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Importance of transboundary transport of biomass burning emissions to regional air quality in Southeast Asia

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Abstract

Smoke from biomass and peat burning has a notable impact on ambient air quality and climate in the Southeast Asia (SEA) region. We modeled the largest fire-induced haze episode in the past decade (2006) in Indonesia using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). We focused mainly on the evolution of the fire plume composition and its interaction with the urbanized area of the city-state of Singapore, and on comparisons of modeled and measured aerosol and CO concentrations. Two simulations were run with the model using the complex Volatility Basis Set (VBS) scheme to reproduce primary and secondary aerosol evolution and concentration. The first simulation referred to as WRF-FIRE included anthropogenic, biogenic, and biomass burning emissions from the Global Fire Emissions Database (GFED3) while the second simulation referred to as WRF-NOFIRE was run without emissions from biomass burning. To test model performance, we used three independent datasets for comparison including airborne measurements of Particulate Matter with a diameter of 10 µm or less (PM_{10}) in Singapore, CO measurements in Sumatra, and Aerosol Optical Depth (AOD) column observations from 4 satellite-based sensors. We found reasonable agreement of the model runs with both ground-based measurements of CO and PM_{10}. The comparison with AOD was less favorable and indicated the model underestimated AOD, although the degree of mismatch varied between different satellite data sets. During our study period, forest and peat fires in Sumatra were the main cause of enhanced aerosol concentrations from regional transport over Singapore. Analysis of the biomass burning plume showed high concentrations of primary organic aerosols (POA) with values up to 600 µg m^{-3} over the fire locations. The concentration of POA remained quite stable within the plume between the main burning region and Singapore while secondary organic aerosol (SOA) concentration slightly increased. The absolute values of SOA (up to 20 µg m^{-3}) were much lower than those from POA, indicating a minor role of SOA in biomass burning plumes. Our results show that about 21 % of the total mass loading of ambient PM_{10} during the July–October

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study period in Singapore was due to biomass and peat burning in Sumatra, but this contribution increased during high burning periods. In total, our model results indicated that during 35 days aerosol concentrations in Singapore were above the threshold of 50 $\mu g\,m^{-3}\,day^{-1}$ indicating poor air quality. During 17 days this was due to fires, based on the difference between the simulations with and without fires. Local pollution in combination with recirculation of air masses was probably the main cause of poor air quality during the other 18 days, although fires from Sumatra and probably also from Borneo added to the enhanced PM_{10} concentrations. The model vs. measurement comparisons highlighted that for our study period and region the GFED3 biomass burning aerosol emissions were more in line with observations than found in other studies. This indicates that care should be taken when using AOD to constrain emissions or estimate ground-level air quality. This study also shows the need for relatively high resolution modeling to accurately reproduce the advection of air masses necessary to quantify the impacts and feedbacks on air quality.

1 Introduction

Biomass burning plays an important role in atmospheric composition and chemistry (Crutzen and Andreae, 1990; Lamarque et al., 2010). Fires occurring close to populated areas severely impact air quality affecting millions of inhabitants (Johnston et al., 2012; Marlier et al., 2013). Governments and international organizations such as the World Health Organization (WHO) have produced pollution guidelines in the last decade (WHO, 2006), but the contribution of biomass burning emissions to local air quality is not well understood nor quantified.

SEA, especially Indonesia, has the highest concentration of fire emissions globally due to the intensive burning in areas with high fuel loads including peatlands (Page et al., 2002; van der Werf et al., 2010). Fire activity is highly modulated by the El-Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Hong et al., 2008; Field et al., 2009; Reid et al., 2013). Densely populated areas such as Java and

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the city of Singapore are located relatively close to hot spots (intense fires) mainly in Sumatra and Borneo and regularly show high particulate pollution levels which may be impacted by emissions from forest, agriculture, and peat fires (Hyer and Chew, 2010; Salinas et al., 2013a, b; Wang et al., 2013). Models that accurately simulate biomass burning plumes and their air quality impacts in this complex orographic and meteorological region are necessary to better understand the transport and evolution of smoke plumes.

Air pollution caused by aerosol particles is of concern because of reduction in visibility and adverse environmental and health impacts (Mauderly and Chow, 2008). Depending on their size and chemical composition, aerosol particles can penetrate into the respiratory system and increase throat and lung infections (Karthikeyan et al., 2006; Pavagadhi et al., 2013). In addition, aerosols also increase the risk of developing lung cancers (Abba et al., 2012). Fires emit high concentrations of particles of small sizes as well as volatile and semi-volatile organic compounds which may act as precursors in the formation of secondary aerosols (See et al., 2006, 2007; Keywood et al., 2003; He et al., 2010; Yee et al., 2013). In this study, we focus on transboundary particulate pollution levels affecting the Republic of Singapore (population of over 5 million) due to the release of aerosol particles from biomass burning in Indonesia. We used WRF-Chem to (1) advect the aerosol and gaseous precursors concentrations emitted by biomass burning, (2) represent the evolution of the aerosol plume dynamics and chemistry, and (3) evaluate the interactions between this transported and aged air mass from fires with freshly emitted urban pollution in Singapore.

2 WRF-Chem set-up and evaluation

2.1 Model set-up

We used the online-coupled regional Weather Research and Forecasting model with Chemistry (WRF-Chem) (Grell et al., 2005) v3.4 to simulate meteorology and

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atmospheric composition at a regional scale. The fully coupled model WRF-Chem computes at each time step the dynamic processes as well as the microphysics and the atmospheric chemistry and aerosol processes.

The simulation was done for a domain with 100 by 100 grid points, each with a 15 km horizontal resolution. The domain included Sumatra (Indonesia), the Republic of Singapore and the southern part of the Malaysian peninsula (see Fig. 1). The model had 30 vertical levels from ground level up to 23 km height with a stretching resolution from 60 m to 1.6 km for the bottom and top level, respectively. The simulation was run from 1 July 2006 to 31 October 2006 (a 4 month period) including a high fire episode in Sumatra occurring in October. The temporal resolution of the simulation was 90 s.

The domain was initialized by the National Centers for Environmental Prediction FiNaL reanalysis data for the meteorological variables (NCEP-FNL, 2000) and by the MOZART4-NCEP model output for the chemical gases and primary aerosols initialization (Emmons et al., 2010). The boundaries of the domain were also forced by the NCEP-FNL and MOZART4-NCEP re-analyses model outputs which were called for input every 6 h. The WRF-Chem configuration used the VBS scheme for aerosol chemistry (Ahmadov et al., 2012), the MADE (Modal Aerosol Dynamics Model for Europe) module for the aerosol dynamic processes and the RACM (Regional Atmospheric Chemistry Modeling) (Stockwell et al., 1997) reaction scheme for the gaseous chemistry reactions. The aerosol particle population was described by 3 modes (aitken, accumulation and coarse), each of them following a lognormal distribution. Each aerosol mode was composed of primary particles (primary organic carbon, black carbon, dust and sea salt) and secondary particles (sulfate, nitrate, ammonium, 4 classes of anthropogenic secondary organic aerosol, 4 classes of biogenic secondary aerosols and resulting water). Dust, sea salt and biogenic particles showed concentration values lower than 1 % of the total aerosol concentrations and are therefore not discussed in the rest of this study, but were included in the model runs. The simulation included anthropogenic, biogenic and biomass burning emissions prepared by the prep-chem-src tool (Freitas et al., 2011).

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The anthropogenic emissions were derived from the EDGARv4 (EDGAR, 2009) and RETRO (Pulles et al., 2005) inventory. The biogenic emissions were computed by the MEGAN model v2.1 (Guenther et al., 2012). The daily biomass burning emissions were taken from GFED3 (van der Werf et al., 2010; Mu et al., 2011) and the emission factors for the volatile organic compounds as well as for the primary aerosol particles are deduced from Akagi et al. (2011). Table 1 shows the emission factors of aerosol species as used in the GFED3 database and deduced from the newer emission factors from Akagi et al. (2011) as used in the simulations. Table 1 shows that for the 4 months of interest, the aerosol particle emissions from biomass burning as input for the simulation are 27.7 % higher than in the GFED3 database. Emissions of primary organic carbon from anthropogenic sources and biomass burning sources are shown in Fig. 1.

2.2 Comparison with observations

We compared the model outputs with observations to gain confidence in our model set-up. The model results indicate that there were 3 distinct time periods with regard to aerosol concentrations in Singapore (Fig. 2). The first period lasted from July to the end of September, and the 24 h averaged aerosol concentrations in Singapore were relatively low and almost never exceeded the value of 50 $\mu g\,m^{-3}$ for PM_{10}, indicated by the World Health Organization (WHO, 2006) as the threshold for classifying the ambient air quality as polluted. The averaged value for this period was 35 $\mu g\,m^{-3}$ representing urban background concentrations in Singapore. During this time period, only small fires occurred in Sumatra and the wind regime did not advect the resulting plumes in the direction of Singapore. During the second period, from the end of September until the middle of October, the aerosol concentrations (PM_{10}) were high (values reaching 160 $\mu g\,m^{-3}$) and were coupled with relatively steady Southeasterly winds with a surface mean velocity values of 7 $m\,s^{-1}$. The third period ran from the middle of October until the end of October, and the aerosol concentrations remained high (values reaching 160 $\mu g\,m^{-3}$). The wind regime over Singapore showed relatively low velocities (4 $m\,s^{-1}$) and directions varied between day and night, indicating that the main wind component

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in Singapore during this period was the thermal wind regime between land and sea. Fires also occurred in Sumatra during this period, but the wind regime did not advect the resulting plumes to Singapore.

In Fig. 2, the 24 h modeled average values of aerosol mass concentrations in Singapore at ground level and the 50 $\mu g\,m^{-3}$ threshold as used by the WHO to define polluted air are shown. The modeled results agreed reasonably well with surface observations. The observations are the averaged values of 5 ambient air quality stations located in different part of Singapore measuring PM_{10} mass concentrations. Figure 2 shows that the WRF-Chem model manages to reproduce the evolution of the aerosol mass concentration in Singapore both for background aerosol concentrations and during the smoke haze period, characterized by elevated aerosol concentration occurring in October. The correlation coefficient (R) between field observations and model results for the whole period was 0.62.

Besides the local aerosol concentration at ground level, we also compared our modeled results to Aerosol Optical Depth (AOD) as measured by various satellite instruments. This comparison was done for a $1^{\circ} \times 1^{\circ}$ area centered over Singapore. Figure 3 shows 2 weekly average AOD modelled at the wavelength of 550 nm and observed by different satellite sensors. For the first period (July–September) with low values, the different observations and model results were in relatively good agreement with AOD. However, Fig. 3 also shows that the modelled AOD was low during the month of October compared to observations from the Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR) and Sea viewing Wide Field of view Sensor (SeaWiFS). The quantitative disagreement varies between the different sensors but is largest when compared to MODIS observations with up to a factor of 2.5 in the middle of October. There is, however, agreement on the temporal trend in aerosol concentrations with most of observations. The discrepancy of AOD can probably be explained by an elevated aerosol layer observed over Singapore as described by Campbell et al. (2013); Chew et al. (2013). This pollution layer appears to come from outside the domain and is represented in the boundary conditions entering

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the domain from the east. After entering the domain, the model locates this advected pollution layer south of Singapore and therefore is not represented in the simulated AOD over Singapore. Due to the height of the tranported pollution layer (2500 m) it does not affect our results which focus on the lower atmophere. Another explanation of the model AOD underestimation may be a contamination of the observed AOD due to tropical cirrus cloud and opaque cloud as described by several studies (Huang et al., 2012, 2011; Chew et al., 2011).

In addition to these comparisons with aerosol observations, we compared our results with one station in Sumatra with continuous carbon monoxide (CO) observations (Zellweger et al., 2007). Figure 4 shows the evolution of the CO concentrations during our 4 month study period at the Bukit Kototabang station (BKT, see Fig. 1). The model results are drawn in blue and red lines standing for simulation excluding biomass burning emissions (referred to as WRF-NOFIRE later on this document) and including biomass burning emssions (referred to as WRF-FIRE), respectively. The model manages to correctly represent the background concentrations as well as the high level of CO concentrations (up to 1300 ppb) due to biomass burning, inducing that both model transport and CO emissions from the GFED3 database are correctly represented in this study. One can also note however, that several smaller fire episodes are not well captured by either WRF or GFED3.

3 Aerosol plume analyses: composition and distribution

The comparison of model outputs with observations shows that the WRF-Chem model set-up is capable of representing quite accurately the evolution of the aerosol concentrations for the 4 months of simulation. This part of the study focuses on the composition of aerosol particles at the biomass burning emission location, along the plume, and in Singapore. Figure 5 shows the horizontal cross section of primary aerosol mass concentration on the left and SOA mass concentration on the right, at the surface level on 3 October 2006 at noon local time. Although being a snapshot, it is a representative

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one involving the interaction between remotely emitted biomass burning aerosols and freshly emitted urban aerosols in Singapore.

Figure 5 illustrates that primary aerosols were highly concentrated over emission sources and reached values of 350 $\mu g\,m^{-3}$ at biomass burning location (marked as point A) and 180 $\mu g\,m^{-3}$ in Singapore (marked as point B). Those high concentration of primary aerosols rapidly decreased away from the emission sources. On the other hand, SOA reached high concentrations few kilometers away from the emissions sources. While the amplitude of the variability is much lower than for the primary aerosols (from 1 to 10 $\mu g\,m^{-3}$ compared with 20 to 600 $\mu g\,m^{-3}$), Fig. 5b shows that SOA are formed remotely from the biomass burning emissions along the plume and are mixed with freshly formed secondary organic aerosols from fast chemical reactions in Singapore. The modelled SOA concentrations appear relatively low, but are based on the VBS module which includes a semi-volatility approach to compute the SOA concentrations and has been tested to be one of the most accurate and computationally efficient scheme at present (Matsui et al., 2014; Ahmadov et al., 2012). In addition, these results appear consistent with recent studies confirming that the net SOA to POA ratio for biomass burning emissions is far lower than for urban emissions (Ortega et al., 2013).

Not only does the aerosol concentration change rapidly along the plume, its chemical composition also shows substantial fluctuations, as seen Fig. 6. The figure shows a transect from the source in Sumatra marked by A in Fig. 5 to the city of Singapore marked with a B. The main message from Fig. 6 is that the total aerosol population, in the A to B transect, is largely dominated by primary organic carbon (OC_p) representing 83 to 95 % of the total aerosol mass concentration. This high contribution of OC_p varies along the plume with highest values at the biomass burning location. This OC_p concentration sharply decreases about 75 km away from the biomass burning location, but then slightly increases along the plume. This initial decrease is due to a fluctuation of the wind regime leading to an alternating pattern between steady winds from south and the associated plume along the ocean, and low wind regime associated with

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accumulation of particles as for the local maximum in Sumatra. The contribution of OC_p to total aerosol concentration is relatively stable along the plume around 92 %, but drops to 83 % close to the city of Singapore largely due to increased non-OC_p concentrations. While the percentage of OC_p may appear high in regard to other recent studies (See et al., 2006, 2007), it remains consistent for this intense fire episode with the emission ratios reported in Akagi et al. (2011).

The non-OC_p aerosols (represented in Fig. 6b) show first relatively high values at the biomass burning location and is dominated for 63 % by black carbon (BC). The non-OC_p fraction then sharply decreases by a factor of 2. The absolute values of non-OC_p aerosol mass concentration increases slightly along the plume due to an increase of the secondary organic aerosol formation. Finally in Singapore, the local anthropogenic emissions of black carbon dominate the non-OC_p aerosol concentrations while the SOA concentration remains stable. The differences in the contribution of primary aerosols between BC and OC_p in the biomass burning location and in Singapore are due to the difference in the emission factors for peat fires and combustion. (EPA, 2010; Akagi et al., 2011)

4 Relative and absolute contribution of aerosols from biomass burning to pollution level in Singapore

In order to identify and quantify the impact of biomass burning on aerosol pollution level in Singapore, we ran two different simulations to isolate the impact of fires on the region. The first one included the biomass burning emissions and is referred to as WRF-FIRE. The second one only includes anthropogenic and biogenic emissions and is referred to as WRF-NOFIRE.

The results for both simulations with regard to aerosol mass concentration in Singapore are shown in Fig. 7. From July to the end of September the two simulations vary marginally. From early October until the middle of October large fires in Sumatra induced big differences between the two simulations in Singapore. The maximum

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difference was found on 10 October with values of 40 and 140 $\mu g\,m^{-3}$ for the WRF-NOFIRE and WRF-FIRE, respectively. Somewhat surprisingly, the second half of the month of October shows high values of aerosol concentrations but no major differences between the two simulations. During this period, 12.7 % of the aerosol concentration was coming from outside the domain and was probably due to advected fire plumes emitted in southern Borneo as shown by Engling et al. (2014) and Wang et al. (2013), and 14.4 % was due to fires occuring in Sumatra. Thus, the model indicates that during the second half of October, 73 % of the aerosol concentration was due to anthropogenic emissions occuring within the domain. This can be explained by the fact that from 13 October to the end of the simulation the wind regime showed quite low intensities and a recirculation of the wind pattern resulting in an accumulation of anthropogenic pollution over Singapore. Although the results from this modelling study show a relatively good match with observations and indicate that the high aerosol concentrations for the second half of October 2006 are dominated by local pollution, it should be noted that other studies attribute this high pollution levels to biomass burning occuring in southern Borneo (Engling et al., 2014; Wang et al., 2013). In order to study the aerosol pollution levels in Singapore, aerosol composition for the two simulations is compared as well as the number of day for which the 24 h averaged aerosol mass concentration was above the threshold of 50 $\mu g\,m^{-3}$.

Table 2 shows the average mass concentrations for total aerosol, POA, black carbon, SOA and inorganic particles for the two simulations. Those values are presented both for the total 4 month period and for the 2 week period when Singapore was affected most by biomass burning. The relative difference (as a percentage) between the WRF-FIRE and WRF-NOFIRE simulations is also reported for each aerosol component. For the 4 months of simulation, 21 % of the total aerosol particles in Singapore are due to fires in Sumatra. This increase of particles from biomass burning is largely dominated by primary organic carbon. On the other hand black carbon, inorganics and SOA concentrations in Singapore show less than 7 % increase due to fires in Sumatra.

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Focusing on the 28 September–13 October period during which fires in Sumatra had the highest impact on Singapore, Table 2 shows that almost half of the total aerosol particles in Singapore were due to fires. Again, this pollution is highly dominated by primary organic carbon particles (54 %). SOA showed low absolute concentrations but the relative increase due to fires is substantial (39 % increase).

Finally, the number of days when 24 h averages of aerosol mass concentration in Singapore were above the threshold of 50 $\mu g\,m^{-3}$ shows that while observations indicates 37 days with such values, WRF-FIRE and WRF-NOFIRE showed 35 and 17 days, respectively. These results indicate once more the importance of biomass burning in affecting local and regional air quality. However, they also highlight the importance of properly accounting for regional meteorology. In the past, GFED estimates have been found too low to properly model AOD (e.g. Petrenko et al., 2012; Marlier et al., 2013). Our results support this notion because the aerosol estimates we used were 27.7 % higher than standard GFED3 emissions due to applying new emission factors. However, this increase is substantially lower that in Petrenko et al. (2012) where they show an underestimation up to 300 % of biomass burning aerosol emissions in Indonesia, or in Marlier et al. (2013) where they increase the aerosol emissions from fires by a scaling factor up to 226 %. In our study region, coarse scale inverse model setups would probably boost fire emissions to account for lower than observed AOD, while in reality the discrepancy in AOD may come from various other causes than an underestimation of the biomass burning aerosol emissions, such as a too rough representation of the aerosol size and chemistry leading to wrong optical properties. Although just a case study, our results highlight the complexity of the various processes involved in the evolution of the regional and long-range transported aerosol particles.

5 Conclusions

We used the atmospheric model WRF-Chem with VBS configuration to simulate the aerosol evolution during 4 months over Sumatra and Singapore. The main objectives

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were to estimate, simulate and analyze the aerosol particle emission and evolution due to biomass burning in Sumatra. We focused on the year 2006, the highest fire year in the last decade in the region. The comparison with observations of PM_{10}, AOD and CO showed that the WRF-Chem model managed to reproduce quite accurately the aerosol concentrations in Singapore. This agreement confirms that relatively high spatial resolution is required when studying regional air quality cases. However we underestimated AOD probably due to regionally transported elevated particle layer misrepresented in the simulation, or tropical cirrus clouds affecting the AOD measurements. Nevertheless AOD is not a variable affecting directly air quality. For this simulation, we used new emission factors which were 28 % above those used in GFED3. This increase is much smaller than suggested by several other studies, yet it resulted in a good match with observations.

The analysis of the biomass burning plume composition mixing with the freshly emitted urban aerosol population in Singapore highlighted the very high concentrations of primary organic carbon with maximum values of 600 $\mu g\,m^{-3}$ at the fire source. SOA were formed within the plume but with much lower values of up to 20 $\mu g\,m^{-3}$. Black carbon concentrations were highest in Singapore where combustion processes from anthropogenic sources such as traffic are dominating with high black carbon emission factors. The analysis of the differences between two simulations, including and omitting fire emissions, allowed us to isolate and quantify the impact of biomass burning to aerosol pollution levels in Singapore. We showed that 21 % of the total aerosol concentration was due to biomass burning occurring in Sumatra during the 4 month period of the simulation, and 48 % when focusing on a 2 week period in October when smoke reaching Singapore was most intense. This contribution of fires resulted in 18 days when the 50 $\mu g\,m^{-3}$ threshold was exceeded, in addition to 17 days due to a mixture of mainly local anthropogenic pollution and smaller contributions from fires in Sumatra and probably Borneo. This study has revealed the impact of the high contribution of biomass burning smoke in Indonesia on aerosol pollution levels in Singapore.

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Accurate quantification of the contribution from biomass burning to particulate pollution levels in highly populated cities such as Singapore, Kuala Lumpur, and Jakarta may help to develop strategies to either control the timing of biomass and peat burning depending on the meteorology and the urban pollution levels, or apply more effective urban air pollution reduction plans when fire plumes impact the air pollution levels in populated areas significantly.

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Table 1. Comparison of aerosols emission factors (in g per kg dry matter) from GFED 3 and from Akagi et al. (2011) as used in the simulations. The relative differences in percentage are given in parenthesis.

	OC_p	BC	PM_{10}
GFED	4.49	0.55	5.04
Akagi et al. (2011)	6.23 (+38.6 %)	0.20 (−165 %)	6.43 (+27.7 %)

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Table 2. Comparison of speciated averaged aerosol mass concentrations over Singapore for the FIRE simulations (columns 2 and 4) and the NOFIRE simulations (columns 3 and 5) for the 4 month period (columns 2–3) and for the 1 month October period (columns 4–5). The relative differences between the two runs are given in columns 3 and 5 in parentheses.

	4 month period (Jul–Oct)		28 Sep–13 Oct	
	WRF-FIRE	WRF-NOFIRE	WRF-FIRE	WRF-NOFIRE
Total Aerosol	53.3	42.1 (−21 %)	97.4	50.5 (−48 %)
Black Carbon	10.7	10.1 (−6 %)	14.1	12.3 (−13 %)
Organic Carbon	40.7	30.0 (−26 %)	81.0	36.4 (−54 %)
Secondary Organic Carbon	1.5	1.4 (−7 %)	3.3	2.0 (−39 %)
Inorganic Aerosols	0.4	0.4 (0 %)	0.6	0.4 (−67 %)

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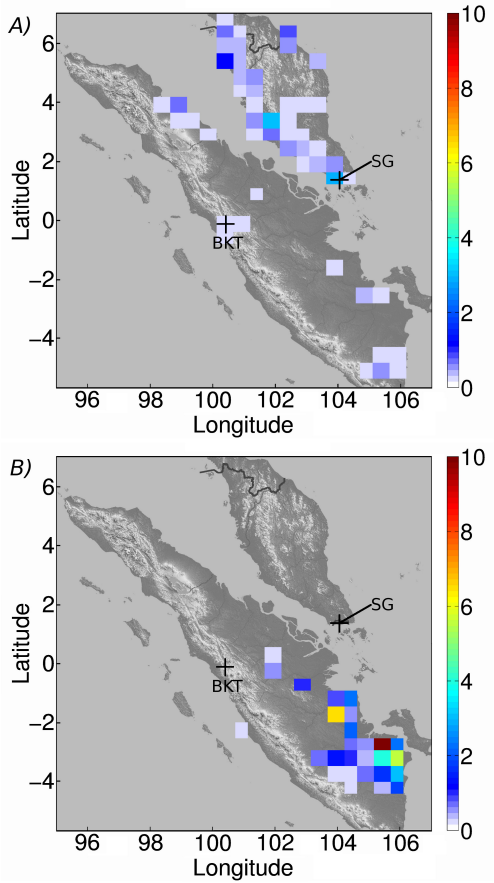

Fig. 1. Monthly averaged emissions in $\mu g\,m^{-2}\,s^{-1}$ of primary organic carbon from anthopogenic **(A)** and biomass burning **(B)** sources for October 2006. Singapore is marked with a black cross and the symbol SG and the CO measurement station Bukit Kototabang with the symbol BKT.

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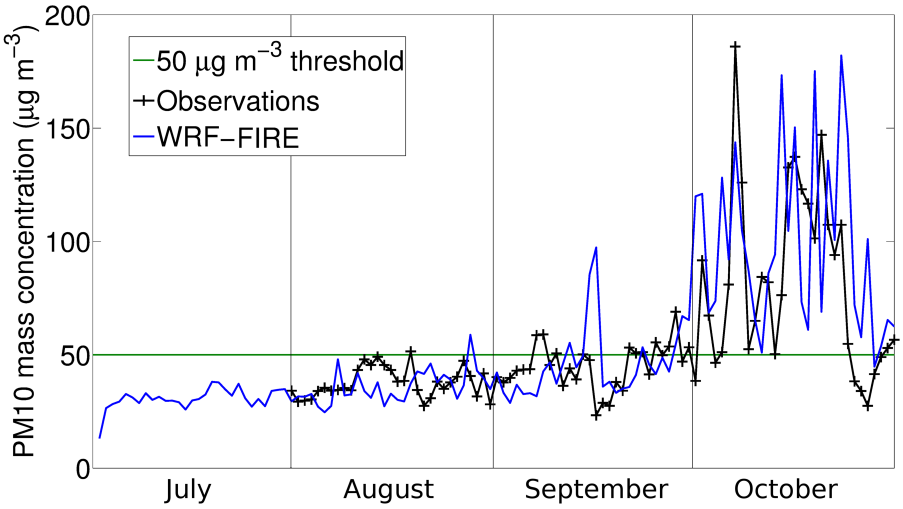

Fig. 2. 24 h averaged aerosol mass concentration observed (in black crosses) and modelled (in blue line) over Singapore for the year 2006. The 50 $\mu g\,m^{-3}$ indicates the WHO definition of polluted air.

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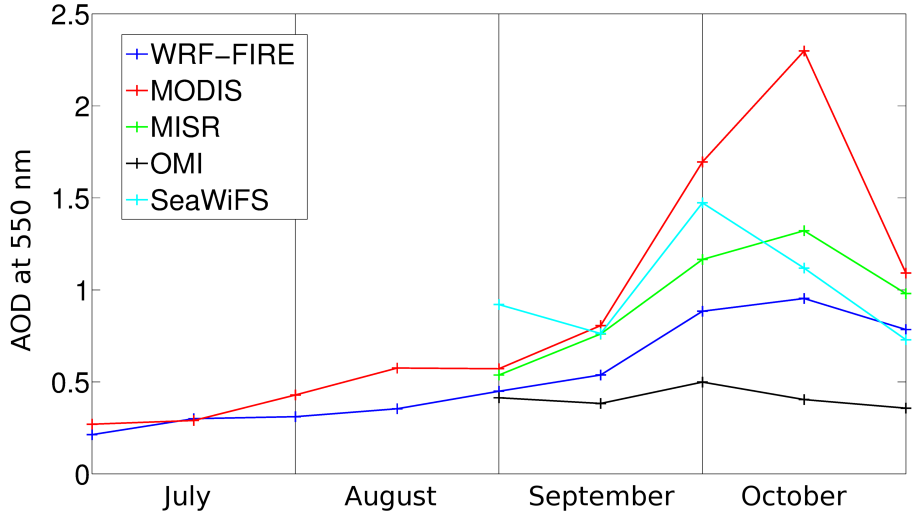

Fig. 3. WRF-Chem modelled Aerosol Optical Depth (AOD) and AOD observed by MODIS, MISR, OMI and SEAWIFS. AOD values are averaged over the 1° × 1° area centered over Singapore for the year 2006.

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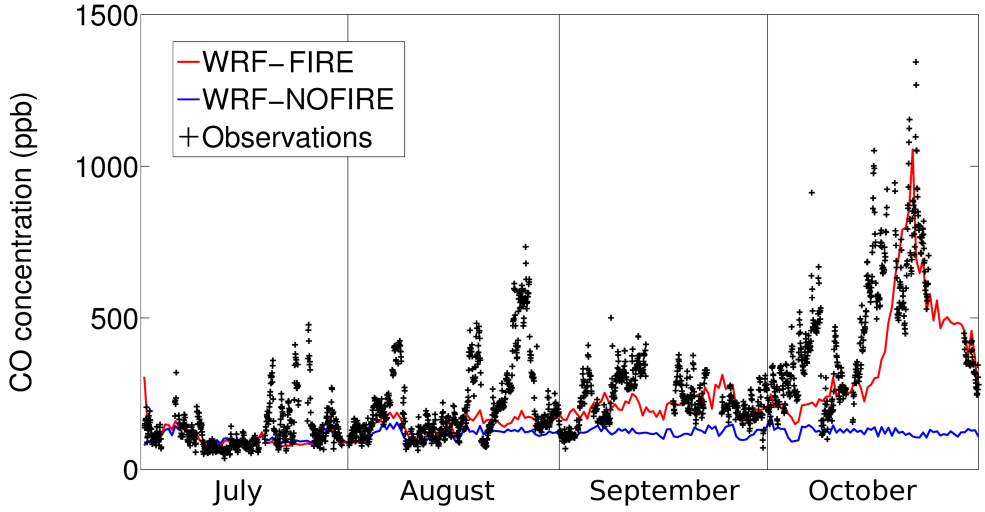

Fig. 4. CO concentration observed (in black crosses) and modelled with WRF-Chem either with fires (red) or without (blue) over Bukit Kototabang for the year 2006.

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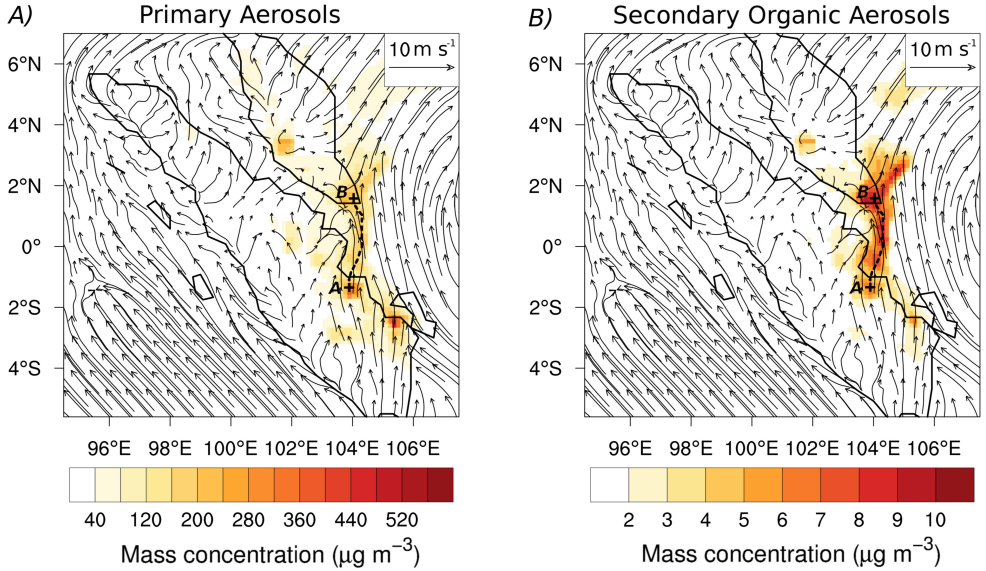

Fig. 5. (A) Primary aerosol mass concentrations with values higher than 10 µg m^{-3} and **(B)** secondary organic aerosol mass concentrations with values higher than 1 µg m^{-3} at the surface level on 3 October 2006 at 12:00 LT. The wind speed vectors are overlaid in white arrows.

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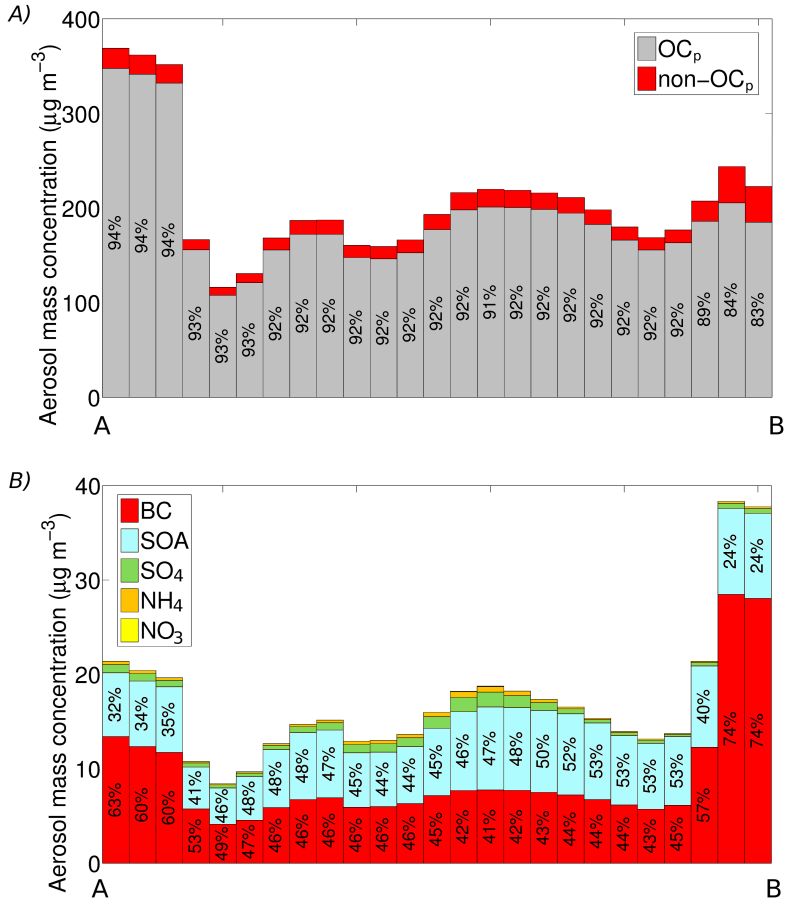

Fig. 6. Aerosol mass composition evolution from point A to point B in Fig. 5 with **(A)** showing the primary organic carbon vs. non primary organic carbon speciation, and **(B)** details the non primary organic aerosol composition.

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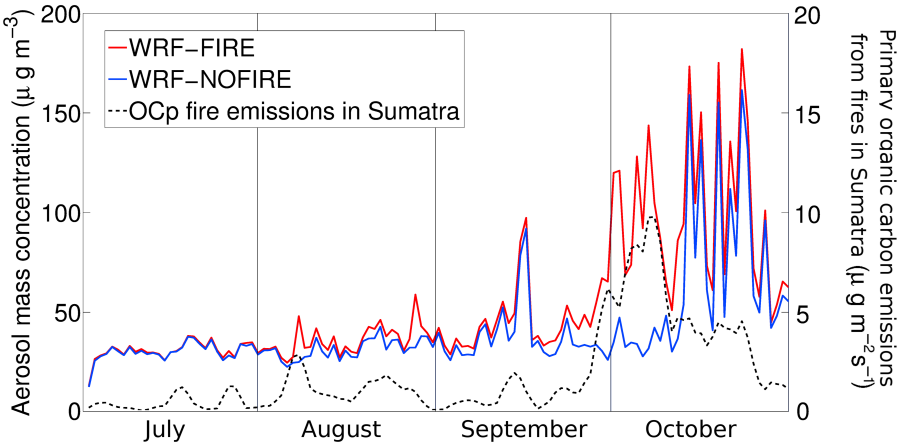

Fig. 7. Aerosol mass concentrations from the simulations WRF-FIRE (red line) and WRF-NOFIRE (blue line) in Singapore for our study period in 2006. The fire emissions of primary organic carbon aerosols in Sumatra are also drawn in dashed black line.

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