Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

Atmospheric Chemistry and Physics
Open Access
Discussions

Haze in Singapore - Source Attribution of Biomass Burning from Southeast Asia

Ayoe Buus Hansen[1], Wei Ming Chong[2], Emma Kendall[1], Boon Ning Chew[2], Christopher Gan[2], Matthew Craig Hort[1], Shao-Yi Lee[2], and Claire Suzanne Witham[1]

[1]Met Office, Exeter, UK
[2]Meteorological Service Singapore, Singapore

Correspondence to: Dr. A. B. Hansen (Ayoe.Hansen@metoffice.gov.uk)

Abstract. This paper presents a study of haze in Singapore caused by biomass burning in Southeast Asia over the six year period from 2010 to 2015, using the Lagrangian dispersion model, NAME.

The major contributing source regions are shown to be Riau, Peninsular Malaysia, South Sumatra, and Central and West Kalimantan. However, we see differences in haze concentrations and variation in the relative contributions from the various source regions between monitoring stations across Singapore, as well as on an inter-annual timescale. These results challenge the current popular assumption that haze in Singapore is dominated by emissions/burning from only Indonesia. It is shown that Peninsular Malaysia is a large source for the Maritime Continent off-season biomass burning impact on Singapore.

As should be expected, the relatively stronger Southeast monsoonal winds that coincide with increased biomass burning activities in the Maritime Continent create the main haze season from August to October, which brings particulate matter from several and varying source regions to Singapore. In contrast, atypical haze episodes in Singapore are characterised by atypical weather conditions, ideal for biomass burning, and emissions dominated by a single source region (for each event). The two most recent atypical haze events in mid 2013 and early 2014 have different source regions, whereas a different set of five regions dominate as major contributing source regions for most of the recent ASO haze seasons.

Haze in Singapore varies across year, season, and location it is influenced by local and regional weather, climate, and regional burning. The study shows that even across small scales, such as in Singapore, variation in local meteorology can impact concentrations of particulate matter significantly, and emphasises the importance of the scale of modelling both spatially and temporally.

1 Introduction

Biomass burning is a global phenomenon, it is an ancient practice of human occupation and a natural process which modifies Earth surface characteristics (Pereira et al., 2016). The haze from biomass burning impacts human health (Crippa et al., 2016; Sigsgaard et al., 2015; Youssouf et al., 2014; Reddington et al., 2015), crops, climate, bio-diversity, tourism, and agricultural production (Jones, 2006), and also aviation and marine navigation through visibility degradation(Crippa et al., 2016; Lee et al., 2016b).

Though haze occurs in Singapore (Hertwig et al., 2015; Lee et al., 2016b; Nichol, 1997, 1998; Sulong et al., 2017), it is not caused by activities within Singapore, rather it is a transboundary problem caused by biomass burning across the wider region (Fig. 1), which occurs during distinct 'burning seasons'. Though the popular press often attribute peatland destruction and related haze in the region to Indonesia (Reid et al., 2013), the haze cannot be attributed to one region alone. To mitigate this the Association of Southeast Asian Nations (ASEAN) Haze Agreement has been formed between the Southeast Asian nations to reduce haze and mitigate the related impacts using a scientific approach (Nazeer and Furuoka, 2017; Lee et al., 2016a).

Considerable inter-annual variation in biomass burning and related emissions of particulate matter (PM) in Southeast Asia is due to a combination of variation in El Niño Southern Oscillation (ENSO) (Fing, 2012) and anthropogenic land-use changes (Field et al., 2009; Shi and Yamaguchi, 2014).

The Met Office (MO) and the Meteorological Service Singapore (MSS) have previously established a haze forecast system to predict haze in Singapore (Hertwig et al., 2015). This study advances the previous work to improve our understanding of haze and the underlying causes by analysing and attributing haze events of the recent past to their sources. Several previous studies have looked at attributing air pollution across the world. Source attribution can be performed both through modelling and by looking at observations of air pollution in detail. For example, Heimann et al. (2015) carried out a source attribution study of UK air pollution using observations to distinguish between local and regional emissions, whereas, Redington et al. (2016) estimated the source of annual emissions of particulate matter from the UK and EU, by using the NAME model to look at threshold exceedences and episodes. In Southeast Asia, Reddington et al. (2014) used an Eulerian model to study haze and estimated emissions through a bottom up approach and source apportionment has been applied by Lee et al. (2017) and Engling et al. (2014) for studies of biomass burning related degradation of air quality and visibility.

Haze concentrations in Singapore vary throughout the six year period from 2010 to 2015 and even though biomass burning contributes to (low) PM_{10} concentrations in Singapore throughout large parts of the year, some peaks in the PM_{10} observations can be explained by haze almost exclusively. In the six year period, haze occurs almost annually during the season of August, September, and October (ASO), known as the haze season. Haze events occurring during other periods of the year are referred to as atypical or off-season haze. In 2013 and 2014 two unique atypical haze events occurred in June and in February, March, April (FMA), respectively (Hertwig et al., 2015; Gaveau et al., 2014; Duc et al., 2016). These events caused extremely high PM_{10} concentrations in Singapore, and raise the question of whether high concentrations of, or long term exposure to, PM which has the most significant health impacts.

The weather and climate in Singapore is dominated by monsoon periods and influenced by the variations of the El Niño Southern Oscillation (ENSO), such as the El Niño Modoki which influences temperatures in the central equatorial pacific (Ashok et al., 2007; Yeh et al., 2009; Reid et al., 2012; Yuan and Yang, 2012). Meteorologically, the year in Singapore is split into four seasons, two monsoon seasons separated by two inter-monsoon seasons: the north-east monsoon season is generally from December to early March, the first inter-monsoon period from late March through May, the south-west monsoon from June through September, and the second inter-monsoon period in October and November (Fing, 2012). Between years, there is large variability in the onset of the monsoon over Mainland Southeast Asia (Zhang et al., 2002). Generally, the inter-monsoon periods are characterised by light and variable winds, influenced by land and sea breezes with afternoon and early evening thunderstorms. The later inter-monsoon period is often wetter than the earlier inter-monsoon period. Furthermore, the inter-monsoon periods with weaker winds lead to air arriving in Singapore originating from the countries immediately west of and surrounding Singapore. Previous studies have shown the importance of the ENSO in relation to reduction in convection and precipitation over the Martime Continent (MC) and corresponding increase in haze in Southeast Asia (Ashfold et al., 2017; Inness et al., 2015; Reid et al., 2012). The ENSO conditions have varied significantly during the six year period. During 2010, the conditions transitioned from a moderate El Niño to a moderate La Niña lasting through 2011. From 2012 to 2014 the ENSO conditions were neutral transitioning to very strong El Niño conditions in 2015, which lasted into 2016 (NOAA, 2017). In terms of biomass burning, the year in this region can be divided into seasons that relate to the monsoon seasons: February, March, and April (FMA) is dominated by burning in Mainland Southeast Asia, during May, June, and July (MJJ) burning starts in northern Sumatra and traverses southward, ASO is characterised by burning in Southern Kalimantan and, in general, there is little or no burning influencing Singapore in November, December, and January (NDJ) (Campbell et al., 2013; Chew et al., 2013; Reid et al., 2012, 2013).

From annual weather reports by MSS (NEA, 2017), unusual weather events from 2010 to 2015 and related haze events are linked. In 2010 a prolonged Madden-Julien Oscillation (MJO) dry phase caused a dry October, creating ideal conditions for biomass burning in the region and related haze in Singapore. 2011 began as an ENSO neutral year transitioning to La Niña, with dry conditions in early September and prevailing low level winds bringing PM_{10} from biomass burning in central and southern Sumatra. During the Southwest monsoon of 2012, an MJO dry phase created dry and ideal haze conditions in September. In June 2013 a typhoon (Gaveau et al., 2014) coincided with major atmospheric emissions from peat fires in Southeast Asia. 2014 experienced haze during another intense MJO dry phase and drought, described by Mcbride et al. (2015). 2015 was the joint warmest year (with 1997 and 1998) and second driest year on record. ASO 2015 saw the worst haze in recent history in Singapore (Huijnen et al., 2016; Crippa et al., 2016; Koplitz et al., 2016), caused by southwest/southeasterly winds and fires in Southern and Central Sumatra and Southern Kalimantan. Fire carbon emissions over maritime South-East Asia in 2015 were the largest since 1997 (Huijnen et al., 2016). This paper links meteorology, biomass burning, and dispersion modelling to study how the origin of haze have varied across Singapore during this whole period.

The paper is composed as follows: Sec. 2, describes the methods used in the study and Sec. 3 presents an overview of emissions, air history, and validation, along with a more detailed study of atypical haze events in Sec. 3.1 and 3.2. The results and related implications are discussed in Sec. 4 and the paper is concluded by Sec 5.

2 Methods

This section describes how the model was set up and the input used for the simulations. Individual simulations using the Lagrangian dispersion model, NAMEIII v6.5 (Jones et al., 2007) were performed for each of the years from 2010 to 2015 for PM_{10} in a setup similar to that of the haze forecast described in Hertwig et al. (2015) including wet and dry deposition. The domain considered covers 14°S - 23°N and 90°E - 131°E. Archived meteorology from the global version of the Met Office Unified Model (UM) (Davies et al., 2005) was used to drive the NAME. Throughout the period the dynamical core and spatial resolution of the UM have changed, however, always resolving Singapore as a part of the Malaysian Peninsula, from ∼40 km over ∼25 km to ∼17 km resolution., some of those upgrades are described in Walters et al. (2011, 2017). As discussed in Redington et al. (2016) and Hertwig et al. (2015), the uncertainties from the meteorological data feed into the dispersion simulation. The emissions used were calculated from the Global Fire Assimilation System (GFAS, Kaiser et al. (2012)) v1.2 daily gridded fire radiative power (FRP) and injection height (IH) products, integrated with high resolution land-use data and emission factors in an approach aimed at combining the benefits of the MSS and GFAS v1.2 source approaches described in Hertwig et al. (2015). Additionally, the land cover map used has been updated to the 2015 version by Miettinen et al. (2016b), which now covers the entire Southeast Asia region, as compared to the earlier 2010 version (Miettinen et al., 2016a). The horizontal dimensions of the emissions were dx=dy=0.1°, and were released at varying heights based on the GFAS injection height information. Using the Lagrangian nature of the model, all emissions are tagged with source information to allow for assessment of contributing source regions and relative contributions. The choice of the GFAS data set as basis for the source calculation was based on the need for daily emissions, as in the operational setup of Hertwig et al. (2015), and the good agreement of this with observations and consistency with the GFED data set documented previously, e.g., Kaiser et al. (2012) and Rémy et al. (2017).

For this study, 29 source regions have been defined to better distinguish where the PM_{10} from biomass burning originated from (see Fig 1). Given the Lagrangian nature of the NAME model, it is possible to label and follow each emitted pollutant with its source location. This in turn enables us to attribute the PM_{10} concentrations at specific locations in Singapore to the individual source regions. Some 20 observation sites are located across Singapore, of these, one eastern and one western station have been chosen for best representation of trans-boundary PM_{10} concentrations across the main island of Singapore. In this analysis, the western station, Nanyang Technological University (NTU), is located relatively close to the industrial western part of Singapore and the eastern station, Temasek Polytechnic (TP), is placed next to the polytechnic but is also near open fields and a water reservoir.

The following analysis is based on hourly PM_{10} observations and modelled time series at the two selected monitoring stations. Annual and seasonal pie charts showing the percentage contribution from each source region at each monitoring station have been produced, to capture the spatial variation of biomass burning across the island. During the period considered, several haze events occurred in Singapore.

To validate the model results, four performance metrics have been calculated. These evaluate each species at the two monitoring stations for each year and select seasons in each of the six years with available observations. The observations used are hourly PM_{10} measurements from the National Environment Agency, Singapore. The metrics considered are the Pearson correlation coefficient (R), i.e., the correlation between the model and observations used to get an indication of the match between patterns in the modelled and observed time series; the modified normalised mean bias (MNMB) which assesses the bias of the forecast and can have values between -2 and +2; the fractional gross error (FGE) which gives the overall error of the model prediction and is limited between 0 and +2 (Ordóñez et al., 2010; Savage et al., 2013); and finally, Factor of 2 (FAC2) which gives an indication of the fraction of the model results that fall within a factor 2 of the observations (Hertwig et al., 2015). Because the emissions used are at a daily resolution as compared to the hourly observations of PM_{10}, a possible gap

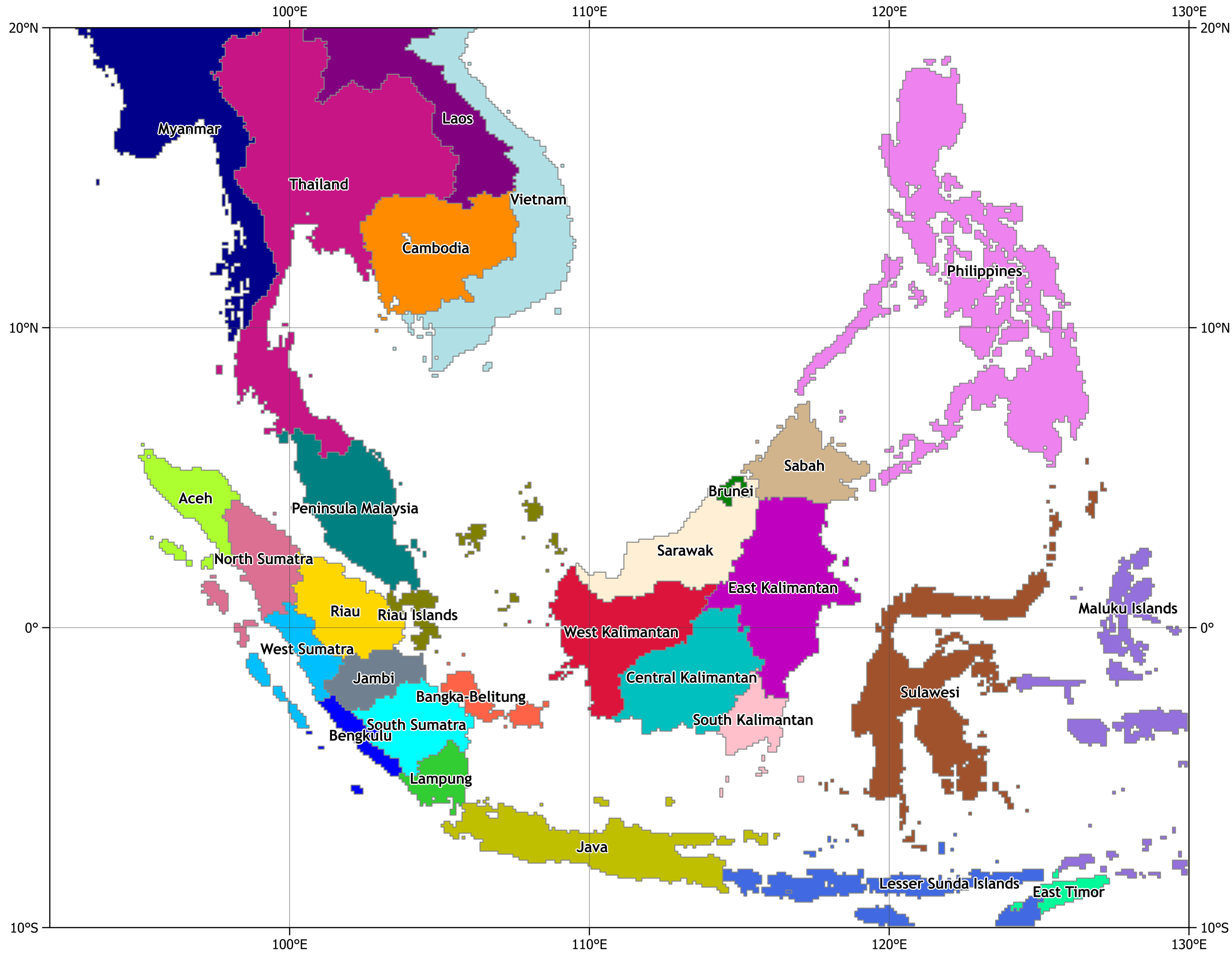

Figure 1. Locations and colour codes used for each of the 29 biomass burning source region within the domain from 10°S - 20°N and 90°E - 130°E considered in this study. Singapore is located south of Peninsular Malaysia and East of Riau.

or mismatch in timing of peak concentrations between modelled results and observation time series is possible. Bias between modelled time series and the observations are expected as some fires will be missed due to the fact that they are too small for the satellites to register and the extent and/or duration of the other fires are over or under estimated due to cloud cover (Kaiser et al., 2012; Reid et al., 2013; Campbell et al., 2016).

Air history maps are able to provide an indication of where air at a given location has originated from. Fig. 2, illustrates an air history map for Singapore for 2010 - 2015. This helps determine the regions that influence the composition of the air in Singapore. NAME backruns were conducted using the UM global NWP model, with PM_{10} as a tracer within a domain of

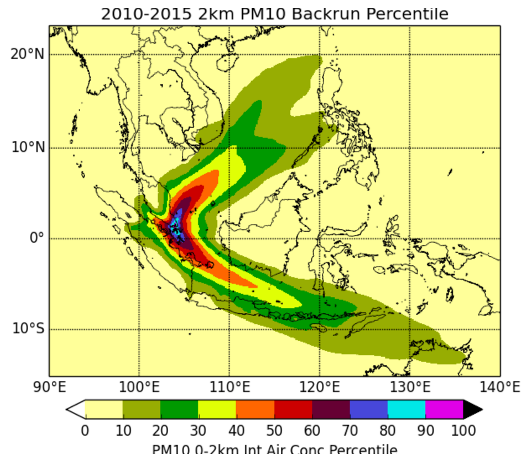

Figure 2. Air history map for 2010 - 2015, showing where air arriving in Singapore during this period originated from. The backruns shown were conducted from a receptor site in central Singapore. Comparison between a coastal receptor site and this inland site showed insignificant variation, meaning that the central receptor site can be considered representative for the whole island.

90.0°E, 140.0°E, 15.0°S, 23.0°N (Fig. 2). Wet and dry deposition are both turned on to simulate actual scenarios during the modelled time periods. Concentration values in the 0-2km layer were integrated at 10 minute time steps up till 10 days previous. The emission rate was set at a unit 1 g/s and emitted over 24 hours. A 10-day backrun was conducted for every single day in the six year time period from 2010 to 2015. The resulting10-day back air concentration for each day's run was summed for each analysis period and a percentile value calculated to ascertain the likelihood of air originating from a particular geographical area vis-à-vis other areas. The percentile is derived by taking a fractional contribution of each grid point ($0.1° \times 0.1°$) concentration value as compared to the total concentration present in the entire model domain. The fractional concentration contribution of all the gridpoints were then arranged in ascending order and cumulatively summed and each 10 % band is shown in Fig. 2.

3 Results

The air history map in Fig. 2 shows that most air arriving in Singapore has travelled from either the northeast or southeast directions, illustrating the two monsoon seasons experienced in Singapore. The northeastern component of the bifurcation in the wind pattern is representative of the northeast monsoon in FMA, and the southeastern "fork" shows the southeast monsoon period during ASO. During the six years represented by the figure, significant variation occurs during the individual years (see Fig. A2). In 2010 winds were quite weak and the air arriving in Singapore mainly came from a north-easterly direction and did not show the expected "fork" from the two monsoon seasons. This means that the air impacting Singapore that year mainly traversed through countries and regions very near to or east of Singapore, e.g., the Philippines, Peninsular Malaysia, Riau, and Riau Islands. The air history map for 2011 shows a clear bifurcation, with air arriving from northeast and southeast, as expected from the two monsoon seasons. The air arriving in Singapore is therefore likely to have originated from Vietnam, Cambodia, all areas of Kalimantan, Java, and the island of Sumatra including Riau. During 2012 the northeasterly wind component was significantly weaker than average, also a small northwesterly component is visible in the air history map (not shown here). This means that air was mainly coming from the expected directions given the monsoons in the region with a small additional northwesterly component, so most air arriving in Singapore will have travelled through Peninsular Malaysia, or the island of Sumatra including Riau. During 2013, the same general pattern as 2012 is seen but with stronger northeasterly and westerly components and somewhat weaker southeasterly component. The air history maps show a very small region of influence for the MJJ season of 2013. The majority of air arriving in Singapore had travelled through Peninsular Malaysia or Riau. During the event of June 2013, a typhoon northeast of Singapore pulled air from westerly directions over Singapore (Gaveau et al., 2014; Hertwig et al., 2015). During other seasons of this year the air in Singapore arrived from as far away as Vietnam and the Philippines. 2014 was characterised by strong northeasterly and southeasterly components, both of which were stronger than those for 2013 and stronger southeasterly component compared to 2012. The air history map for 2015 shows a strong northeasterly component and the strongest southeasterly component of all six years, these winds brought air from Peninsular Malaysia, Riau and Islands, Sumatra, Kalimantan, Sulawesi, Java, and the Lesser Sunda Islands to Singapore.

Analysis of the annual PM_{10} emissions, see Fig. 3, shows that there is a very similar bimodal pattern in the seasons/months with significant burning and also in the dominant source regions, similar to that of Reddington et al. (2014) but hugely varying and with different temporal distribution. The most significant difference between the six years is in the magnitude of burning, note the different scales of vertical axis. Overall, 2015 and 2014 were the years with the highest and second highest annual ($\sim 6.7 \times 10^6$ T and $\sim 4.2 \times 10^6$ T) and monthly ($\sim 2.7 \times 10^6$ T, October 2015 and $\sim 1.1 \times 10^6$ T, March 2014) emissions, respectively. 2010 and 2011 saw the lowest annual emissions ($\sim 2 \times 10^6$ T), though 2010 saw the third highest emissions when looking at individual months ($\sim 8.5 \times 10^5$ T, March). 2012 and 2013 saw fairly similar emissions ($\sim 2.5 \times 10^6$ T), which supports the fact that emissions are lower during La Niña and ENSO neutral conditions.

Over the six years, the highest emissions were generally seen during El Niño years and the drought of 2014. This makes sense as the majority of the fires are expected to be anthropogenic, and dry weather provides ideal conditions for initiating and maintaining burning (Reid et al., 2012, 2013). Lee et al. (2016b) looked at fire seasons and saw that there is anti-correlation between seasonal variation of fire emissions and that of rainfall, which is likely to be because underground peatland burning may not be immediately extinguished by precipitation. This also supports other papers, e.g., Reddington et al. (2014) who looked at fire/smoke seasons during the period 2004-2009 and found burning peaked from June to October and February to March, with the most burning during September - October.

Observations of PM_{10} in Singapore from 2010 - 2015 show an overall background concentration of approximately 20 - 30 $\mu g/m^3$. These values fit well with those determined in other studies for Singapore, for example Hertwig et al. (2015) estimated background concentrations for PM_{10} to be around 30 $\mu g/m^3$, based on the 2013 haze episode. In general, both background and peak concentrations vary between NTU and TP. Here we assume a constant background of 25 $\mu g/m^3$ for the PM_{10} observations at both sites, but because we are intentionally leaving out sources of PM_{10} other than biomass burning and there is uncertainty in the biomass burning emissions, we cannot expect perfect scores from the valuation metrics presented in Tables 1 and 2. In the present study a significant haze event has been defined as any period lasting more than one week with

Table 1. Statistics for PM_{10}, for both monitoring stations and all years. Background concentration of 25 $\mu g/m^3$ is subtracted from the observations for all stations for all years.

	2010		2011		2012		2013		2014		2015	
	NTU	TP	NTU	TP	NTU	TP	NTU	TP	NTU	TP	NTU	TP
R	0.12	0.12	0.08	0.13	0.17	0.18	0.79	0.80	0.27	0.35	0.44	0.43
MNMB	0.14	0.17	0.10	0.11	0.09	0.05	0.04	0.12	-0.09	0.07	-0.19	0.01
FGE	0.39	0.45	0.37	0.35	0.39	0.37	0.37	0.38	0.36	0.36	0.44	0.43
FAC2	0.83	0.76	0.85	0.86	0.83	0.85	0.84	0.83	0.86	0.87	0.78	0.79

Table 2. Statistics for PM_{10}, for both monitoring stations, for selected haze seasons. Background concentration of 25 $\mu g/m^3$ is subtracted from the observations for all stations for all years.

	2010		2011		2012		2013		2014		2014		2015	
	ASO		ASO		ASO		MJJ		FMA		ASO		ASO	
	NTU	TP	NTU	TP	NTU	TP	NTU	TP	NTU	TP	NTU	TP	NTU	TP
R	0.15	0.14	0.08	0.15	0.14	0.14	0.81	0.83	0.30	0.42	0.29	0.40	0.35	0.32
MNMB	0.12	0.13	-0.07	-0.01	-0.24	-0.22	-0.14	0.03	-0.13	-0.07	-0.31	-0.06	-0.65	-0.47
FGE	0.41	0.49	0.38	0.34	0.40	0.38	0.40	0.43	0.29	0.30	0.35	0.36	0.71	0.61
FAC2	0.80	0.72	0.86	0.87	0.83	0.84	0.82	0.78	0.93	0.93	0.76	0.86	0.49	0.60

modelled PM_{10} concentrations from biomass burning reaching 50 $\mu g/m^3$ or above at at least one of the monitoring stations. Concentrations below 10 $\mu g/m^3$ are considered negligible in terms of haze events.

For years like 2013, that are dominated by one extreme haze event, the correlation between the modelled time series and the observations is very high (Table 2). To some extent, this is also the case for the 2014 and 2015 events. Whereas the correlations for 2010, 2011, and 2012 are very low, which is likely to be due to the low biomass burning PM_{10} emissions and few haze events. In general it can be seen from the MNMB that the model under predicts, even when taking a constant background value of 25 $\mu g/m^3$ into account. This makes sense as the background in reality cannot be assumed to be constant, we know that we are not capturing all fires, which will lead to a negative bias, and there are further uncertainties in emissions, and the NWP and dispersion models. It should be expected that not all model results fall within a factor of 2 of the observations and it is not surprising that the fractional gross error is around 40 %. When comparing the scores to other studies such as Chang and Hanna (2004) and Rea et al. (2016), it is important to keep in mind that even though the scores presented in Tables 1 and 2 are relatively lower (specifically R) these statistics are calculated for a three month period and compared studies of periods covering a couple of days or 1 - 2 weeks, respectively, also the FAC2 is mostly better for the results presented here. In the discussions of the results below, the estimated background value of 25 $\mu g/m^3$ has been subtracted from all observations.

Looking at PM_{10} concentrations at the two monitoring sites (Fig. 4), five years (all but 2013) have haze during ASO and three years (2011, 2013, and 2014) have haze in FMA. 2013 is the only year with significant haze in June, although the years 2012 to 2015 all experience some additional PM_{10} from biomass burning in June. When comparing concentrations between the two stations it can be seen that the concentrations are higher at the western monitoring station most of the time. The opposite, concentrations at the eastern monitoring stations being higher than at the western station, was the case during March in 2011 and 2014. Of the haze events that occurred from 2010 through 2015, some were insignificant (e.g., during FMA 2010, 2012, 2013, and 2015, and MJJ 2012 and 2014), some were significant but showed very little variation between monitoring stations (ASO 2010, MJJ 2013, FMA 2011 and 2014) (Sec. 3.1) the remaining four events (ASO 2011, 2012, 2014, and 2015) (Sec. 3.2), were significant events, though, with variation in the main contributing source regions at the two monitoring stations. Common for all four events is that they occurred during the haze season in ASO during the southeast monsoon, when the winds are the strongest for the region and the air history maps show the largest region of influence for air arriving in Singapore. Not all peaks in the observations coincide with biomass burning due to real PM levels also containing anthropogenic and other biogenic species, however, most peaks in the modelled time series coincide with peaks in observations.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

Atmospheric Chemistry and Physics Discussions
Open Access
EGU

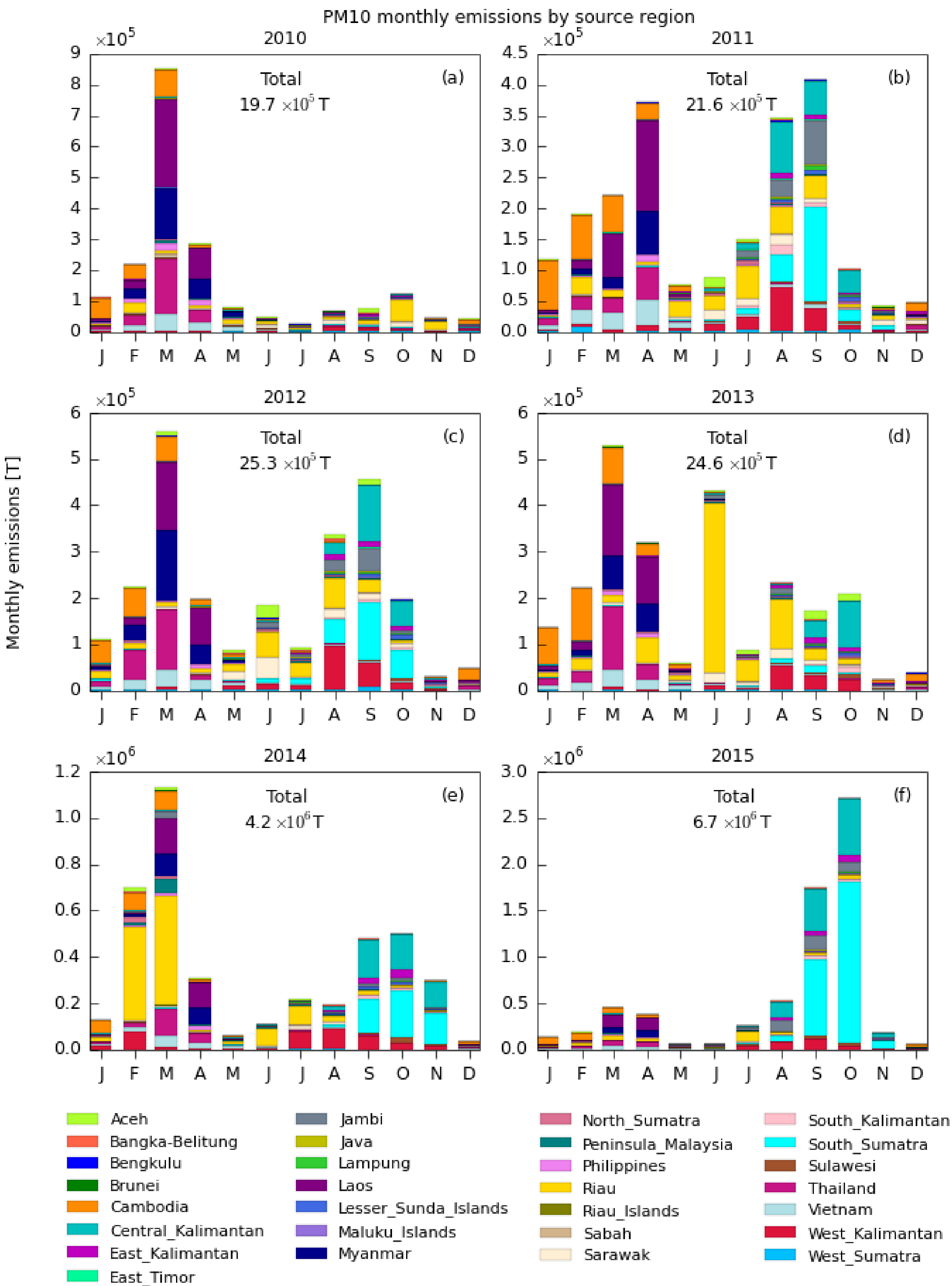

Figure 3. Caption on next page

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

Atmospheric Chemistry and Physics
Discussions

Figure 3 (Continued). Regional PM_{10} biomass burning emissions, calculated based on GFAS FRP and IH and emission factors described in Sec. 2, for each of the six years from 2010 to 2015, summed over each month. Colours for each source region for all years are listed below the plots. Note the different scales on the y-axis, units: tonnes emitted per month.

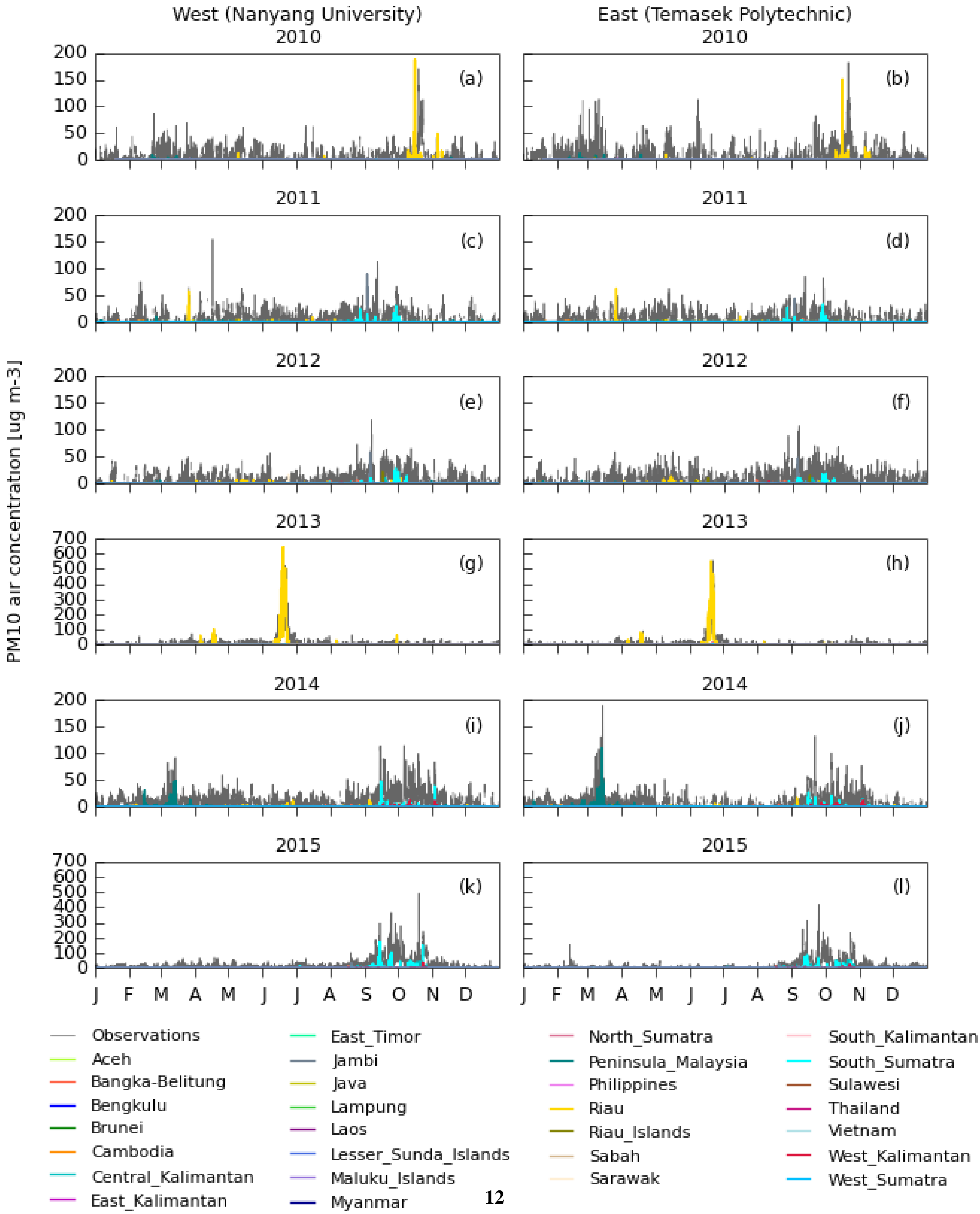

Figure 4. Caption on next page

Figure 4 (Continued). Modelled PM_{10} time series with observations (solid black line) at each of the two monitoring stations West (NTU, left) and East (TP, right) for the six years with observations available, 2010 (top row) - 2015 (bottom row). A constant background concentration of $25\mu g/m^3$ has been subtracted from the observations and any resulting negative values have been removed.
Note the different scales on the y-axis, units: $\mu g/m^3$

3.1 Atypical haze

During the six years, the most notable atypical haze events occurred in June 2013 and February 2014.

2013 was a very unique year, both in terms of meteorology and burning (Fig. 5), the event of 2013 was caused by a typhoon coinciding with intense burning in Riau during June (Fig. 3), in what was generally a year with weak winds and average burning. The air history map for MJJ in Fig. 5 shows that, during this weather event, there was a small source region with air arriving in Singapore from Peninsular Malaysia, Riau Islands, and Sumatra including Riau. This is the only year of this six year period with significant burning in June, though in general the annual emissions are neither especially high nor low. In June about 98 % of the modelled PM_{10} emissions reaching the two monitoring stations in Singapore were from Riau. The maximum modelled/observed concentrations in June reached 640/525 and 550/550 $\mu g/m^3$ at NTU and TP, respectively, as is seen from the time series in Fig 4. Although the peak concentrations observed at NTU were lower than those of the modelled time series, overall the concentrations are fairly similar during the event.

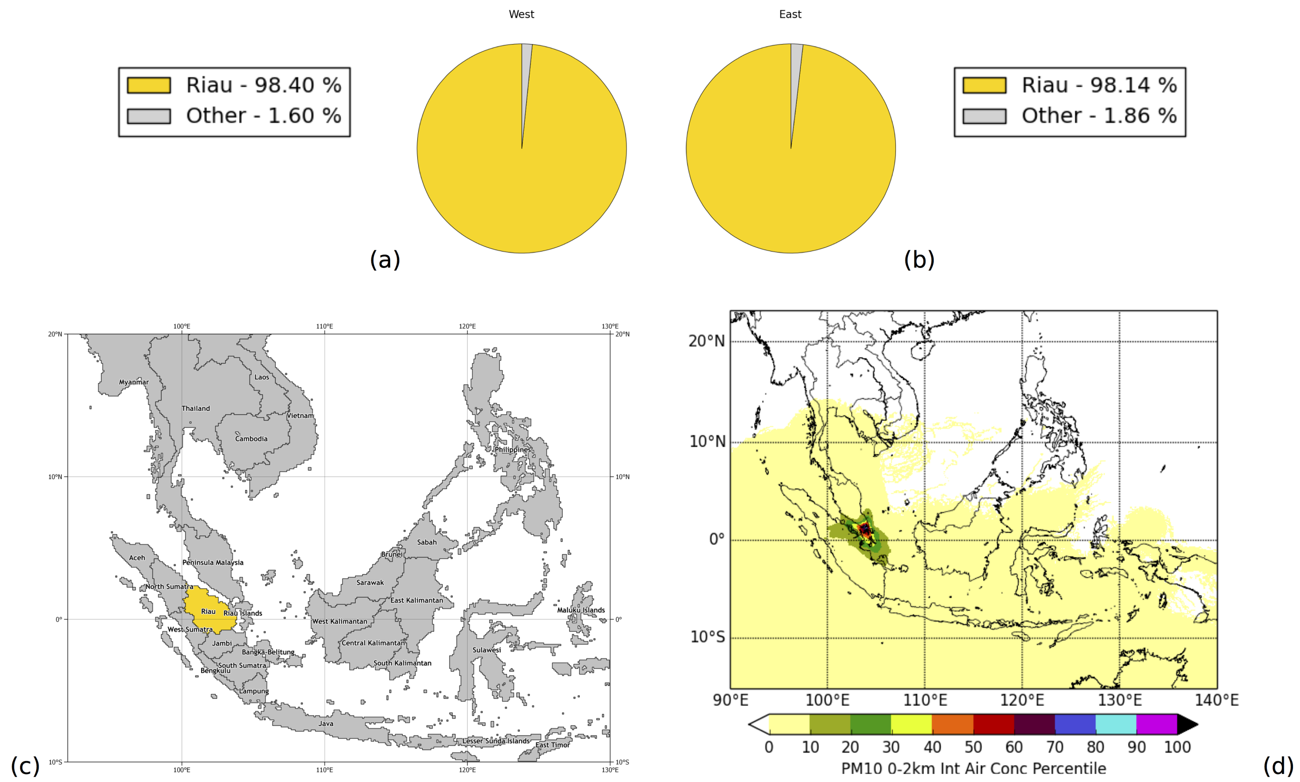

Figure 5. This figure shows results for PM_{10} for MJJ 2013: Pie charts for the western (NTU) (a) and eastern (TP) (b) monitoring stations showing major contributing source regions, (c) shows the regional map highlighting the major contributing source region, and the air history map (d) showing where the air arriving in Singapore originated from in MJJ 2013. The 'Other' category in the pie charts is the contributions from sources which individually contribute with less than 1 %.

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

Atmospheric Chemistry and Physics
Open Access
Discussions

In early 2014, a drought coincided with air arriving in Singapore from a northeasterly direction and intense burning in the whole region giving the second highest emissions of the six year period. This resulted in unexpected haze in Singapore in FMA (Fig. 6). The months with the largest emissions were March and February which were dominated by emissions from Riau, Laos, Myanmar, Thailand, Cambodia, Peninsular Malaysia, and West Kalimantan (Fig. 3). In general the region of influence for 2014 covered an area reaching far to the northeast and south-east and was much larger than for MJJ 2013. During FMA the winds brought air from Peninsular Malaysia, Riau, Riau Islands, and the Philippines to Singapore. The event saw modelled and observed PM_{10} concentrations of up to 50/100 $\mu g/m^3$ and 110/200 $\mu g/m^3$ at NTU and TP, respectively, i.e., concentrations at TP are about double of those at NTU for both the modelled time series and the observations. The event lasted for about 3 months total, and was dominated by Peninsular Malaysia, which contributed over 90 % of the haze at both monitoring stations, with smaller contributions from Riau, Cambodia, Vietnam, and Riau Islands.

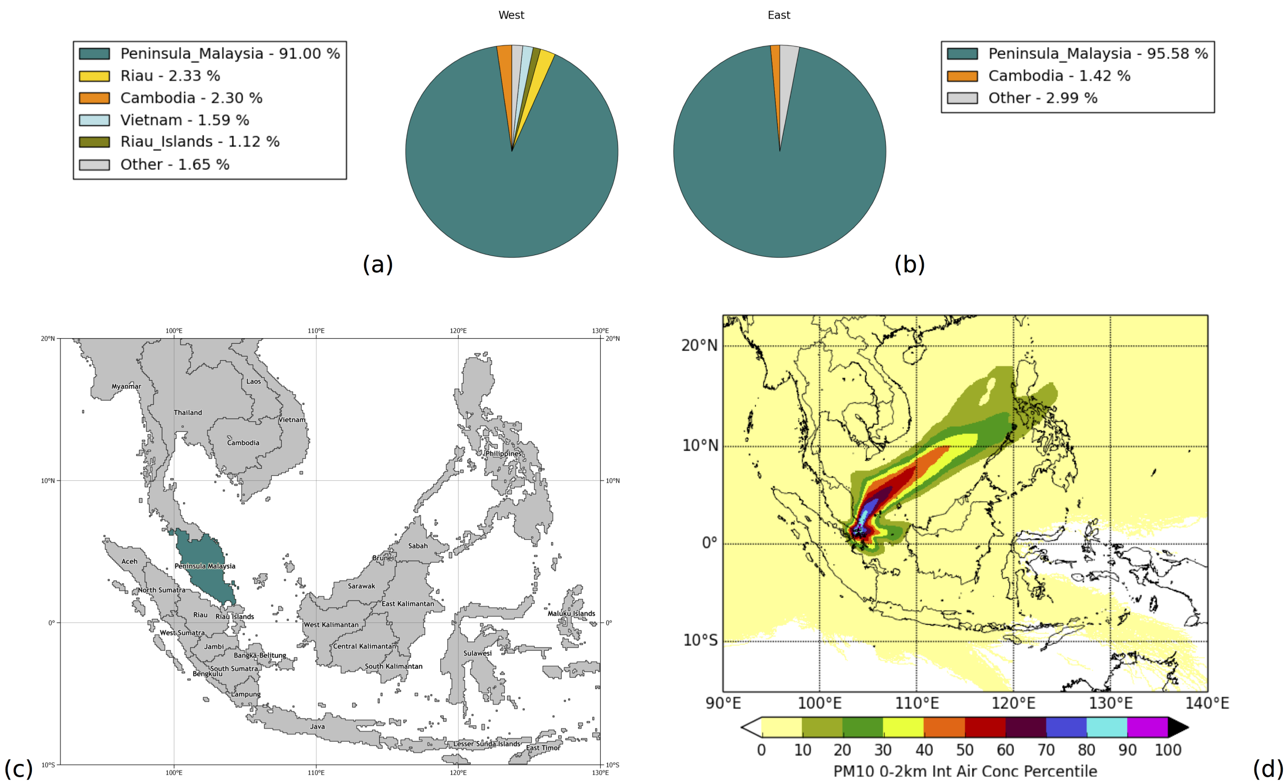

Figure 6. This figure shows results for PM_{10} for FMA 2014: Pie charts for the western (NTU) (a) and eastern (TP) (b) monitoring stations showing major contributing source regions, (c) shows the regional map highlighting the major contributing source region, and the air history map (d) showing where the air arriving in Singapore originated from in FMA 2014. The 'Other' category in the pie charts is the contributions from sources which individually contribute with less than 1 %.

Common for these two atypical haze events is little variation in the source regions across the monitoring stations, in spite of the atypical and different meteorological conditions, and the clear dominance of one source region.

3.2 Southeast monsoon season haze

The southeast monsoon season occurs during ASO and coincides with almost annual haze episodes. The two most recent episodes with highest concentrations were in 2014 and 2015.

In addition to the haze event in FMA 2014 discussed above, another haze event occurred in 2014 during ASO (Fig. 7). This season saw the largest southeasterly region of influence for air arriving in Singapore during the six year period, with air and PM_{10} from biomass burning pollution arriving from Peninsular Malaysia, Riau, Riau Islands, Kalimantan, Java, and the Lesser Sunda Islands, during a period of average biomass burning emissions. In September-October the major contributing source regions to PM_{10} concentrations in Singapore were Central Kalimantan, South Sumatra, and West Kalimantan. The event lasted about two months, and reached peak modelled and observed concentrations of about 50/120 $\mu g/m^3$ and 30/125 $\mu g/m^3$ at NTU and TP, respectively. ASO is the expected haze season, however, this is also one of the seasons with the highest number of significant contributing source regions: South Sumatra, Central Kalimantan, West Kalimantan, Bangka-Belitung, Riau, Riau Islands, and the Lesser Sunda Islands (around 2000 km from Singapore). In spite of the large annual variation (Fig. A3) in the major contributing source regions between the two monitoring stations, the difference between the relative contributions at the two stations for ASO 2014 is insignificant.

The plots for ASO 2015, Fig. 8, show a large, though seasonally "normal" region of influence, and this coincided with extreme emissions. In ASO the southeasterly monsoon winds brought air from Peninsular Malaysia, Riau Islands, Sumatra including Riau, Kalimantan, Sulawesi, Java, and the Lesser Sunda Islands. During this season the largest contributing regions were Central Kalimantan, South Sumatra, and West Kalimantan. The event lasted approximately 2.5 months, and peak modelled/observed concentrations reached over 200/500 $\mu g/m^3$ at NTU - the modelled concentrations up to twice as high as those at TP, where concentrations reached 100/425 $\mu g/m^3$. During ASO 2015 the biggest variation between the two monitoring stations of the year and any season with significant burning was seen. By monitoring station the most significant source regions at the western and eastern monitoring stations (NTU, TP) were South Sumatra (38.22 %, 21.82 %), Central Kalimantan (31.19 %, 41.45 %), Bangka-Belitung (11.32 %, 13.64 %), West Kalimantan (6.64 %, 9.41 %), and Jambi (6.53 %, 5.98 %). Common for ASO 2014 and ASO 2015, and also other years with burning and related haze during this season (e.g., 2011 and 2012), are the relatively large regions influencing PM_{10} concentrations in Singapore and the significant variation between monitoring stations.

In addition to the four events discussed in detail above, events also occurred during the expected haze season in ASO 2010, 2011, and 2012, as well as during FMA 2011. The ASO event in 2010 was, except for significantly lower magnitude, fairly similar to the MJJ event of 2013, with an unusually small source region for the season and at least 90 % of PM_{10} concentrations arriving at both monitoring stations in Singapore originating from Riau. The other two ASO events, in 2011 and 2012, were fairly similar to the events of 2014 and 2015 with contributions from the expected southeast monsoon region and a high number

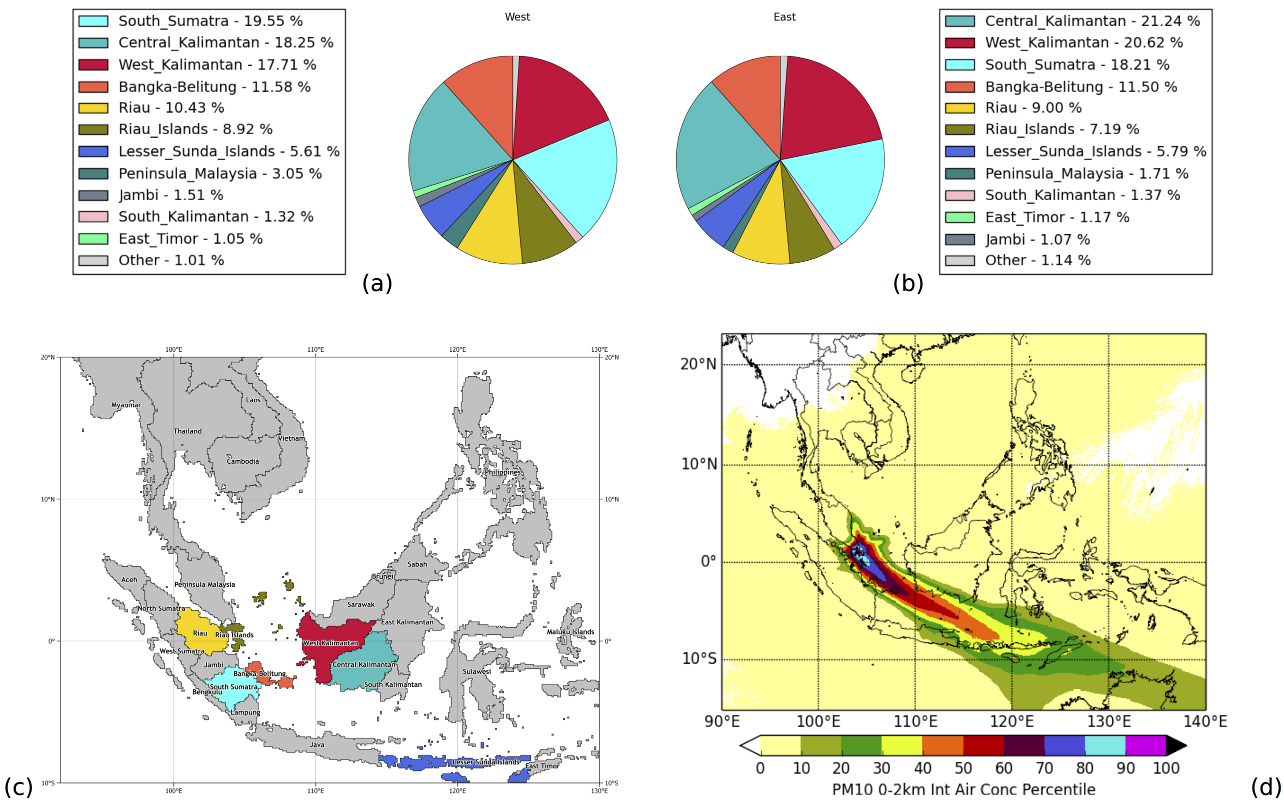

Figure 7. This figure shows results for PM_{10} for ASO 2014: Pie charts for the western (NTU) (a) and eastern (TP) (b) monitoring stations showing major contributing source regions, (c) shows the regional map highlighting the major contributing source regions, and the air history map (d) showing where the air arriving in Singapore originated from in ASO 2014. The 'Other' category in the pie charts is the contributions from sources which individually contribute with less than 1 %.

of contributing source regions at the two monitoring stations. The remaining event of the period was during FMA 2011, with Riau, Peninsular Malaysia, and Cambodia as major contributing source regions.

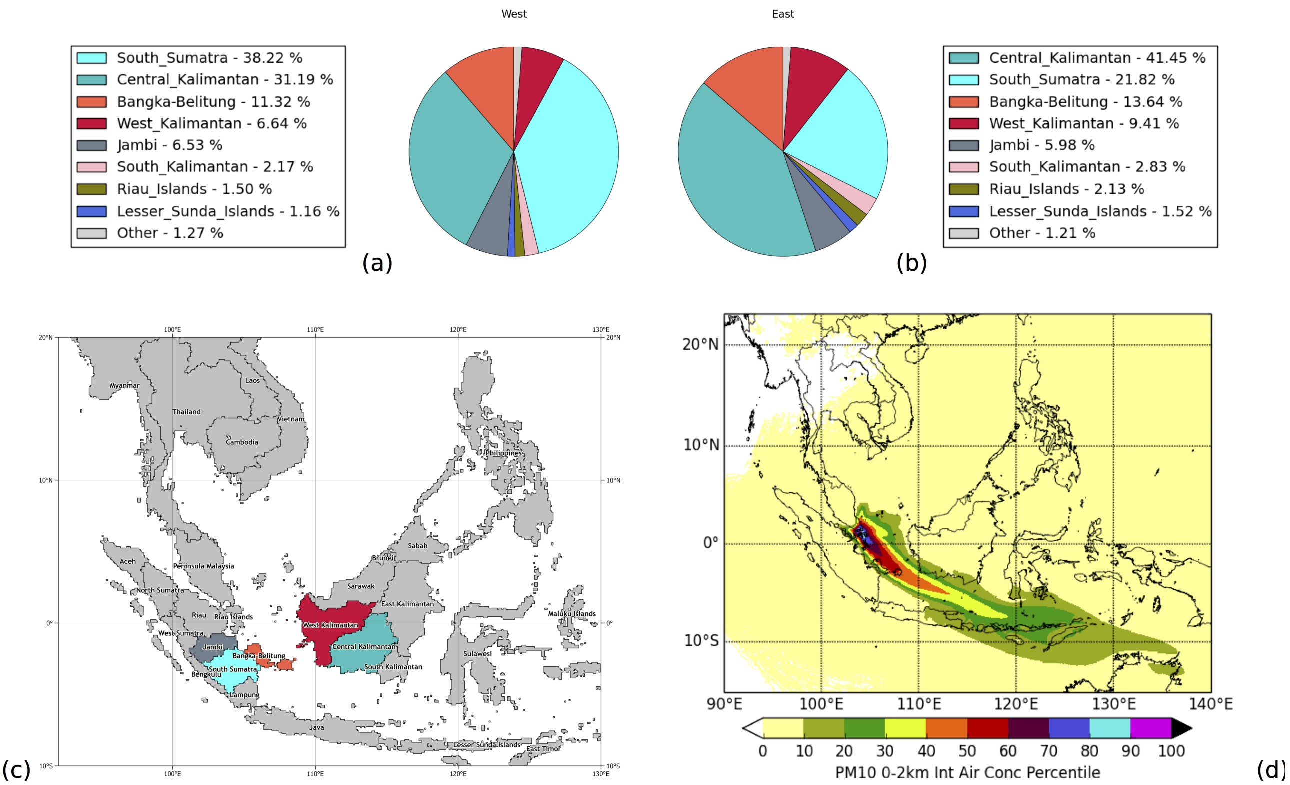

Figure 8. This figure shows results for PM_{10} for ASO 2015: Pie charts for the western (NTU) (a) and eastern (TP) (b) monitoring stations showing major contributing source regions, (c) shows the regional map highlighting the major contributing source regions, and the air history map (d) showing where the air arriving in Singapore originated from in ASO 2015. The 'Other' category in the pie charts is the contributions from sources which individually contribute with less than 1 %.

4 Discussions

For the seasons with the most significant haze events (e.g., MJJ 2013, FMA 2014, ASO 2014, and ASO 2015) in Singapore, the air history maps show that the region of influence for Singapore generally covers the largest area during ASO with air coming from southeasterly directions. Of the four years (2011, 2012, 2014, 2015) with haze events during ASO, 2014 saw the largest region of influence. Of the two years with events during FMA (2011 and 2014) the winds were generally from a northeasterly direction and 2014 was, again, the year influenced by the largest source region. For seasons with southeasterly winds, but not during ASO, e.g., 2012 MJJ, the region of influence is relatively small compared to that of ASO. Similarly to the results presented in Figure 3, Lee et al. (2016b) determined the source region for Singapore to be mainly Sumatra and Borneo (i.e., Kalimantan, Sarawak, Sabah, and Brunei), and Shi and Yamaguchi (2014) also saw that the biggest emitters include South Sumatra and South Kalimantan, showing that spring emissions mainly originate from Cambodia, Laos, Myanmar, Thailand, Vietnam, and on occasion Peninsular Malaysia, whereas, autumn burning is seen in Central Kalimantan, Jambi, South Sumatra, West Kalimantan, and to a lesser extent Aceh and East Kalimantan. Emissions from Riau vary significantly throughout the years and individual months, though there are emissions from Riau in most months during most years, which is consistent with the emissions shown in Fig. 3.

When comparing all years, the results show large variability in PM_{10} concentrations and major contributing source regions between years and ASO events. Common for the atypical haze events is little variation across monitoring stations in spite of the unique and different meteorological conditions. The biggest difference between both modelled and observed concentrations at the two stations were seen during FMA 2014 and ASO 2015, with highest concentrations at TP and NTU, respectively. Common for ASO 2014 and ASO 2015, and also for some of the other years with burning and related haze during this season, are PM_{10} contributions from a large area arriving in Singapore and related significant variation between monitoring stations. The results show that low emissions often lead to low concentrations that still affect the air quality in Singapore, and that a larger area of influence brings more variation between major contributing source regions at the two monitoring stations. The largest differences between monitoring stations are seen in the annual comparison of the major contributing source regions, the variation during ASO is likely due to the larger region of influence seen during the south-easterly monsoon, which brings air and PM_{10} from biomass burning from further away. In general there were often bigger differences in contributing source regions between the two monitoring stations when no significant haze events occurred in Singapore. Atypical events are often dominated by one and the same source region at both monitoring stations, whereas there is more difference between dominating source regions at the two monitoring stations for haze events during the expected haze seasons.

The yearly and seasonal variations in emissions of PM_{10} from biomass burning from the region are not always correlated with PM_{10} concentrations in Singapore, which shows that haze in Singapore is impacted by (1) burning emissions under human influence (e.g., Fig. 3), (2) the weather through the monsoon and related winds (Fig. A2), and (3) climate, especially the variations in ENSO, this also in line with the findings by Reid et al. (2012, 2013). As discussed by Hertwig et al. (2015), sources of uncertainty in these results originate from the emissions and the meteorology. For the former, the uncertainties result from the fact that the emissions used here are based on one daily snapshot of FRP and IH, and though some attempts are made

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

to solve issues caused by the lack of transparency of clouds the data will naturally be incomplete. At the same time, hourly emissions are calculated based on this one daily snapshot adding a temporal resolution that the data does not provide, which also means that peak concentrations won't always be captured in the model simulations. One significant source of uncertainty in atmospheric modelling is the meteorology. When considering the resolution of the analysis meteorology used here and the size of Singapore it is clear that there will be unresolved features in both topography and in the meteorology and hence in the dispersion modelling. The varying difference between observed and modelled time series is due to the many other sources of PM_{10} in Singapore. However, in spite of these uncertainties our results show that we are able to model dispersion of particulate matter from biomass burning in Southeast Asia and the resulting haze in Singapore with reasonable confidence.

5 Conclusions

In this study we have used the atmospheric dispersion model, NAME, to attribute PM_{10} concentrations in Singapore caused by biomass burning to their originating source region. In order to gain a deeper understanding of the causes of haze in Singapore we have compared air history maps, showing where air arriving in Singapore originates from, with modelled and observed PM_{10} concentrations at two monitoring stations located at a western and an eastern location, respectively. For those two monitoring stations we have also compared the difference between relative contributions from all of the source regions.

The concentrations and major contributing source regions at the two monitoring stations vary significantly both on a yearly and seasonal basis. The results show that haze caused by off-season/atypical burning often occurs during periods of low wind, which results in little variation in both source regions and in the relative contributions across the Singapore. However, the southeasterly monsoon wind creates ideal conditions for variation in contributing source regions and concentrations across Singapore, i.e., the larger region of influence during the "expected" biomass burning/haze periods means that the air arriving in Singapore originates from several regions with biomass burning, however it is important to note that the region with highest emissions isn't necessarily the major contributing source region in Singapore. Smaller contributions of PM_{10} from biomass burning arrive in Singapore throughout the year, most years, and in addition larger events occur on an approximately yearly basis. The variation between monitoring stations is often caused by smaller events with varying contribution across Singapore. These simulations only consider emissions from biomass burning, no background concentrations are taken into consideration, which explains some of the difference between the modelled and observed concentrations.

Emissions from many regions contribute to the concentrations of PM_{10} in Singapore, the biggest contributors for the period 2010 - 2015 are Riau, Peninsular Malaysia, and South Sumatra, with smaller yet significant contributions from Jambi, Cambodia, Bangka-Belitung, Riau Islands, Central Kalimantan, and the Philippines. Seeing as Riau and Peninsular Malaysia are the nearest neighbours to Singapore and local wind pattern this makes sense. Looking at emissions during ASO for the four years with largest variation across the island (2011, 2012, 2014, and 2015), large emissions were seen from Central Kalimantan, South Sumatra, Jambi, and also West Kalimantan, whereas Cambodia, East Kalimantan, Myanmar, Thailand, and Vietnam showed larger emissions during FMA.

Difference in magnitude between monitoring stations and higher PM_{10} concentrations does not necessarily impact the ratio of contributing source regions between the monitoring stations, over the six year period the biggest annual difference between stations was seen in 2011, 2014, and 2015. The highest concentrations during periods with contributions from a large region of influence was seen in 2014 all year and ASO 2015 and with smaller region of influence during 2010 and 2013. Generally, a larger southeasterly region of influence is seen during ASO for all years except 2010, whereas the northeasterly winds that dominate FMA, and were seen in 2011 and 2014, generally are weaker than the southeast monsoon winds. The two 2014 events have the largest region of influence for the two seasons over the six year period. Southeasterly winds not during ASO (e.g., MJJ 2012) are relatively weaker. The air history map for MJJ 2013 shows a small region of influence for air arriving in Singapore during the atypical event where a typhoon was dragging air from Riau over Singapore.

In conclusion, we saw that haze events occur during seasons with both small and large regions of influence, however, most often during ASO, coinciding with a larger region of influence and often when higher emissions/increased burning occurs, resulting in variation in relative contributions from major contributing source regions across Singapore. The results emphasise the inter-annual variation between haze events and major contributing source regions, and show that Peninsular Malaysia is a dominant source of particulate matter from biomass burning for the maritime continent off-season burning impact on Singapore, see Figure A1. For haze to occur in Singapore, burning is required, but so is dry weather and wind in the "right" direction. Haze comes from burning across Southeast Asia, making it a transboundary issue for the whole region. Considering that the distance from, e.g., Kalimantan to Singapore is over 500 km, this study emphasises the long-range nature of the problem.

As it is known that biomass burning varies on time sub-daily timescales (Reid et al., 2013), and this study has used daily GFAS FRP and IH (Kaiser et al., 2012) for source calculation, in the future it would be interesting to study the impact of sources based on higher than daily resolution. One could also use post fire inventories based on burnt area or conduct an inversion study, running NAME backwards from detection sites to estimate the emissions in certain areas corresponding to concentrations observed in Singapore and other locations in Southeast Asia. These results could also be compared to inventories based on satellite observations to help quantify how much burning is missing in such inventories.

Code and data availability. The NAME model and data are available by request to the Met Office, GFAS data available through the Copernicus Atmospheric Monitoring Service (CAMS).

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

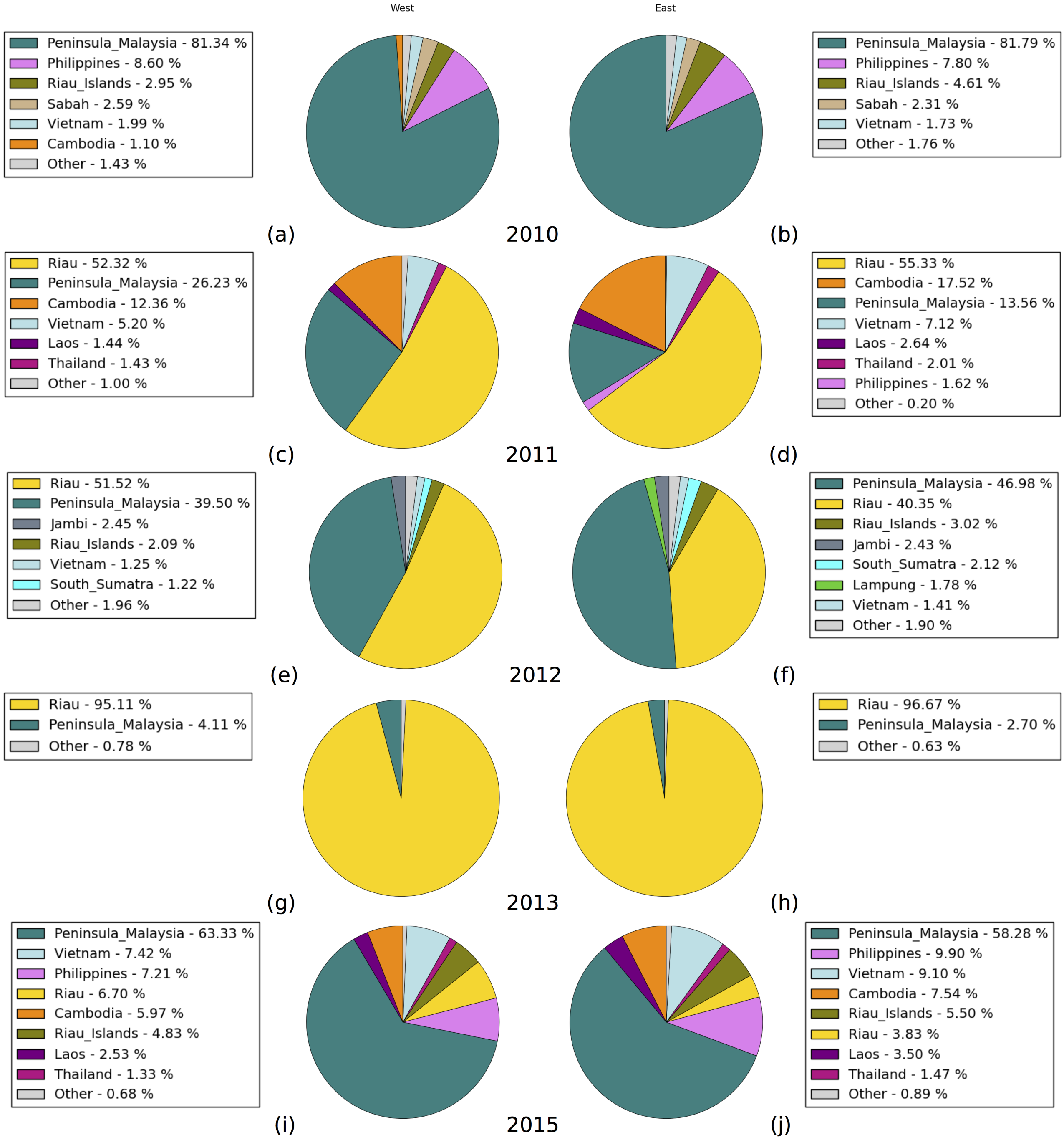

Figure A1. This figure shows results for PM_{10} for years 2010 - 2013 and 2015 for FMA: major contributing source regions for the western (NTU) (left) and eastern (TP) (right) monitoring stations. (For 2014 FMA, see Fig. 6.)

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

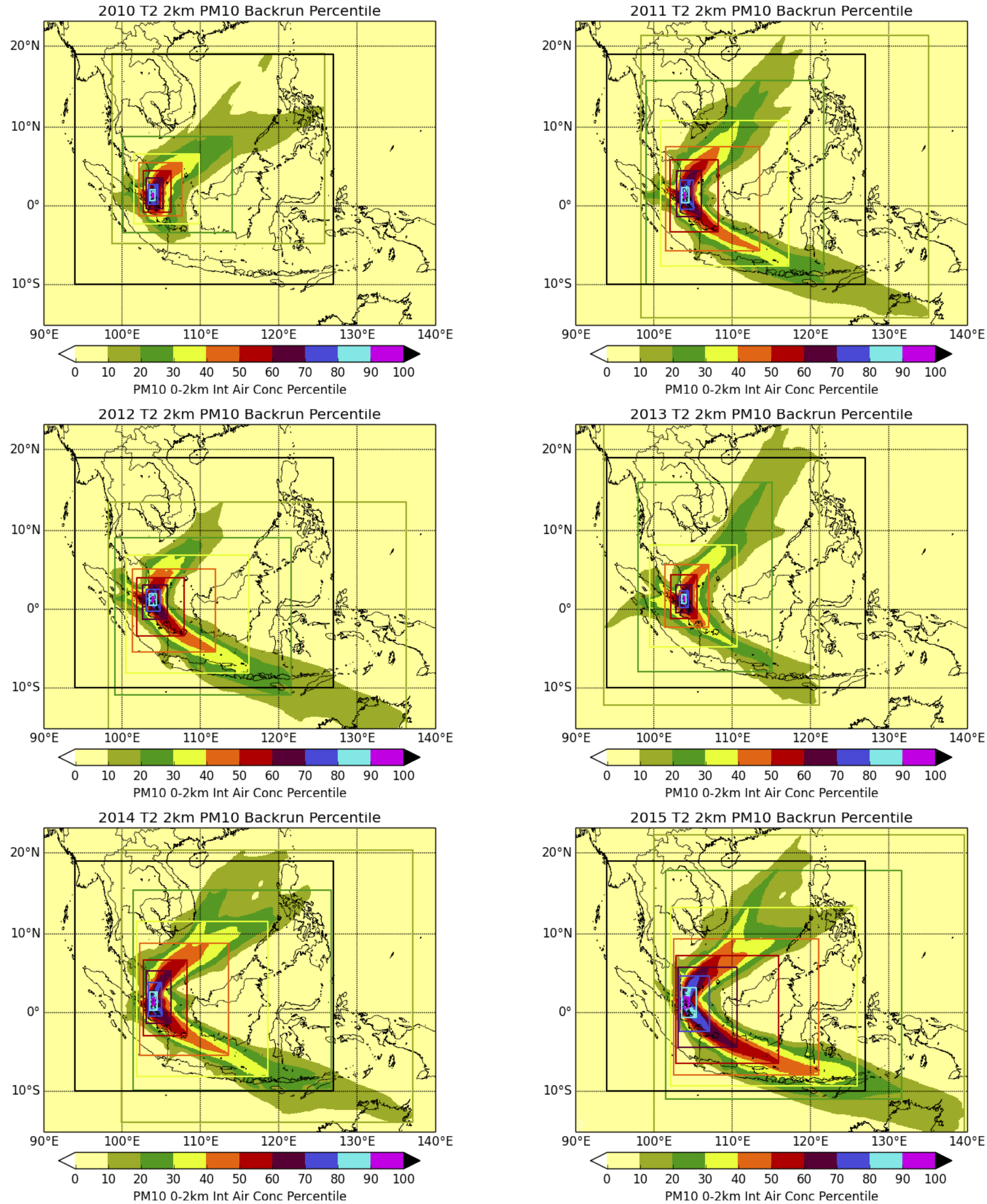

Figure A2. Caption on next page

Figure A2 (Continued). Air history maps for the years 2010 to 2015, showing where air arriving in Singapore during each year originated from. The backruns shown were conducted from a receptor site in central Singapore. Comparison between a coastal receptor site and this inland site showed insignificant variation, meaning that the central receptor site can be considered representative for the whole island.

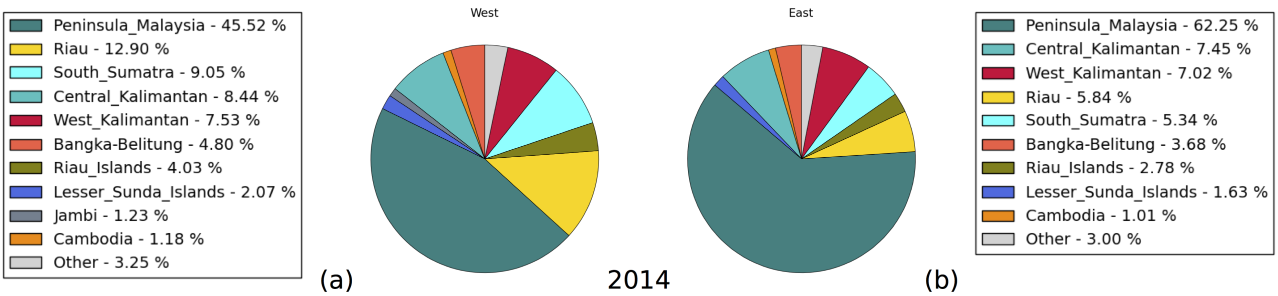

Figure A3. This figure shows results for PM_{10} for 2014: major contributing source regions for the western (NTU) (left) and eastern (TP) (right) monitoring stations.

Author contributions. ABH performed most of the attribution model simulations, the data analysis and wrote the paper, WMC performed the simulations for and the visualisation of the air history maps, EK performed additional attribution model simulations, and assisted with visualisation and calculation of error metrics, BNC, CG, CW, MCH, and SYL helped design the model setup and provided feedback on the manuscript.

Competing interests. No competing interests are present

Acknowledgements. We would like to acknowledge the National Environment Agency, Singapore for supplying us with PM_{10} observations in this study. We are thankful for the support from the CAMS GFAS developers in using the GFAS v1.2 emissions data. We would like to thank the Centre for Remote Imaging, Sensing and Processing (CRISP) at the National University of Singapore for providing the 250 m resolution 2015 land cover map for Southeast Asia

References

Ashfold, M., Latif, M., Samah, A., Mead, M., and Harris, N.: Influence of Northeast Monsoon cold surges on air quality in Southeast Asia, Atmospheric Environment, 166, 498 – 509, https://doi.org/https://doi.org/10.1016/j.atmosenv.2017.07.047, http://www.sciencedirect.com/science/article/pii/S135223101730496X, 2017.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., and Yamagata, T.: El Niño Modoki and its possible teleconnection, Journal of Geophysical Research: Oceans, 112, https://doi.org/10.1029/2006JC003798, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006JC003798, 2007.

Campbell, J. R., Reid, J. S., Westphal, D. L., Zhang, J., Tackett, J. L., Chew, B. N., Welton, E. J., Shimizu, A., Sugimoto, N., Aoki, K., and Winker, D. M.: Characterizing the vertical profile of aerosol particle extinction and linear depolarization over Southeast Asia and the Maritime Continent: The 2007–2009 view from CALIOP, Atmospheric Research, 122, 520 – 543, https://doi.org/http://dx.doi.org/10.1016/j.atmosres.2012.05.007, http://www.sciencedirect.com/science/article/pii/S0169809512001366, 2013.

Campbell, J. R., Ge, C., Wang, J., Welton, E. J., Bucholtz, A., Hyer, E. J., Reid, E. A., Chew, B. N., Liew, S.-C., Salinas, S. V., Lolli, S., Kaku, K. C., Lynch, P., Mahmud, M., Mohamad, M., and Holben, B. N.: Applying Advanced Ground-Based Remote Sensing in the Southeast Asian Maritime Continent to Characterize Regional Proficiencies in Smoke Transport Modeling, Journal of Applied Meteorology and Climatology, 55, 3–22, https://doi.org/10.1175/JAMC-D-15-0083.1, https://doi.org/10.1175/JAMC-D-15-0083.1, 2016.

Chang, J. C. and Hanna, S. R.: Air quality model performance evaluation, Meteorology and Atmospheric Physics, 87, 167–196, https://doi.org/10.1007/s00703-003-0070-7, https://doi.org/10.1007/s00703-003-0070-7, 2004.

Chew, B. N., Campbell, J. R., Salinas, S. V., Chang, C. W., Reid, J. S., Welton, E. J., Holben, B. N., and Liew, S. C.: Aerosol particle vertical distributions and optical properties over Singapore, Atmospheric Environment, 79, 599 – 613, https://doi.org/https://doi.org/10.1016/j.atmosenv.2013.06.026, http://www.sciencedirect.com/science/article/pii/S1352231013004822, 2013.

Crippa, P., Castruccio, S., Archer-Nicholls, S., Lebron, G. B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C., and Spracklen, D. V.: Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia, Scientific Reports, 6, 37 074 EP –, http://dx.doi.org/10.1038/srep37074, 2016.

Davies, T., Cullen, M. J. P., Malcolm, A. J., Mawson, M. H., Staniforth, A., White, A. A., and Wood, N.: A new dynamical core for the Met Office's global and regional modelling of the atmosphere, Q. J. R Meteorol. Soc, 131, 1759–1782, 2005.

Duc, H. N., Bang, H. Q., and Quang, N. X.: Modelling and prediction of air pollutant transport during the 2014 biomass burning and forest fires in peninsular Southeast Asia, Environmental Monitoring and Assessment, 188, 106, https://doi.org/10.1007/s10661-016-5106-9, https://doi.org/10.1007/s10661-016-5106-9, 2016.

Engling, G., He, J., Betha, R., and Balasubramanian, R.: Assessing the regional impact of indonesian biomass burning emissions based on organic molecular tracers and chemical mass balance modeling, Atmospheric Chemistry and Physics, 14, 8043–8054, https://doi.org/10.5194/acp-14-8043-2014, https://www.atmos-chem-phys.net/14/8043/2014/, 2014.

Field, R. D., van der Werf, G. R., and Shen, S. S. P.: Human amplification of drought-induced biomass burning in Indonesia since 1960, Nature Geosci, 2, 185–188, http://dx.doi.org/10.1038/ngeo443, 2009.

Fing, M.: The Weather and Climate of Singapore, Meteorological Service Singapore, 2012.

Gaveau, D. L. A., Salim, M. A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M. E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P., and Sheil, D.: Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires, Scientific Reports, 4, 6112 EP –, http://dx.doi.org/10.1038/srep06112, 2014.

Heimann, I., Bright, V., McLeod, M., Mead, M., Popoola, O., Stewart, G., and Jones, R.: Source attribution of air pollution by spatial scale separation using high spatial density networks of low cost air quality sensors, Atmospheric Environment, 113, 10 – 19, https://doi.org/http://dx.doi.org/10.1016/j.atmosenv.2015.04.057, http://www.sciencedirect.com/science/article/pii/S1352231015300583, 2015.

Hertwig, D., Burgin, L., Gan, C., Hort, M., Jones, A., Shaw, F., Witham, C., and Zhang, K.: Development and demonstration of a Lagrangian dispersion modeling system for real-time prediction of smoke haze pollution from biomass burning in Southeast Asia, Journal of Geophysical Research: Atmospheres, 120, 12 605–12 630, https://doi.org/10.1002/2015JD023422, http://dx.doi.org/10.1002/2015JD023422, 2015.

Huijnen, V., Wooster, M. J., Kaiser, J. W., Gaveau, D. L. A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B., and van Weele, M.: Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997, Scientific Reports, 6, 26 886 EP –, http://dx.doi.org/10.1038/srep26886, 2016.

Inness, A., Benedetti, A., Flemming, J., Huijnen, V., Kaiser, J. W., Parrington, M., and Remy, S.: The ENSO signal in atmospheric composition fields: emission-driven versus dynamically induced changes, Atmospheric Chemistry and Physics, 15, 9083–9097, https://doi.org/10.5194/acp-15-9083-2015, https://www.atmos-chem-phys.net/15/9083/2015/, 2015.

Jones, A. R., Thomson, D. J., Hort, M., and Devenish, B.: The U.K. Met Office's next-generation atmospheric dispersion model, NAME III, in: Air Pollution Modeling and its Application XVII (Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application), edited by Borrego, C. and Norman, A.-L., pp. 580–589, Springer, 2007.

Jones, D. S.: ASEAN and transboundary haze pollution in Southeast Asia, Asia Europe Journal, 4, 431–446, https://doi.org/10.1007/s10308-006-0067-1, https://doi.org/10.1007/s10308-006-0067-1, 2006.

Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.-J., Razinger, M., Schultz, M. G., Suttie, M., and van der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power, Biogeosciences, 9, 527–554, https://doi.org/10.5194/bg-9-527-2012, https://www.biogeosciences.net/9/527/2012/, 2012.

Koplitz, S. N., Mickley, L. J., Marlier, M. E., Buonocore, J. J., Kim, P. S., Liu, T., Sulprizio, M. P., DeFries, R. S., Jacob, D. J., Schwartz, J., Pongsiri, M., and Myers, S. S.: Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure, Environmental Research Letters, 11, 094 023, http://stacks.iop.org/1748-9326/11/i=9/a=094023, 2016.

Lee, H.-H., Bar-Or, R. Z., and Wang, C.: Biomass burning aerosols and the low-visibility events in Southeast Asia, Atmospheric Chemistry and Physics, 17, 965–980, https://doi.org/10.5194/acp-17-965-2017, https://www.atmos-chem-phys.net/17/965/2017/, 2017.

Lee, J. S. H., Jaafar, Z., Tan, A. K. J., Carrasco, L. R., Ewing, J. J., Bickford, D. P., Webb, E. L., and Koh, L. P.: Toward clearer skies: Challenges in regulating transboundary haze in Southeast Asia, Environmental Science & Policy, 55, Part 1, 87 – 95, https://doi.org/https://doi.org/10.1016/j.envsci.2015.09.008, http://www.sciencedirect.com/science/article/pii/S1462901115300770, 2016a.

Lee, S.-Y., Gan, C., and Chew, B. N.: Visibility deterioration and hygroscopic growth of biomass burning aerosols over a tropical coastal city: a case study over Singapore's airport, Atmospheric Science Letters, 17, 624–629, https://doi.org/10.1002/asl.712, http://dx.doi.org/10.1002/asl.712, 2016b.

Mcbride, J. I., Sahany, S., Hassim, M. E. E., Nguyen, C. M., Lim, S.-Y., Rahmat, R., and Cheong, W.-K.: The 2014 Record Dry Spell at Singapore: An Intertropical Convergence Zone (ITCZ) Drought, Bulletin of the American Meteorological Society, 96, S126–S130, https://doi.org/10.1175/BAMS-D-15-00117.1, https://doi.org/10.1175/BAMS-D-15-00117.1, 2015.

Miettinen, J., Shi, C., and Liew, S. C.: Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990, Global Ecology and Conservation, 6, 67 – 78, https://doi.org/https://doi.org/10.1016/j.gecco.2016.02.004, http://www.sciencedirect.com/science/article/pii/S2351989415300470, 2016a.

Miettinen, J., Shi, C., and Liew, S. C.: 2015 Land cover map of Southeast Asia at 250 m spatial resolution, Remote Sensing Letters, 7, 701–710, https://doi.org/10.1080/2150704X.2016.1182659, https://doi.org/10.1080/2150704X.2016.1182659, 2016b.

Nazeer, N. and Furuoka, F.: Overview of ASEAN environment, transboundary haze pollution agreement and public health.” Excerpt From: Nazia Nazeer et al. “Overview of Asean Environment, Transboundary Haze Pollution Agreement and Public Health., International Journal of Asia Pacific Studies, 31, 73–94, 2017.

NEA, 2017: http://www.nea.gov.sg/training-knowledge/publications/annual-weather-review, 2017.

Nichol, J.: Bioclimatic impacts of the 1994 smoke haze event in Southeast Asia, Atmospheric Environment, 31, 1209 – 1219, https://doi.org/https://doi.org/10.1016/S1352-2310(96)00260-9, http://www.sciencedirect.com/science/article/pii/S1352231096002609, 1997.

Nichol, J.: Smoke haze in Southeast Asia: A predictable recurrence, Atmospheric Environment, 32, 2715 – 2716, https://doi.org/https://doi.org/10.1016/S1352-2310(98)00086-7, http://www.sciencedirect.com/science/article/pii/S1352231098000867, 1998.

NOAA, 2017: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, 2017.

Ordóñez, C., Elguindi, N., Stein, O., Huijnen, V., Flemming, J., Inness, A., Flentje, H., Katragkou, E., Moinat, P., Peuch, V.-H., Segers, A., Thouret, V., Athier, G., van Weele, M., Zerefos, C. S., Cammas, J.-P., and Schultz, M. G.: Global model simulations of air pollution during the 2003 European heat wave, Atmospheric Chemistry and Physics, 10, 789–815, https://doi.org/10.5194/acp-10-789-2010, https://www.atmos-chem-phys.net/10/789/2010/, 2010.

Pereira, G., Siqueira, R., Rosário, N. E., Longo, K. L., Freitas, S. R., Cardozo, F. S., Kaiser, J. W., and Wooster, M. J.: Assessment of fire emission inventories during the South American Biomass Burning Analysis (SAMBBA) experiment, Atmospheric Chemistry and Physics, 16, 6961–6975, https://doi.org/10.5194/acp-16-6961-2016, https://www.atmos-chem-phys.net/16/6961/2016/, 2016.

Rea, G., Paton-Walsh, C., Turquety, S., Cope, M., and Griffith, D.: Impact of the New South Wales fires during October 2013 on regional air quality in eastern Australia, Atmospheric Environment, 131, 150 – 163, https://doi.org/https://doi.org/10.1016/j.atmosenv.2016.01.034, http://www.sciencedirect.com/science/article/pii/S1352231016300486, 2016.

Reddington, C. L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y. Y., Arnold, S. R., and Spracklen, D. V.: Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia, Environmental Research Letters, 9, 094 006, http://stacks.iop.org/1748-9326/9/i=9/a=094006, 2014.

Reddington, C. L., Butt, E. W., Ridley, D. A., Artaxo, P., Morgan, W. T., Coe, H., and Spracklen, D. V.: Air quality and human health improvements from reductions in deforestation-related fire in Brazil, Nature Geosci, 8, 768–771, http://dx.doi.org/10.1038/ngeo2535, 2015.

Redington, A., Witham, C., and Hort, M.: Source apportionment of speciated PM10 in the United Kingdom in 2008: Episodes and annual averages, Atmospheric Environment, 145, 251 – 263, https://doi.org/http://dx.doi.org/10.1016/j.atmosenv.2016.09.047, http://www.sciencedirect.com/science/article/pii/S1352231016307555, 2016.

Reid, J. S., Xian, P., Hyer, E. J., Flatau, M. K., Ramirez, E. M., Turk, F. J., Sampson, C. R., Zhang, C., Fukada, E. M., and Maloney, E. D.: Multi-scale meteorological conceptual analysis of observed active fire hotspot activity and smoke optical depth in the Maritime Continent, Atmospheric Chemistry and Physics, 12, 2117–2147, https://doi.org/10.5194/acp-12-2117-2012, https://www.atmos-chem-phys.net/12/2117/2012/, 2012.

Reid, J. S., Hyer, E. J., Johnson, R. S., Holben, B. N., Yokelson, R. J., Zhang, J., Campbell, J. R., Christopher, S. A., Girolamo, L. D., Giglio, L., Holz, R. E., Kearney, C., Miettinen, J., Reid, E. A., Turk, F. J., Wang, J., Xian, P., Zhao, G., Balasubramanian, R., Chew, B. N., Janjai, S., Lagrosas, N., Lestari, P., Lin, N.-H., Mahmud, M., Nguyen, A. X., Norris, B., Oanh, N. T., Oo, M., Salinas, S. V., Welton, E. J., and Liew, S. C.: Observing and understanding the Southeast Asian aerosol system by remote sensing: An initial review and analysis for the Seven Southeast Asian Studies (7SEAS) program, Atmospheric Research, 122, 403 – 468, https://doi.org/http://dx.doi.org/10.1016/j.atmosres.2012.06.005, http://www.sciencedirect.com/science/article/pii/S0169809512001809, 2013.

Rémy, S., Veira, A., Paugam, R., Sofiev, M., Kaiser, J. W., Marenco, F., Burton, S. P., Benedetti, A., Engelen, R. J., Ferrare, R., and Hair, J. W.: Two global data sets of daily fire emission injection heights since 2003, Atmospheric Chemistry and Physics, 17, 2921–2942, https://doi.org/10.5194/acp-17-2921-2017, https://www.atmos-chem-phys.net/17/2921/2017/, 2017.

Savage, N. H., Agnew, P., Davis, L. S., Ordóñez, C., Thorpe, R., Johnson, C. E., O'Connor, F. M., and Dalvi, M.: Air quality modelling using the Met Office Unified Model (AQUM OS24-26): model description and initial evaluation, Geoscientific Model Development, 6, 353–372, https://doi.org/10.5194/gmd-6-353-2013, https://www.geosci-model-dev.net/6/353/2013/, 2013.

Shi, Y. and Yamaguchi, Y.: A high-resolution and multi-year emissions inventory for biomass burning in Southeast Asia during 2001–2010, Atmospheric Environment, 98, 8 – 16, https://doi.org/http://dx.doi.org/10.1016/j.atmosenv.2014.08.050, http://www.sciencedirect.com/science/article/pii/S1352231014006529, 2014.

Sigsgaard, T., Forsberg, B., Annesi-Maesano, I., Blomberg, A., Bølling, A., Boman, C., Bønløkke, J., Brauer, M., Bruce, N., Héroux, M.-E., Hirvonen, M.-R., Kelly, F., Künzli, N., Lundbäck, B., Moshammer, H., Noonan, C., Pagels, J., Sallsten, G., Sculier, J.-P., and Brunekreef, B.: Health impacts of anthropogenic biomass burning in the developed world, European Respiratory Journal, 46, 1577–1588, https://doi.org/10.1183/13993003.01865-2014, http://erj.ersjournals.com/content/46/6/1577, 2015.

Sulong, N. A., Latif, M. T., Khan, M. F., Amil, N., Ashfold, M. J., Wahab, M. I. A., Chan, K. M., and Sahani, M.: Source apportionment and health risk assessment among specific age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia, Science of The Total Environment, 601–602, 556 – 570, https://doi.org/https://doi.org/10.1016/j.scitotenv.2017.05.153, https://www.sciencedirect.com/science/article/pii/S0048969717312536, 2017.

Walters, D., Boutle, I., Brooks, M., Melvin, T., Stratton, R., Vosper, S., Wells, H., Williams, K., Wood, N., Allen, T., Bushell, A., Copsey, D., Earnshaw, P., Edwards, J., Gross, M., Hardiman, S., Harris, C., Heming, J., Klingaman, N., Levine, R., Manners, J., Martin, G., Milton, S., Mittermaier, M., Morcrette, C., Riddick, T., Roberts, M., Sanchez, C., Selwood, P., Stirling, A., Smith, C., Suri, D., Tennant, W., Vidale, P. L., Wilkinson, J., Willett, M., Woolnough, S., and Xavier, P.: The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations, Geoscientific Model Development, 10, 1487–1520, https://doi.org/10.5194/gmd-10-1487-2017, https://www.geosci-model-dev.net/10/1487/2017/, 2017.

Walters, D. N., Best, M. J., Bushell, A. C., Copsey, D., Edwards, J. M., Falloon, P. D., Harris, C. M., Lock, A. P., Manners, J. C., Morcrette, C. J., Roberts, M. J., Stratton, R. A., Webster, S., Wilkinson, J. M., Willett, M. R., Boutle, I. A., Earnshaw, P. D., Hill, P. G., MacLachlan, C., Martin, G. M., Moufouma-Okia, W., Palmer, M. D., Petch, J. C., Rooney, G. G., Scaife, A. A., and Williams, K. D.: The Met Office

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-311
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 16 April 2018

Unified Model Global Atmosphere 3.0/3.1 and JULES Global Land 3.0/3.1 configurations, Geoscientific Model Development, 4, 919–941, https://doi.org/10.5194/gmd-4-919-2011, https://www.geosci-model-dev.net/4/919/2011/, 2011.

Yeh, S.-W., Kug, J.-S., Dewitte, B., Kwon, M.-H., Kirtman, B. P., and Jin, F.-F.: El Niño in a changing climate, Nature, 461, 511 EP –, http://dx.doi.org/10.1038/nature08316, 2009.

Youssouf, H., Liousse, C., Roblou, L., Assamoi, E.-M., Salonen, R. O., Maesano, C., Banerjee, S., and Annesi-Maesano, I.: Non-Accidental Health Impacts of Wildfire Smoke, International Journal of Environmental Research and Public Health, 11, 11 772–11 804, https://doi.org/10.3390/ijerph111111772, http://www.mdpi.com/1660-4601/11/11/11772, 2014.

Yuan, Y. and Yang, S.: Impacts of Different Types of El Niño on the East Asian Climate: Focus on ENSO Cycles, Journal of Climate, 25, 7702–7722, https://doi.org/10.1175/JCLI-D-11-00576.1, https://doi.org/10.1175/JCLI-D-11-00576.1, 2012.

Zhang, Y., Li, T., Wang, B., and Wu, G.: Onset of the Summer Monsoon over the Indochina Peninsula: Climatology and Interannual Variations, Journal of Climate, 15, 3206–3221, https://doi.org/10.1175/1520-0442(2002)015<3206:OOTSMO>2.0.CO;2, https://doi.org/10.1175/1520-0442(2002)015<3206:OOTSMO>2.0.CO;2, 2002.