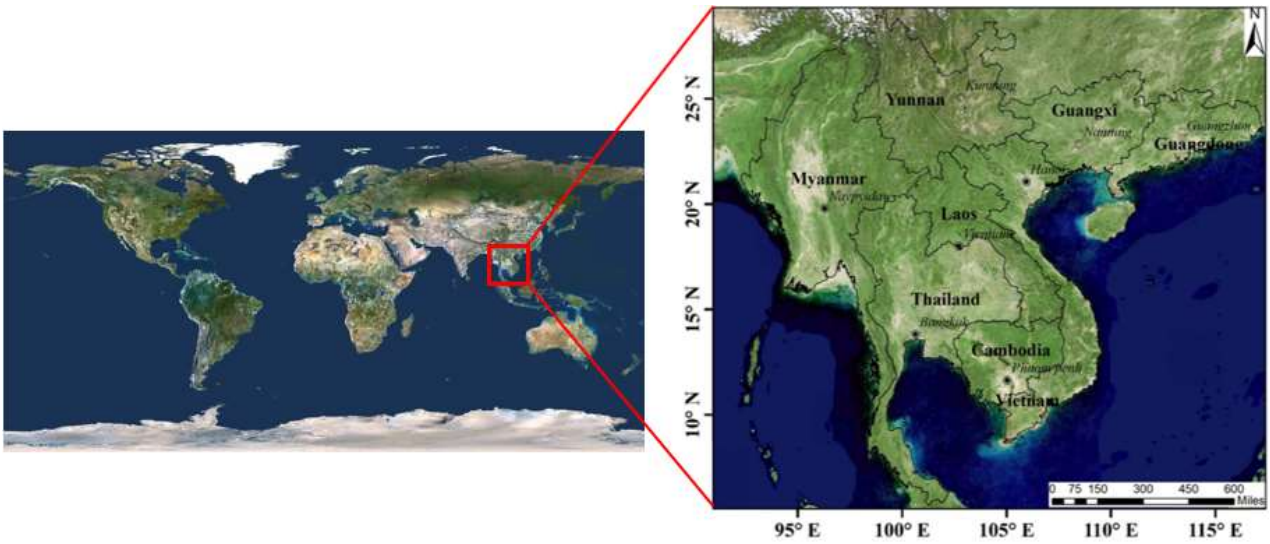


Figure 1. Overview of the study area (90–120° E, 5–30° N).

2.2. MODIS Products about Fire Points and AOD

MODIS on Terra and Aqua is an important instrument used by the EARTH Observing System (EOS) program to observe biological and physical processes around the world. Fire Information Resource Management Systems (FIRMS) distribute near real-time fire data within 3 h of satellite observations via MODIS on Aqua and Terra satellites [27], which can be used to detect active fires and thermal anomalies generated by biomass burning and to locate fires.

In this paper, the MODIS fire data from March to April in the study area were collected to analyze the spatial and temporal variation trend from 2016 to 2020 and to compare the fire situation in southern China and Indochinese Peninsula. Multi-angle MCD19A2 V6 data product of land AOD grid was realized by atmospheric correction (MAIAC) combined with MODIS Terra and Aqua data, with a spatial resolution of 1 km [28]. This experiment mainly utilized AOD data to analyze and judge whether the south of China is affected by the trans-boundary pollution of the Indochinese Peninsula.

2.3. Sentinel 5 Precursor TROPOMI CO Column Concentration Product

TROPOMI on sentinel 5 Precursor (S5P) satellite observed the global abundance of CO using earth radiometric measurements in the SWIR spectrum of the 2.3 μm band of the solar spectrum. Tropospheric OMI clear sky observations provide CO general column and are sensitive to tropospheric boundary layer. Biomass burning emits a lot of pollution gases, such as CO_2/CO/CH_4/VOCs [29]. Biomass burning emissions of CO accounted for 32% of the total production, seriously affecting air quality and human health. This paper focuses on the comparison of CO column concentration between the whole year and March and April in the study area in order to highlight the serious pollutant emission caused by biomass burning.

2.4. Suomi NPP OMPS Ultraviolet Aerosol Index Product

The ozone mapping and profiler suite (OMPS) was launched from the National Polar-Orbiting Cooperative Satellite (Suomi NPP). This satellite dataset provides near real-time, high-resolution images of the UVAI, also known as the absorbing aerosol index (AAI). The absorbing aerosol index values were provided by the OMPS Bottom Plotter (NM) on the Suomi-NPP satellite [30]. The OMPS index refers to the presence of light-absorbing aerosol particles in the air, such as dust. Absorptive aerosols have strong absorption of solar radiation, and the aerosol absorption index is related to the thickness and height of aerosol layer. UVAI can be applied to qualitative identification of aerosol source and transport type. In this paper, UVAI is used to explore the impact degree and transmission process of typical pollution events in 2021.

2.5. NCEP/NCAR Meteorological Datasets

NCEP/NCAR is jointly produced by the National Center for Weather and Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). It is based on the quality control and assimilation of observational data from different sources (ground, ship, sounding, large balloon, aircraft, satellite, etc.). A set of complete reanalysis data containing multiple elements, over a wide range and a long time, was obtained [31]. In this study, NCEP wind direction data and boundary layer height were used to analyze typical cases of pollutant transmission under southwest monsoon.

2.6. $PM_{2.5}$ Data from Ground Stations

The $PM_{2.5}$ data we use comes from a real-time air quality monitoring platform called "ZhenQi". The "ZhenQi Environmental Data Center" has air quality data from over 1500 monitoring stations in 338 state-controlled cities and 29 county-level model cities in China for the past 3 years. The State Ministry of Environmental Protection also provides real-time/daily/monthly/yearly rankings for 168 cities.

3. Results

3.1. MODIS Fire Points Information Extraction

Figure 2 shows the distribution of fires on the Indochinese Peninsula region of Southeast Asia and the three provinces of Yunnan, Guangdong and Guangxi in the 5 years from 2016 to 2020. It can be seen intuitively from the figure that the fires on the Indochinese Peninsula are mainly concentrated in the western and eastern parts of Myanmar, Laos, northwestern Thailand, northeastern Cambodia and central Vietnam. Among them, Laos and Myanmar are the most concentrated fire points which border Yunnan, which is located in the upwind area of the southwest monsoon and may affect the air quality of southwestern China to a certain extent.

Figure 3 is a comparison chart of the number of fire spots on the Indochinese Peninsula in Southeast Asia and southern China from March to April in 2016–2020. March–April is the peak period for the number of fires in Southeast Asia. A large number of biomass incineration fires appear in Southeast Asia each year, with a total of up to 120,000. The number of fires in the five countries of the Indochinese Peninsula far exceeds that of the three provinces of China. As for 2020, satellite remote sensing detected 114,760 fires in the five countries of the Indochinese Peninsula, which is 44 times that of the three provinces of Yunnan, Guangdong and Guangxi.

It can be seen from the figure that Myanmar and Laos have the largest number of fire spots, followed by Thailand, while the total number of fire spots in the three provinces of China is much lower than that of the other countries. In addition, compared to 2017–2018, the number of fires in the Indochinese Peninsula region increased significantly in 2019 and 2020, while the total number of fires in the three provinces of Yunnan, Guangxi and Guangdong remained basically unchanged, and there is some reduction in 2019 and 2020.

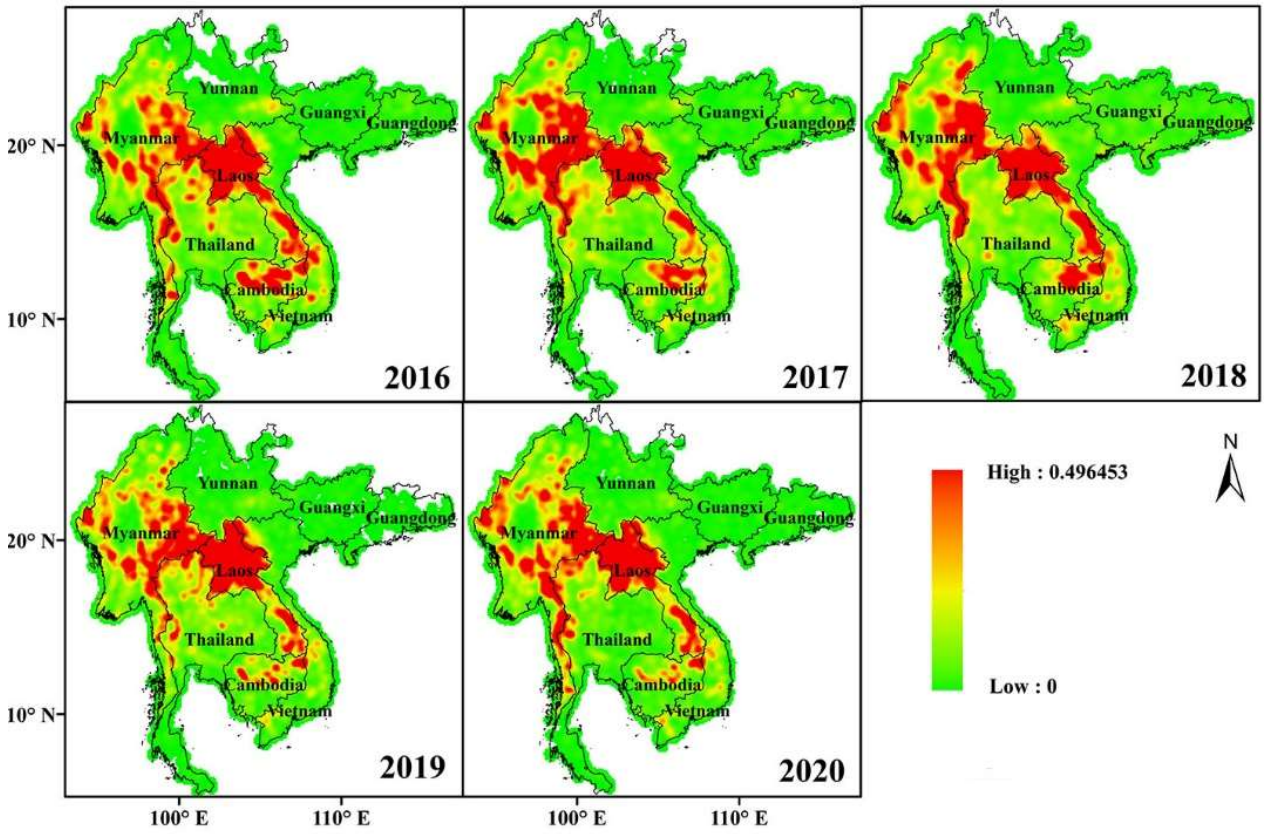


Figure 2. Fire point distribution density map in the study area. (High: 0.496453 is the calculated value of nuclear density, indicating the number of fire points per kilometer).

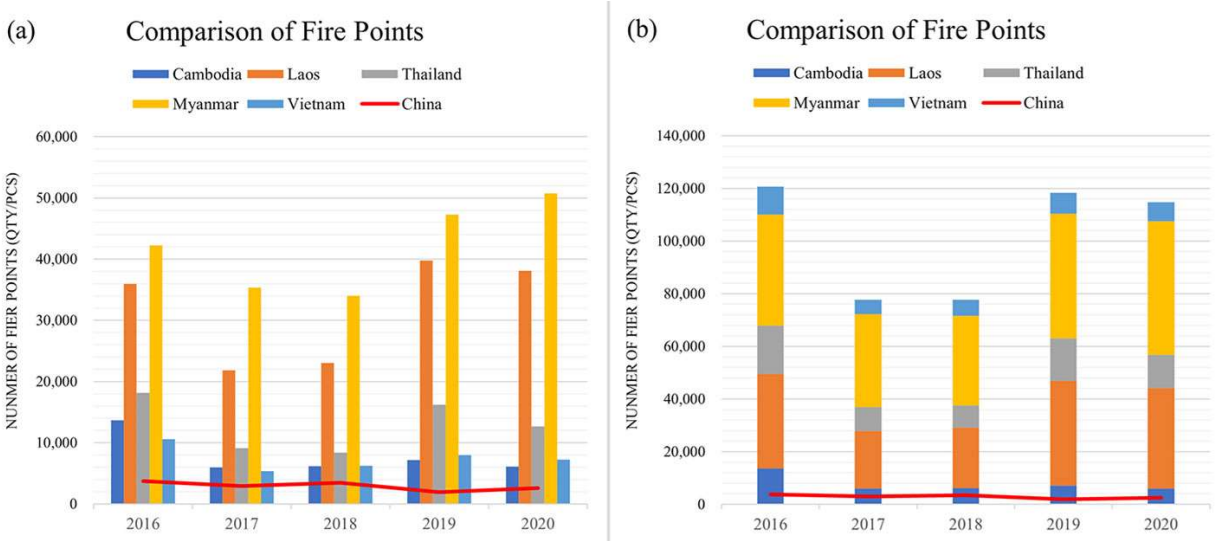


Figure 3. Comparison of the number of fire spots in the five countries of the Indochinese Peninsula and China's Yunnan, Guangxi and Guangdong provinces. (**a**) comparison of fire points separately, (**b**) comparison of fire points in total.

3.2. CO Column Concentration Change Analysis

The change of CO concentration detected by Sentinel-5 TROPOMI was analyzed by Google Earth Engine. The results show that, under the influence of biomass burning on the Indochinese Peninsula, the high annual average concentration of CO in the study area overlaps with the concentrated area of fire points in a large range from 2019 to 2021, and

it increases sharply from March to April every year. Compared with the annual data, the average concentration of CO in the March to April period can reach 3–4 times that of the annual figures. The column concentrations in 2021 were lower than those in 2020 due to COVID-19, but the high value area remains the same.

The three provinces in southern China are all affected by air pollution from the Indochinese Peninsula. Yunnan borders the three countries in the south, and the CO concentration is the highest compared with the province. Because of the high altitude, air pollutants are difficult to transmit to the central and northern parts of China. Guangxi province and Guangdong province suffered the most serious transnational transmission of air pollution from March to April, and the concentration of the CO column was more than 3.0×10^{18} molec/cm^2. It can be inferred from Figure 4 that, under the action of southwest wind direction, a large number of air pollutants, such as the CO generated from biomass burning on the Indochinese Peninsula continuously spread to the nearby sea and southern China, seriously affecting the atmospheric environment of southern cities in China.

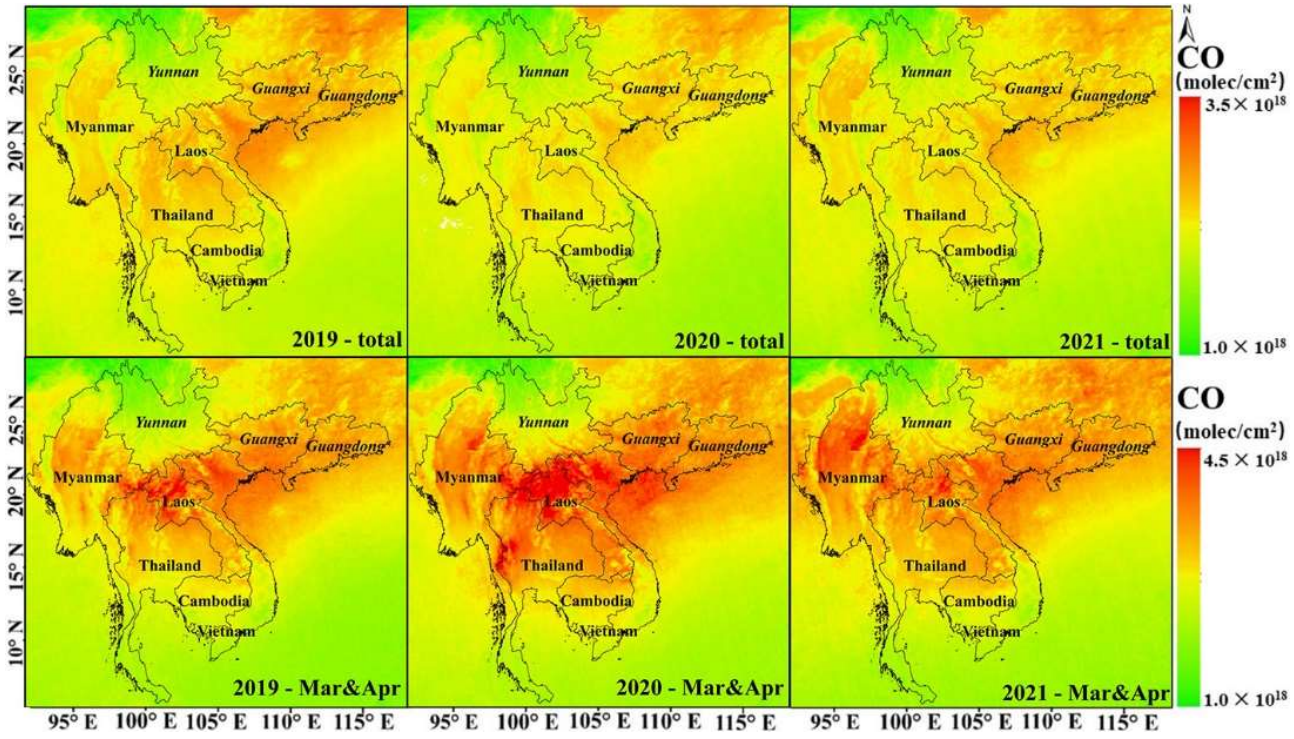


Figure 4. S5P TROPOMI CO column concentration changes in study area from 2019 to 2021.

3.3. Distribution of MODIS AOD Products

Satellite observations provide the regional temporal and spatial changes of aerosol loading in five Southeast Asian countries and Yunnan, Guangdong and Guangxi provinces from 2016 to 2021. This study used MODIS MCD19A6 data from 20 March to 10 April in the study area to analyze its aerosol characteristics in the depth_55 band. Among them, the MODIS AOD in southern Yunnan, southern Guangxi and southern Guangxi from 2016 to 2021 was at a relatively high level (>0.6), and the AOD in southwestern Guangxi and southeastern Yunnan was as high as 0.8. Aerosol radiation effects can regulate the chemical and physical processes of air pollution, and over-loaded aerosol means that there may be serious air pollution problems.

Combining the fire point information, it can be seen in Figure 5 that the fire points in the areas with higher AOD load in the five Southeast Asian countries are also the most concentrated, and the areas with higher AOD in Yunnan, Guangxi and Guangdong are areas bordering or close to the five Southeast Asian countries, so it can be inferred that biomass burning in Southeast Asia has a certain impact on the air quality in Yunnan, Guangxi and

Guangdong provinces, and it is necessary to analyze the source of the polluted air masses in combination with wind direction data or backward trajectory data.

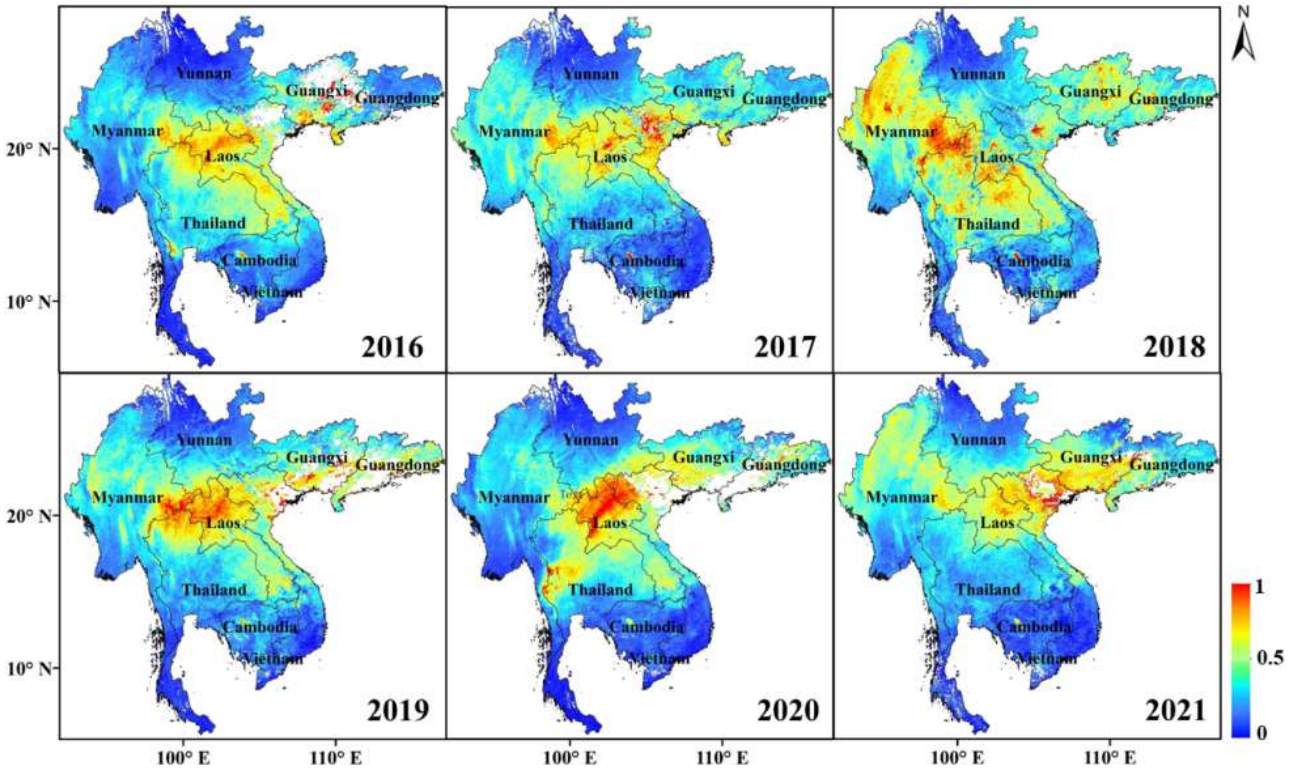


Figure 5. MODIS AOD load changes with time in the study area.

3.4. Analysis of a Typical Pollution Event in 2021

3.4.1. OMPS UVAI Change Trend

The OMPS dataset provides UV aerosol index values from 22 March to 2 April. Because of its strong absorption of solar radiation, absorbent aerosols can also affect climate by heating the atmosphere, changing the stability of the atmosphere, evaporating cloud droplets, reducing cloud cover and other "semi-direct ways". UV absorbability aerosol can be applied to qualitative identification of aerosol source and transport type.

According to the data in Figure 6, serious transnational transport of biomass burning pollutants from Southeast Asia occurred from 22 March to 2 April 2021. On 22 March, a small area of aerosol pollution occurred in Thailand, Vietnam and Laos and moved eastward from 23 March to 25 March, affecting southern Guangxi and Guangdong provinces. From 26 to 27 March, a serious and large-scale air pollution event occurred in Myanmar. From 27 March to 28, the air mass crossed the South China Sea and reached the southern coast of China, seriously affecting the air quality of southern cities in China, and the influence lasted from 30 March to 2 April.

3.4.2. NCEP-Assisted Analysis of Meteorological Data

The NCEP dataset was used to analyze the information about wind direction and boundary layer height. From 22 March to 25 March, the boundary layer height in Yunnan, Guangxi and Guangdong provinces was low, making it difficult for high-level pollutants to be transmitted, and only a small amount of low-level pollutants could be transmitted to southern China. From 26 March, the boundary layer height in southern China was increasing, and transnational pollution transmission intensified. A large amount of biomass burning emissions were transmitted downwind to Guangdong and Guangxi provinces. The wind speed sudden increased from 29 March to 31 March (See Figure 7), which is reflected in the UVAI mutation in Figure 6.

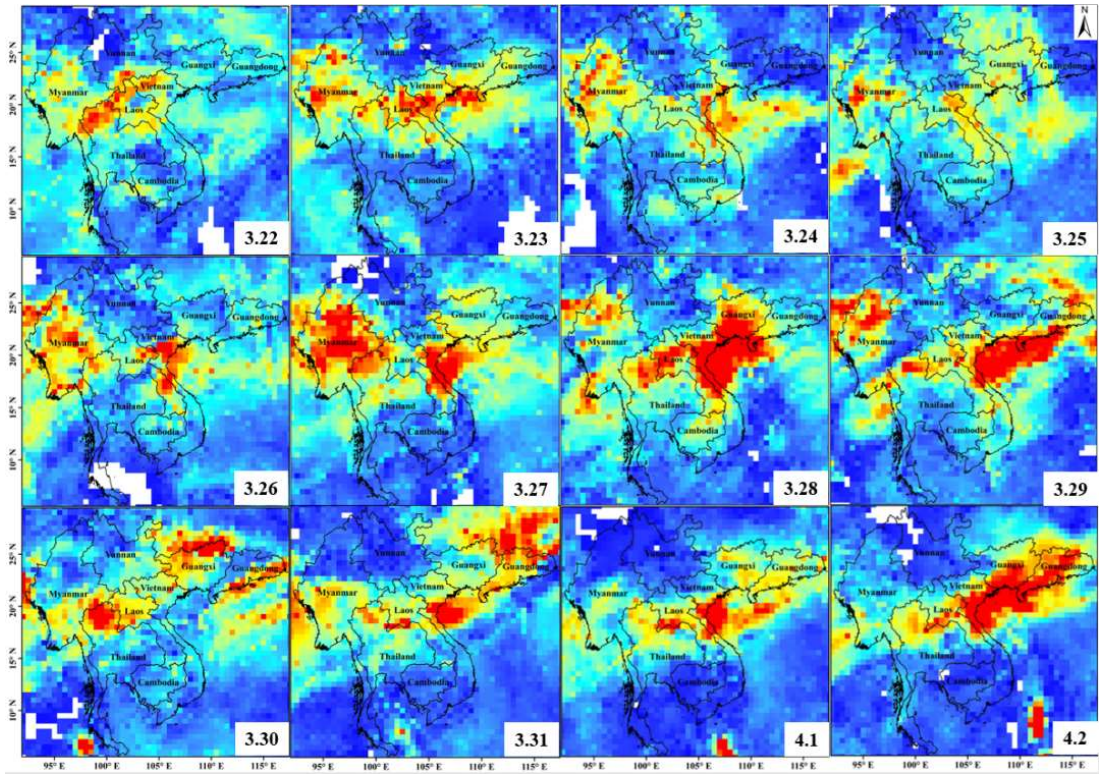


Figure 6. UVAI distribution on OMPS satellite from 22 March to 2 April 2021. (The number in the upper-right corner represents the date.)

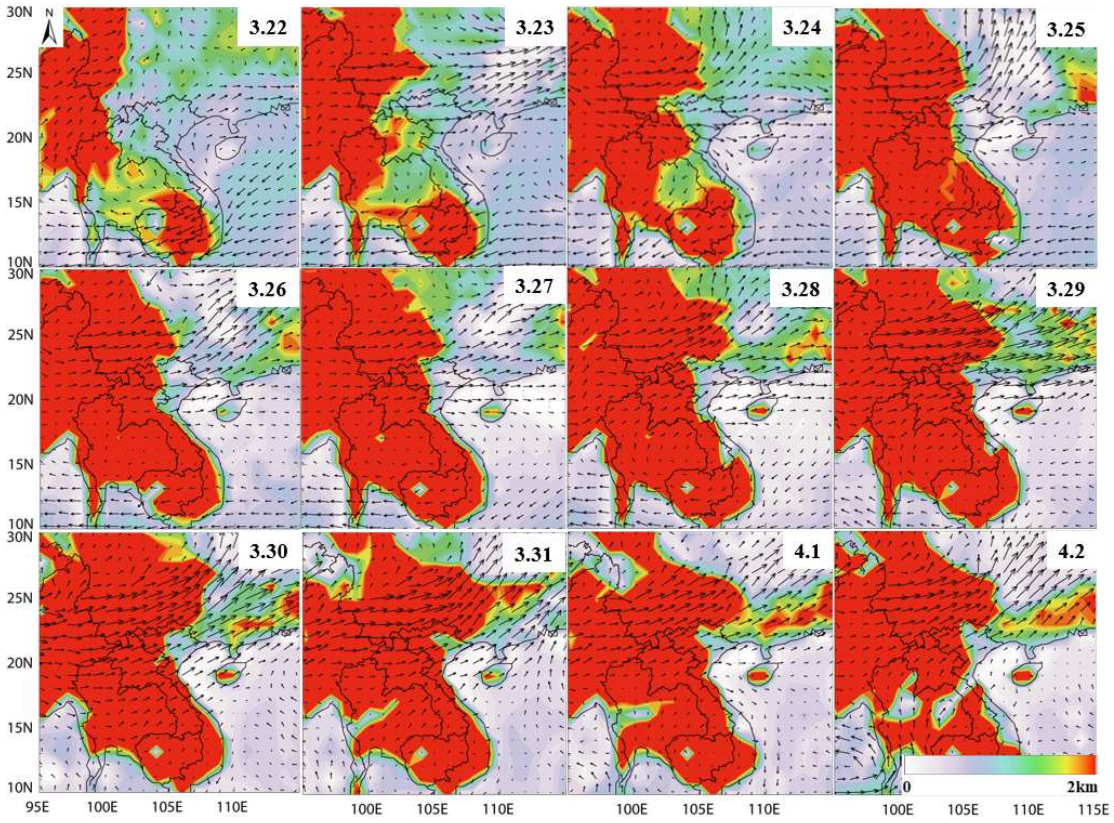


Figure 7. Wind field and boundary layer height at 750 hPa.

3.4.3. Validation

Based on the previous analysis, it can be preliminarily inferred that Yunnan, Guangdong and Guangxi provinces are all affected by transnational pollution from biomass burning in Southeast Asia to a certain extent. $PM_{2.5}$ data from ground stations and backward trajectory data are used to verify this.

According to the $PM_{2.5}$ data of ground stations, from 1 March to 10 April, (a) $PM_{2.5}$ content in Kunming, Yunnan was mostly higher than 35 μg/m^3 and even exceeded the 75 μg/m^3 pollution standard some days, reaching the light pollution level. Nanning, Guangxi (b) is farther from the Indochinese Peninsula than Kunming, Yunnan province, and closer than Zhanjiang, Guangdong province, so its pollution degree ranks the second among the three. As can be seen from Figure 8b, about half of the days in Nanning, Guangxi, $PM_{2.5}$ is higher than 35 μg/m^3 and even higher than 75 μg/m^3 some days. Most of the time, the $PM_{2.5}$ content in Zhanjiang, Guangdong province (c) is below 35 μg/m^3, which is the farthest from the Indochinese Peninsula. However, due to local influence or transnational pollution, the $PM_{2.5}$ content may increase sharply.

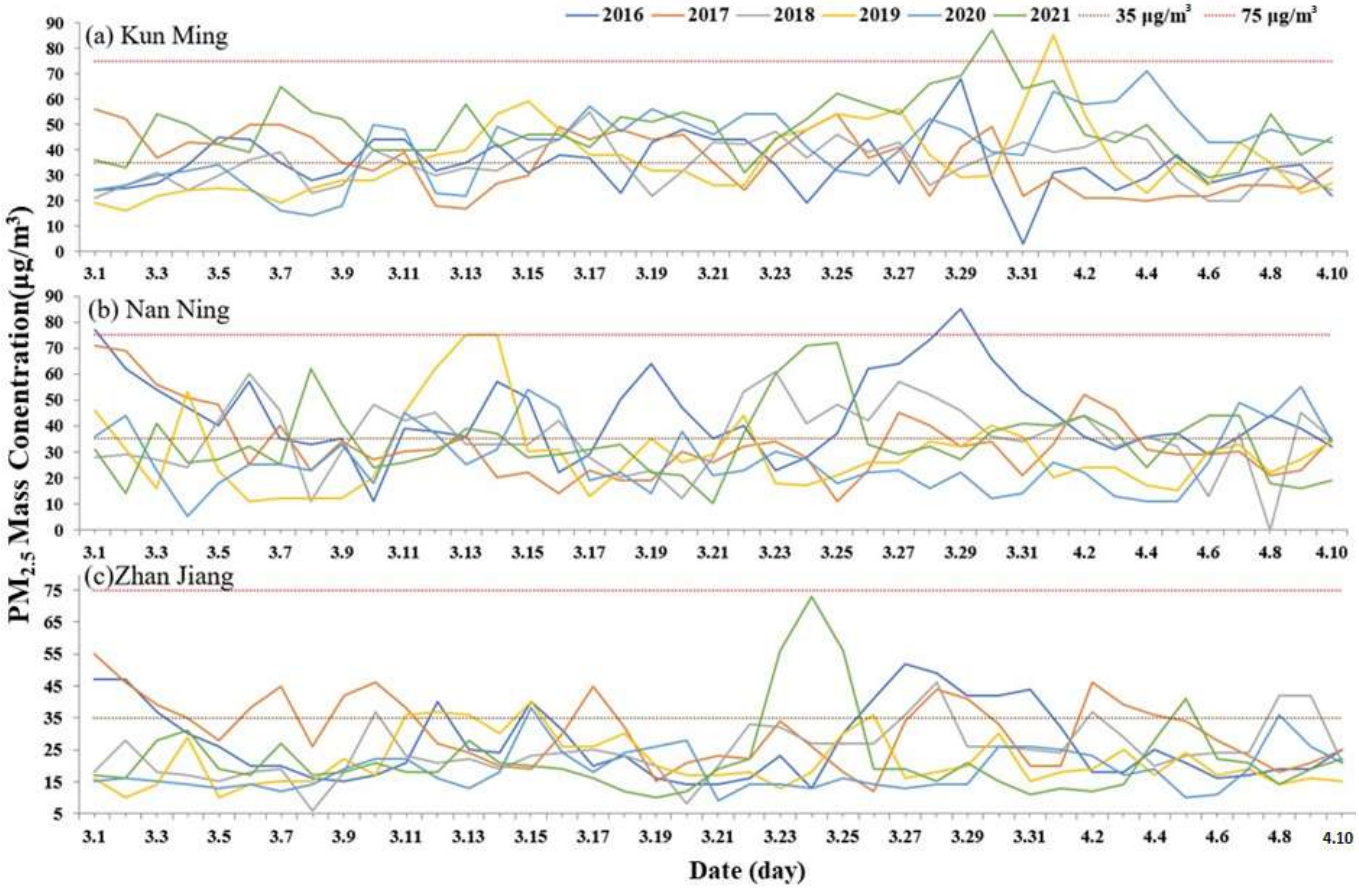


Figure 8. Changes in $PM_{2.5}$ in (**a**) Kunming, (**b**) Nanning and (**c**) Zhanjiang. (The $PM_{2.5}$ concentration data is the result of averaging the hourly data from the main environmental protection station on the same day).

It can be concluded that the degree of influence of the transboundary pollution of biomass burning in Southeast Asia is related to distance: the closer to the Indochinese Peninsula, the greater the pollution; the farther away from the Indochinese Peninsula, the lower the degree of pollution. The pollution is the most severe on the border with Southeast Asia.

Backward track analysis of polluting air mass in Guangxi on 24 March, Yunnan on 30 March and Guangdong on 31 March (See Figure 9) shows that:

1. Guangdong is affected by biomass burning in the Indochinese Peninsula to an extent. The main way is that pollutants are transferred from the Indochinese Peninsula to the South China Sea and then moved to the south of Guangdong under the action of wind.
2. The polluted air masses in the upper atmosphere of Guangxi in China come from the Indochinese Peninsula and have a certain impact on the pollution index in the province.
3. Affected by the spring southwest monsoon, the polluted air masses of different heights in Yunnan mainly come from Southeast Asia in the southwest.

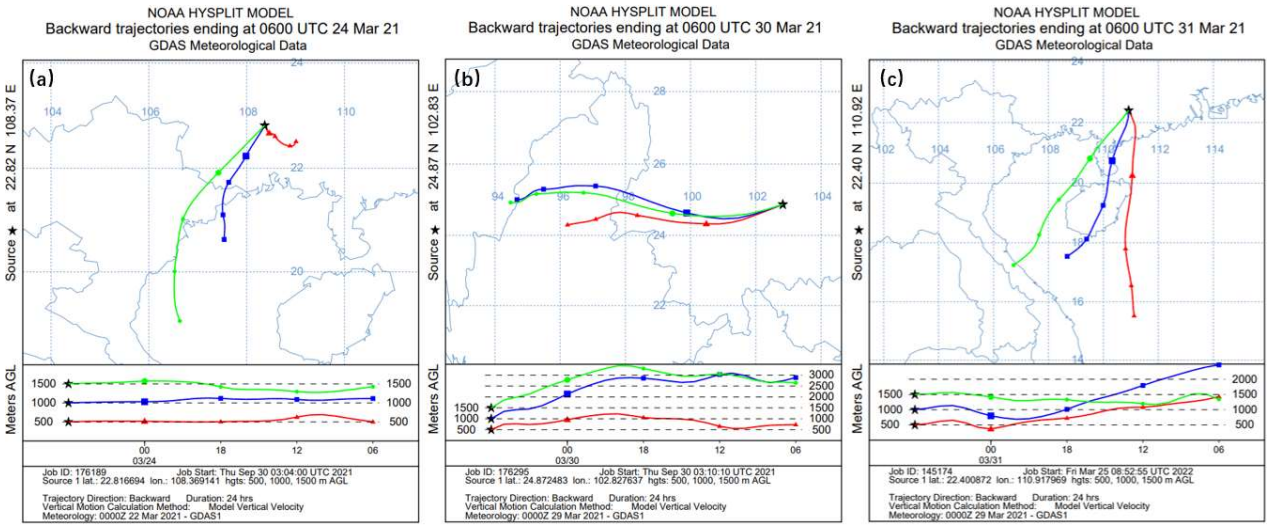


Figure 9. Backward trajectories of polluting air mass in Guangxi on 24 March (**a**) Yunnan on 30 March, (**b**) and Guangdong on 31 March, (**c**) at different altitudes above ground level. (Red: 500 m; Blue: 1000 m; Green: 1500 m).

4. Discussion

The results of multi-source satellite data analysis show that biomass burning in Southeast Asia can lead to the degradation of air quality in southern China (Yunnan, Guangxi and Guangdong). Emissions from the fires in Southeast Asia in March–April spread across the South China Sea and continue to cause polluted weather in parts of Guangdong and Guangxi provinces. At the same time, biomass burning emissions are directly transported to Yunnan province under the action of the southwest monsoon. Polluting gases emitted by biomass burning enhance local aerosol optical thickness and cause pollution in cities downwind after transnational transmission. For example, aerosol emitted by biomass burning in Myanmar is the largest aerosol contribution source [32], which to some extent leads to $PM_{2.5}$ concentration and haze weather in the southern cities of China [33]. Under the action of the airborne southwest jet, it can be transmitted from 800–600 hPa to most areas of South China [34].

The emissions of biomass burning pollutants from the Indochinese Peninsula increase the concentration levels of various air pollutants in the Pacific [35,36], especially in the southern cities of China (Yunnan, Guangxi and Guangdong). Studies have shown that biomass burning plumes in Southeast Asia account for about 35–40% of the mass of fine inorganic aerosols in the Pacific [37], while CO column concentration, AOD and $PM_{2.5}$ concentrations in southern China increased significantly from March to April (the two months when biomass burning concentrated in Southeast Asia). In addition, UVAI can represent the black carbon and organic aerosols of biomass burning [38], and the UVAI produced by biomass burning in Southeast Asia can be transmitted to southern China under the circulation.

Research on the uncertainty of the accurate estimation of biomass burning emissions in China was conducted by studying transboundary pollution from biomass burning in Southeast Asia [39]. In the past five years, there has been no improvement in large-scale biomass burning in Southeast Asia every year. Using a comprehensive analysis of various polluting gases, biomass burning directly contributes to the polluted weather in southern China. The occurrence of pollution weather is generally contributed by regional transport and local emissions. For example, in some areas of southwest China, the contribution of biomass burning from Southeast Asia is similar to that from local anthropogenic sources, especially when $PM_{2.5}$ is high [40]. Carrying out quantitative assessment research on the impact of biomass combustion on air quality to distinguish the contribution of local sources and external sources can achieve accurate control of various air pollution sources, such as biomass incineration, industrial enterprises and bare land dust, thus improving local environmental quality.

5. Conclusions

On the Indochinese Peninsula, biomass burning mainly occurs in March and April and is most concentrated from late March to early April. All the five countries of the Indochinese Peninsula (Myanmar, Laos, Thailand, Cambodia and Vietnam) have concentrated biomass burning fires, which can reach up to 120,000 in the peak period of each year, and the numbers of biomass burning fire points in Myanmar and Laos are the most widely distributed and abundant among the five countries. There is also a small amount of agricultural waste burning in the south and southwest of China, but the annual total number of incidents only accounts for a few tenths of that of the Indochinese Peninsula. According to the analysis of the MODIS AOD product, the AOD load of southern and southwestern China bordering the Indochinese Peninsula is higher (>0.6), while the AOD of southwestern Guangxi and southeastern Yunnan can be as high as 0.8 or above. Heavy aerosols represent serious air pollution problems in China. The analysis result of the CO column concentration is similar to AOD. The concentration of the CO column in Yunnan, Guangxi and Guangdong increases dramatically from March to April due to the influence of biomass burning on the Indochinese peninsula. Except for the high altitude area of Yunnan, the concentration of the CO column in other areas is $>3.0 \times 10^{18}$ molec/cm^2. Although the concentrations of all pollutant emissions decreased due to COVID-19 in 2021, the high value range of biomass burning pollutants did not change.

According to the analysis of the serious transnational transport event of biomass burning pollutants in Southeast Asia from 22 March to 2 April 2021, the transport of pollutants emitted from biomass burning were analyzed using UVAI at sufficient boundary layer height, and the results show that the pollutants can be carried downwind to Yunnan, Guangdong and Guangxi provinces by a southwest monsoon of sufficient strength to seriously affect the local air quality. Analysis of $PM_{2.5}$ data from ground stations in Zhanjiang, Nanning and Kunming revealed a sudden increase, and the study of the backward trajectory on the day of the sudden increase verified the presence of local air masses from the Indochinese Peninsula. It is directly determined that the polluted weather generated in southern China is partly due to the transnational transport of biomass burning emissions from Southeast Asia.

Large-scale biomass burning on the Indochinese Peninsula has led to moderate pollution weather in southern China and even severe pollution weather in western and southern Yunnan, which has a negative impact on the atmospheric climate and people's health in China. Countries need to cooperate to carry out pollution source research and control, focus on air pollution source control, closely monitor fires in Southeast Asia, build regional collaborative management mechanisms for pollution from biomass burning emissions and carry out favorable environmental diplomacy. Considering international relations and the complex nature of air pollutants, the quantitative assessment of the impact of biomass incineration on air quality and the quantitative differentiation of contributions from local and external sources still need further research.

Author Contributions: Conceptualization, H.C. and L.Z.; data curation, A.Z.; formal analysis, Y.Y. and W.Q.; funding acquisition, S.Z. (Shimin Zhao); validation, G.W. and M.T.; writing—original draft, L.Z. and S.D.; writing—review & editing, L.Z., S.Z. (Shaohua Zhao) and Z.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program (Grant No. 2018YFE0106900) and the National Natural Science Foundation of China (Grant No. 41971324).

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Adam, M.G.; Tran, P.T.; Bolan, N.; Balasubramanian, R. Biomass burning-derived airborne particulate matter in Southeast Asia: A critical review. *J. Hazard. Mater.* **2021**, *407*, 124760. [CrossRef] [PubMed]
2. Othman, M.; Latif, M.T.; Hamid, H.H.A.; Uning, R.; Khumsaeng, T.; Phairuang, W.; Lung, S.C.C. Spatial–temporal variability and heath impact of particulate matter during a 2019–2020 biomass burning event in Southeast Asia. *Sci. Rep.* **2022**, *12*, 7630. [CrossRef] [PubMed]
3. Yin, S.; Wang, X.; Zhang, X.; Guo, M.; Miura, M.; Xiao, Y. Influence of biomass burning on local air pollution in mainland Southeast Asia from 2001 to 2016. *Environ. Pollut.* **2019**, *254*, 112949. [CrossRef] [PubMed]
4. Ito, A.; Ito, A.; Akimoto, H. Seasonal and interannual variations in CO and BC emissions from open biomass burning in Southern Africa during 1998–2005. *Glob. Biogeochem. Cycles* **2007**, *21*, GB2011. [CrossRef]
5. Wiedinmyer, C.; Akagi, S.K.; Yokelson, R.J.; Emmons, L.K.; Al-Saadi, J.A.; Orlando, J.J.; Soja, A.J. The Fire INventory from NCAR (FINN)—A high resolution global model to estimate the emissions from open burning. *Geosci. Model Dev.* **2011**, *4*, 625–641. [CrossRef]
6. Palacios-Orueta, A.; Chuvieco, E.; Parra, A.; Carmona-Moreno, C. Biomass Burning Emissions: A Review of Models Using Remote-Sensing Data. *Environ. Monit. Assess.* **2005**, *104*, 189–209. [CrossRef]
7. Streets, D.G.; Yarber, K.F.; Woo, J.-H.; Carmichael, G.R. Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Glob. Biogeochem. Cycles* **2003**, *17*, 1099. [CrossRef]
8. Huang, K.; Fu, J.S.; Hsu, N.C.; Gao, Y.; Dong, X.; Tsay, S.-C.; Lam, Y.F. Impact assessment of biomass burning on air quality in Southeast and East Asia during BASE-ASIA. *Atmos. Environ.* **2013**, *78*, 291–302. [CrossRef]
9. Zhang, Y.; Yang, Y.; Li, J.; Wang, Y.; Wang, Z. Modeling the Impacts of Biomass Burning in Southeast Asia on $PM_{2.5}$ over China in Spring. *Res. Environ. Sci.* **2016**, *29*, 952–962.
10. Xue, L.; Ding, A.; Cooper, O.; Huang, X.; Wang, W.; Zhou, D.; Wu, Z.; McClure-Begley, A.; Petropavlovskikh, I.; Andreae, M.O.; et al. ENSO and Southeast Asian biomass burning modulate subtropical trans-Pacific ozone transport. *Natl. Sci. Rev.* **2020**, *8*, nwaa132. [CrossRef]
11. Zhu, J.; Xia, X.; Che, H.; Wang, J.; Zhang, J.; Duan, Y. Study of aerosol optical properties at Kunming in southwest China and long-range transport of biomass burning aerosols from North Burma. *Atmos. Res.* **2016**, *169*, 237–247. [CrossRef]
12. Zhou, R.; Zhu, J. Effects of biomass combustion and transportation over southeast Asia on aerosol radiation characteristics in southwest China. *China Environ. Sci.* **2020**, *40*, 1429–1436. (In Chinese)
13. Bond, T.C.; Doherty, S.J.; Fahey, D.W.; Forster, P.M.; Berntsen, T.; DeAngelo, B.J.; Zender, C.S. Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res. Atmos.* **2013**, *118*, 5380–5552. [CrossRef]
14. Olivier, J.G.J.; Aardenne, J.A.V.; Dentener, F.J.; Pagliari, V.; Ganzeveld, L.N.; Peters, J.A.H.W. Recent trends in global greenhouse gas emissions: Regional trends 1970–2000 and spatial distribution of key sources in 2000. *Environ. Sci.* **2005**, *2*, 81–99. [CrossRef]
15. Ciais, P.; Sabine, C.; Bala, G.; Bopp, L.; Brovkin, V.; Canadell, J.; Thornton, P. Carbon and other biogeochemical cycles. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2013; pp. 465–570.
16. Tian, H.; Lu, C.; Ciais, P.; Michalak, A.M.; Canadell, J.G.; Saikawa, E.; Huntzinger, D.N.; Gurney, K.R.; Sitch, S.; Zhang, B.; et al. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature* **2016**, *531*, 225–228. [CrossRef] [PubMed]
17. Crutzen, P.J.; Andreae, M.O. Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* **1990**, *250*, 1669–1678. [CrossRef] [PubMed]
18. Robinson, A.L.; Donahue, N.M.; Shrivastava, M.K.; Weitkamp, E.A.; Sage, A.M.; Grieshop, A.P.; Lane, T.E.; Pierce, J.R.; Pandis, S.N. Rethinking organic aerosols: Semivolatile emissions and photochemical aging. *Science* **2007**, *315*, 1259–1262. [CrossRef] [PubMed]
19. May, A.A.; Levin, E.J.T.; Hennigan, C.J.; Riipinen, I.; Lee, T.; Collett, J.L.; Jimenez, J.L.; Kreidenweis, S.M.; Robinson, A.L. Gas-particle partitioning of primary organic aerosol emissions: 3. Biomass burning. *J. Geophys. Res.* **2013**, *118*, 11327–11338. [CrossRef]
20. Yue, X.; Unger, N. Fire air pollution reduces global terrestrial productivity. *Nat. Commun.* **2018**, *9*, 5413. [CrossRef]

21. Lin, N.H.; Sayer, A.M.; Wang, S.H.; Loftus, A.M.; Hsiao, T.C.; Sheu, G.R.; Chantara, S. Interactions between biomass-burning aerosols and clouds over Southeast Asia: Current status, challenges, and perspectives. *Environ. Pollut.* **2014**, *195*, 292–307. [CrossRef]
22. Fan, J.; Rosenfeld, D.; Yang, Y.; Zhao, C.; Leung, L.R.; Li, Z. Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. *Geophys. Res. Lett.* **2015**, *42*, 6066–6075. [CrossRef]
23. Pope Iii, 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. *JAMA* **2002**, *287*, 1132–1141. [CrossRef] [PubMed]
24. Vincenti, B.; Paris, E.; Carnevale, M.; Palma, A.; Guerriero, E.; Borello, D.; Gallucci, F. Saccharides as Particulate Matter Tracers of Biomass Burning: A Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4387. [CrossRef]
25. Li, W.; Ge, P.; Chen, M.; Tang, J.; Cao, M.; Cui, Y.; Nie, D. Tracers from biomass burning emissions and identification of biomass burning. *Atmosphere* **2021**, *12*, 1401. [CrossRef]
26. Zhang, H.; Zhang, X.; Wang, Y.; Bai, P.; Hayakawa, K.; Zhang, L.; Tang, N. Characteristics and Influencing Factors of Polycyclic Aromatic Hydrocarbons Emitted from Open Burning and Stove Burning of Biomass: A Brief Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3944. [CrossRef]
27. Cong, Z.; Kawamura, K.; Kang, S.; Fu, P. Penetration of biomass-burning emissions from South Asia through the Himalayas: New insights from atmospheric organic acids. *Sci. Rep.* **2015**, *5*, 9580. [CrossRef]
28. Ranjan, A.K.; Patra, A.; Gorai, A. Effect of lockdown due to SARS COVID-19 on aerosol optical depth (AOD) over urban and mining regions in India. *Sci. Total Environ.* **2020**, *745*, 141024. [CrossRef]
29. Takami, K.; Shimadera, H.; Uranishi, K.; Kondo, A. Impacts of biomass burning emission inventories and atmospheric reanalyses on simulated PM_{10} over Indochina. *Atmosphere* **2020**, *11*, 160. [CrossRef]
30. Ziemke, J.R.; Oman, L.D.; Strode, S.A.; Douglass, A.R.; Olsen, M.A.; McPeters, R.D.; Bhartia, P.K.; Froidevaux, L.; Labow, G.J.; Witte, J.C. Trends in global tropospheric ozone inferred from a composite record of TOMS/OMI/MLS/OMPS satellite measurements and the MERRA-2 GMI simulation. *Atmos. Chem. Phys.* **2019**, *19*, 3257–3269. [CrossRef]
31. Lu, S.; Huang, H.-C.; Hou, Y.-T.; Tang, Y.; McQueen, J.; da Silva, A.; Chin, M.; Joseph, E.; Stockwell, W. Development of NCEP Global Aerosol Forecasting System: An overview and its application for improving weather and air quality forecasts. In *NATO Science for Peace and Security Series: Air Pollution Modeling and Its Application XX*; Springer: Dordrecht, The Netherlands, 2010; pp. 451–454.
32. Wang, S.H.; Lin, N.H.; Chou, M.D.; Woo, J.H. Estimate of radiative forcing of Asian biomass-burning aerosols during the period of TRACE-P. *J. Geophys. Res. Atmos.* **2007**, *112*, D10222. [CrossRef]
33. Thepnuan, D.; Chantara, S.; Lee, C.-T.; Lin, N.-H.; Tsai, Y.I. Molecular markers for biomass burning associated with the characterization of PM2.5 and component sources during dry season haze episodes in Upper South East Asia. *Sci. Total Environ.* **2019**, *658*, 708–722. [CrossRef] [PubMed]
34. Ooi, M.C.-G.; Chuang, M.-T.; Fu, J.S.; Kong, S.S.; Huang, W.-S.; Wang, S.-H.; Pimonsree, S.; Chan, A.; Pani, S.K.; Lin, N.-H. Improving prediction of trans-boundary biomass burning plume dispersion: From northern peninsular Southeast Asia to downwind western North Pacific Ocean. *Atmos. Chem. Phys.* **2021**, *21*, 12521–12541. [CrossRef]
35. Duncan, B.N.; Martin, R.V.; Staudt, A.C.; Yevich, R.; Logan, J.A. Interannual and seasonal variability of biomass burning emissions constrained by satellite observations. *Geophys. Res. Atmos.* **2003**, *108*, ACH 1-1–ACH 1-22. [CrossRef]
36. Kondo, Y.; Morino, Y.; Takegawa, N.; Koike, M.; Kita, K.; Miyazaki, Y.; Sachse, G.; Vay, S.; Avery, M.; Flocke, F. Impacts of biomass burning in Southeast Asia on ozone and reactive nitrogen over the western Pacific in spring. *Geophys. Res. Atmos.* **2004**, *109*, D15S12. [CrossRef]
37. Ma, Y.; Weber, R.; Lee, Y.N.; Orsini, D.; Maxwell-Meier, K.; Thornton, D.; Bandy, A.; Clarke, A.; Blake, D.; Sachse, G. Characteristics and influence of biosmoke on the fine-particle ionic composition measured in Asian outflow during the Transport and Chemical Evolution Over the Pacific (TRACE-P) experiment. *Geophys. Res. Atmos.* **2003**, *108*, 8816. [CrossRef]
38. Gadhavi, H.; Jayaraman, A. Absorbing aerosols: Contribution of biomass burning and implications for radiative forcing. *Ann. Geophys.* **2010**, *28*, 103–111. [CrossRef]
39. Tao, M.; Chen, L.; Wang, Z.; Tao, J.; Su, L. Satellite observation of abnormal yellow haze clouds over East China during summer agricultural burning season. *Atmos. Environ.* **2013**, *79*, 632–640. [CrossRef]
40. Chan, C.; Chan, L.; Chang, W.; Zheng, Y.; Cui, H.; Zheng, X.; Qin, Y.; Li, Y.S. Characteristics of a tropospheric ozone profile and implications for the origin of ozone over subtropical China in the spring of 2001. *Geophys. Res. Atmos.* **2003**, *108*, 8800. [CrossRef]