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Assessment of co-benefits of black carbon emission reduction measures in Southeast Asia: Part 2 emission scenarios for 2030 and co-benefits on mitigation of air pollution and climate forcing

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Abstract. Following Part 1 (Permadi et al., 2017a) which focuses on the preparation of emission input data and evaluation of WRF/CHIMERE performance in 2007, this paper presents Part 2 of our research detailing the quantification of co-benefits resulted in the future (2030) from black carbon (BC) emission reduction measures for Southeast Asia (SEA) countries. The business as usual (BAU2030) projected emissions from the base year of 2007 (BY2007) assuming "no intervention" with the linear projection of the emissions based on the past decadal activity data (Indonesia and Thailand) and the sectoral GDP growth for other countries. The RED2030 featured measures to cut down emission in major four source sectors in Indonesia and Thailand (on-road transport, residential cooking, industry, and biomass open burning) while for other countries the representative concentration pathway 8.5 (RCP8.5) emissions were assumed. WRF/CHIMERE simulated levels of aerosol species under BAU2030 and RED2030 for the SEA domain using the base year meteorology and 2030 boundary conditions from LMDZ/INCA. The extended aerosol optical depth module (AODEM) calculated the total columnar AOD and BC AOD assuming the internal mixing state for the two future scenarios. Health benefits were analyzed in term of the avoided number of premature deaths associated with ambient $PM_{2.5}$ reduction while the climate benefits were quantified using the reduction in the BC radiative forcing under RED2030. Under BAU2030, the average number of the premature deaths per 100,000 population in the domain would increase by 30 from BY2007 while under RED2030 the premature deaths would be cut-down (avoided) by 59 from the RED2030. In 2007, the maximum annual average BC radiative forcing in SEA countries was 0.98 W m^{-2} which would increase to 2.0 W m^{-2} under BAU2030 and 1.4 W m^{-2} under RED2030. Substantial co-benefits on human health and BC climate forcing reduction in SEA could be resulted from the emission measures incorporated in RED2030. Future works should consider other benefits such as for the agricultural crop production, and the cost benefit analysis of the measures implementation to provide relevant information for policy making.

1. Introduction

Interaction of aerosol (fine particles suspended in the atmosphere) with climate has gained an increasing attention from the scientific community, especially to assess various emission control measures for near-term climate

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change mitigation. Being black in color, in the atmosphere the black carbon (BC) particles strongly absorb solar radiation, hence exerting a positive direct radiative forcing. BC is known as a short-lived climate forcing pollutant (SLCP) because of its short atmospheric lifetime of a few days to weeks as compared to the long-lived carbon dioxide, for example. BC interacts with the cloud formation processes and once deposits on snow it reduces the surface albedo and consequently affects the Earth's radiation energy balance (Myhre et al., 2001). Several global modeling studies estimated the present day BC radiative forcing of +0.2 – +1.1 W m^{-2} hence BC has been recognized as the second most important global warming agent after CO_2 (Bond et al., 2013; Ramanathan and Carmichael, 2008). Globally, measures aim to reduce emissions of BC (and co-emitting pollutants) have been shown to reduce the number of premature deaths and slow down the temperature increase rate in the near future, i.e. bring in co-benefits, and more to be gained in Asia, where current emissions are high (UNEP-WMO, 2011; Shindell et al., 2012).

Southeast Asia (SEA) has high emissions from anthropogenic sources that contribute significantly to the Asia and global emissions (Permadi et al., 2017a). Overall, Asian emissions have been reported to increase rapidly over last decades (Streets et al., 2003; Zhang et al., 2009; Ohara et al., 2007; EJ/JRC-PBL, 2010). High levels of air pollution, especially the fine particles or $PM_{2.5}$ (particles with aerodynamic diameter ≤2.5 um) that caused severe health effects (WHO, 2012) have been measured in Asian cities (Kim Oanh et al., 2006; Hopke et al., 2008). Global studies reported that efforts to reduce SLCP emissions (BC and ozone precursors) would help to reduce global warming immediately (UNEP and WMO, 2011; Shindell et al., 2012) which should complement those addressing the long-lived greenhouse gases (GHGs) which would require longer time to realize. Developing Asia is also vulnerable to climate change hence reducing emissions of the SLCPs would bring in co-benefits in terms of avoiding excessive premature deaths, reducing the crop yield loss, as well as in slowing down the temperature increase rate (UNEP-WMO, 2011).

The co-benefit approach is being more and more recognized as an important concept to simultaneously address the problems of air quality and climate change. However, so far it has not been adequately considered in the policy making in many developing countries. There is a need to conduct regional co-benefit studies especially in several large emission regions of Asia. A number of studies reported applications of the modeling tool to investigate impacts of emission reduction measures on the premature mortality and radiative forcing in East and South Asia (Saikawa et al., 2009; Aunan et al., 2006; Akimoto et al., 2015). There are no such detail co-benefit studies conducted for the SEA region where the local/domestic and transboundary problems, e.g. regional haze, are important (Heil and Goldammer, 2001). The outcomes of a comprehensive co-benefit study for the SEA countries can provide scientific information to policy makers when consider effectiveness of different emission reduction measures.

In this paper we focus on the simulations of aerosol concentrations in SEA under two emission scenarios projected for 2030 using the chemistry transport model (CTM) of CHIMERE (Vautard et al., 2001; Bessagnet et al., 2004). Our accompanying paper (Permadi et al., 2017a) has detailed the SEA emissions and the evaluation of WRF/CHIMERE performance for PM_{10}, $PM_{2.5}$ and BC in SEA in the base year of 2007 (BY2007). The emission reduction scenario (RED2030) considered reduction measures to be implemented in four major anthropogenic source sectors (on-road transportation, residential cooking, industry and biomass open burning) in two large

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emitting SEA countries of Thailand and Indonesia. The changes in the BC direct radiative forcing (DRF) and in the number of avoided premature deaths between BY2007 and RED2030 were compared to those between BY2007 and the business as usual scenario (BAU2030) to highlight potential co-benefits.

2. Methodology

2.1 Model simulation

Details of the models used and their configurations have been presented in the accompanying paper (Permadi et al., 2017a). The emission inputs were prepared based on two developed emission scenarios (BAU2030 and RED2030). The meteorological fields produced by WRF for 2007 were used for the simulation of scenarios for 2030. However, the future simulations used the chemistry boundary conditions obtained from the global CTM of INteraction avec la Chimie et les Aérosols (INCA) - Laboratoire de Météorologie Dynamique (LMDz) for 2030 generated using the global RCP8.5 emissions (Hauglustaine, 2013). Accordingly, the concentrations of 27 pollutants, including aerosol and trace gases, as the SEA domain boundary conditions (monthly average), were extracted from the global LMDZ/INCA simulation for the base year 2007 (BY2007) and 2030 (BAU2030 & RED2030) for 19 vertical pressure levels. Outputs of LMDZ/INCA for BC and OC for the year of 2007 and 2030 and the changes in their levels between these 2 years, expressed as the ratios between 2030 and 2007 (2030/2007 ratios) are presented in Figure S1, SI. Note that biogenic emissions in 2030 were assumed to be the same as in 2007.

In the discussion of modeling results throughout the paper, two domains are defined as follows:

a) Modeling domain total: covering the SEA countries and the southern part of China
b) SEA domain: covering only the nine (9) SEA countries in the domain.

2.2 Emission scenarios

BAU2030: This is a reference future scenario that is named as “Business as Usual” and represents the emissions in 2030 (BAU2030). BAU was developed based on the assumption that the emissions would grow following the current trend of activity data. For Indonesia and Thailand, two large emitting countries in SEA, the historical activity data available prior to 2007 was collected and the trends were analyzed for a period of 4-19 years (depending on the availability of the data and varying with emission source type). Further, a simple regression analysis was conducted to analyze the linear relationship between the emissions and a selected proxy which was used to project the activity data to 2030 for the respective country. As a way of example, country population and vehicle number data was collected for period of 1998 – 2007 (Indonesia) and 1994 – 2007 (Thailand) to project the residential combustion and on-road traffic emissions to 2030 (BAU2030), respectively. The same EFs of 2007 were used for the emission estimation from the sources in 2030 and this may contribute a certain uncertainty to the projected emissions. For other countries in the domain, due to the limitation of historical activity data, the BAU emissions were projected using their GDP growth trends over the last 10 years. The same spatial and temporal emission distribution patterns of 2007 were used in the BAU2030 emissions for the whole SEA domain.

RED2030: This scenario considers the PM emission cut for major emission sources in 2030. For Indonesia and Thailand, RED2030 emissions were calculated using the available official policy documents that mainstreamed both air quality and climate change mitigations in four major emission sectors (on-road transport, residential, industry, and biomass open burning) as detailed in Table S1. These involved cleaner transportation fleets with at least Euro2 in Indonesia and Euro4 in Thailand for personal cars, while NG gas should be used in all public buses in Indonesia, and all public buses and taxis in Thailand. The measures considered in residential cooking for Indonesia included the national program of conversion of kerosene to LPG for cooking (Permadi et al., 2017b) and introduction of cleaner biomass fuel (for gasifier cookstove) to replace the traditional fuel wood cookstoves. In Thailand, cleaner fuel, such as LPG was introduced to replace fuel wood and charcoal, as well as the implementation of rural electrification to enable application of electric cookstoves. In the industrial sector in Indonesia, fuel switching and process modernization were implemented for key industries such as cement, iron steel, pulp and paper and textile (ICCSR, 2010). In Thailand, measures focused on energy saving program and maximum feasible reduction in the key industries, such as cement and iron steel industry, were considered following the policy action proposed by Chotichanatawewong and Thongplew (2012). For biomass open burning, Indonesia focused on the reduction of forest burning area target and zero burning of solid waste following the National Strategic Plan document (MoF, 2010). A clear target was set for Thailand to follow the National Masterplan of Open Burning Control (PCD, 2010) which mandated that forest area would not be burned over than 48,000 ha yr^{-1} in 2030 and zero burning for crop residue implemented throughout the country.

For other countries in the domain, due to the lack of relevant information, this study assumed that their emissions followed the RCP8.5 pathways (taken from http://tntcat.iiasa.ac.at:8787/RcpDb/) for the Asian region. Accordingly, under RCP8.5, in 2030 the SEA emissions of CH_4 and NH_3 would increase by 1.7 and 1.3 times, respectively, as compared to 2007, while NMVOC remained nearly the same during the period. For other pollutants (SO_2, CO, NOx, BC, and OC), some emission reductions were expected, i.e. 2030 emissions were 0.6-0.9 of the respective 2007 emissions. Note that the same temporal and spatial emission distribution patterns of BY2007 were used also in RED2030 emissions.

2.3 Co-benefit analysis

The potential co-benefits were quantified to scientifically prove tangible benefits of the emission reduction scenarios on improvement of air quality (hence health impacts) and mitigation of climate forcing. Impacts of emission reduction measures under RED2030 as compared to the reference scenario (BAU2030) were analyzed in terms of the premature deaths number and BC DRF in SEA.

2.3.1 Premature death

The number of avoidable premature deaths due to the applied emission reduction measures was quantified based on the changes in ambient $PM_{2.5}$ levels and was calculated using eq. 1 (Wang and Mauzeral, 2006 and Saikawa et al. 2009).

$$cases = I_{ref} \, . \, POP \, . CR \, . \;\; C \qquad (1)$$

Where,

Δ_{cases} : Additional change in number of cases of mortality per year due to change in the ambient $PM_{2.5}$ concentration.

I_{ref} : baseline mortality rate (%)

POP : number of exposed population (person)

CR : concentration response coefficient (CR) for mortality rate (unit is % change in mortality and morbidity as a result of a 1 µg m^{-3} change in annual average $PM_{2.5}$ concentration)

ΔC : change in annual ambient $PM_{2.5}$ concentration under a given different emission scenario.

We considered only the premature deaths because of the less comprehensive information available on the association between the morbidity and air pollution exposure as compared to that of the mortality (Saikawa et al., 2009). The $PM_{2.5}$ annual concentration was used rather than BC alone following the recommendations of the WHO Task Force (WHO, 2012) that $PM_{2.5}$ should continue to be used as the primary metric in quantifying the human exposure to PM and resulting health effects. Concentration response (*CR*) data was obtained from Smith et al. (2009) who indicated that every increase in $PM_{2.5}$ by 1 µg m^{-3} is approximately associated with an 1.006% increase in the risk of all cause adult mortality for individual of 20 years and older. The I_{ref} data representing the adult mortality rate for all causes and both sexes (per 1,000 of population) for every nation included in the study domain was obtained from the United Nations database (http://data.un.org/Data.aspx?d=WHO&f=MEASURE_CODE%3AWHOSIS_000004) for the base year of 2007. The gridded population (*POP*) data of 0.5° resolution was obtained from the Potsdam Institute for Climate Impact Research (PICIR) (http://clima-dods.ictp.it/d10/fcolon_g/) for both 2007 and 2030, and the data were further gridded to a finer resolution of 0.25° of the domain. The proportions of adult population (age ≥20 years) for the countries were taken from the World Bank database (http://data.worldbank.org/indicator/SP.POP.0014.TO.ZS). This study assumed that the baseline mortality and age structure were distributed following the population density and hence were not changed between 2007 and 2030.

2.3.2 Black carbon aerosol optical depth

The BC aerosol optical depth (AOD) values were calculated using AODEM with the 3D aerosol concentration field generated by WRF/CHIMERE for BAU2030 and RED2030. The detail of AODEM software and parameterization has been presented in our accompanying paper (Permadi et al., 2017a).

2.3.3 BC direct radiative forcing

To estimate BC DRF, a radiative transfer equation (eq. 2) was used following the approach presented in Chylek and Wong (1995) and Kim et al. (2012).

$$F = \frac{1}{4}F_0T^2(1 \quad A_c)\{4R\tau_{ab} \quad 2((1 \quad R)^2\beta\tau_{sc}\} \qquad (2)$$

Where, F_0 is the solar irradiance constant (1,370 W m^{-2}) and T is the atmospheric transmission coefficient (0.79). The values of A_c (the total cloud fraction) and R (surface albedo) were taken from the WRF simulation results, respectively. The expression of $(1\text{-}R)^2$ in the equation accounts for the multiple reflection of the aerosol layer. The surface τ_{ab} is the absorption (BC AOD) and τ_{sc} is the scattering optical depths calculated by AODEM based on the BC burden, β is the back-scattering fraction which was assumed to be 0.17 based on the measurements of Schnaiter et al. (2003).

3. Results and Discussion

3.1 Emission scenarios

A summary of the annual emissions of key species in the base year of 2007 and in 2030 under two emission scenarios (BAU2030 and RED2030) from the domain is given in Table 1. The annual emission changes under the scenarios are indicated by the respective ratios for each species. This section discussed in depth the emissions for 2 countries, Indonesia and Thailand, for which the specific activity data trends were considered for the emission scenarios development. Table S2, SI showed the increases in all activity data of the key anthropogenic sources in the countries except for forest fire emissions, which were actually expected to reduce due to a lower GDP from the forestry sector and less forest biomass/area in the future. The most significant increase was for the number registered vehicles in Indonesia which in 2030 would be 3.1 times above that in 2007. In Thailand, petroleum refinery product was also projected to increase by 3.3 times from 2007 to 2030 followed by the number of vehicles, by 2.2 times. The sectoral emissions of key species from these 2 countries under different scenarios are provided in Figure S2, SI.

BAU2030 emissions: For Indonesia, under BAU2030, the emissions of all species would increase with the ratios between BAU2030 and BY2007 of 1.2-1.95 (Table 1). The highest increase (1.95 times) would be expected for SO_2 and this is mainly reflecting the increase in coal usage for the power generation and industry. Note that, the use of the same SO_2 EFs for BY2007 and BAU2030 emission calculation, as well as the assumption on no further emission control devices applied in the power and industry may be the cause of the high increase rate for SO_2. This may not represent the real trend because in the future the regulation on emission control would be more stringent hence less SO_2 increase should be expected. The NOx emission increases by 1.6 times was mainly due to the increasing trends of the oil and gas industry and traffic activities. The population growth in the country during the period of 2007 – 2030 would increase emissions of CO, NMVOC, and PM (PM_{10}, $PM_{2.5}$, BC, OC) by 1.2, 1.5 and 1.35 – 1.39 times, respectively, and this reflects the dominant contributions from residential combustion to these species emissions. NH_3 emission was projected to be increased by 1.6 times due to livestock growth in the country. Among GHGs, CO_2 would increase by 1.5 times while CH_4 would increase 1.4 times from the reference emissions.

For Thailand, the BAU2030/BY2007 ratios showing the increases of all species in Table 1, highest for SO_2 (1.95 times) and lowest for CO (equal values). The increases in SO_2 and NOx emissions reflected the increasing rates of the coal consumption, i.e. the ratio of projected coal consumption 2030/2007 was 2.1 (Table S2, SI) for industry (EPPO, 2008). The intensification of agricultural production would increase the crop residue OB that caused the increased emissions of PM species of PM_{10}, $PM_{2.5}$, BC, OC by 1.42-1.66 depending on PM species. Forest fire emission was projected to reduce with estimated 2030/2007 ratios of 0.7 (Indonesia) and 0.9 (Thailand) which were based on the trend of GDP in forestry (Indonesia) and the trend of forest area (Thailand). The increases in in NH_3 (1.55) and NMVOC (1.54) emission were mainly due to the livestock and industrial growth rates, respectively. GHGs emissions were also projected to increase by 1.10 (CO_2), 1.61 (CH_4) and 1.81 (N_2O).

The substantial increases of activity data levels under BAU2030 for both countries have brought about the increase in emissions for all species in both countries from the BY2007. Due to the limitation in the long-term activity data, emission projection under BAU2030 for other countries in the domain was made based on the GDP growth rate. The annual average GDP growth rates for the period of 2000-2007 were reported the highest for Myanmar (11.5%) followed by China (11%) and Cambodia (10.5%) (WB, 2008). Emissions from other countries in the domain under BAU2030 were assumed to grow following the population weighted average GDP growth rates estimated for other SEA countries and China, averaged at 2.2 times. A summary of the emissions of these countries is also given in Table 1.

RED2030 emissions: For Indonesia, the measures to be implemented in the RED2030 scenario would result in lower emissions as compared to BAU2030, with the ratios RED2030/BAU2030 being 0.3-0.92. The most significant emission reductions would be realized for aerosol species (PM_{10}, $PM_{2.5}$, BC, and OC) with the RED2030/BAU2030 of 0.30-0.56 followed by that for CO (0.62) as seen in Fig. S2, SI. The significant reductions for these species were expected because the included measures (Table S1) in all sectors aimed at reducing PM (BC) emissions which also would reduce CO, an accompanying gas emitted from these combustion sources. Among GHGs, the highest reduction was for CO_2 with RED2030/BAU2030 ratio of 0.7 (and lower reductions for N_2O (0.87) and CH_4 (0.96). As compared to the base year, RED2030 would also feature more emission reductions for major aerosol species with the corresponding ratios of RED2030/BY2007 of 0.4-0.75 for PM species and 0.74 for CO. The RED2030 emissions were lower than the base year of 2007 for most species except for SO_2, NH_3, NMVOC and NO_x which were increased by 1.2 – 1.8 times

For Thailand, RED2030 also featured the lower emission than BAU2030, as expected. The reductions were about in the same ranges as for Indonesia. The emission ratios of RED2030/BAU2030 for different species were 0.37-0.93. More significant reductions were obtained for PM species, i.e. ratios of 0.37-0.55, followed by CO, a ratio of 0.73. Among the GHGs, the highest reduction would be obtained for CH_4 with the ratio of 0.81 followed by CO_2 (0.84) and N_2O (0.95). Similar to the case of Indonesia, the emissions under RED2030 as compared to BY2007 were lower for PM species and CO but higher for other species with the RED2030/BY2007 ratios of 1.2 – 1.6 (Table 1).

Sector-wise emissions in both countries showed that under RED2030 there would be a substantial reduction, as compared to BAU2030, resulted from the mitigation measures (Table S1) in the two countries for all sectors. The emission ratios of RED2030/BAU2030 for biomass OB were 0.09-0.6 while for residential sector corresponding ratios were 0.14 – 0.99 for different species (Fig. S2, SI). There observed some increasing trends of SO_2 emissions from the residential sector when LPG was used to replace wood as cooking fuel because of its higher sulfur content. As for BC species, the emission ratios of RED2030/BAU2030 for biomass OB and residential sectors in Indonesia were 0.48 and 0.49, respectively, and in Thailand were 0.37 and 0.41, respectively. For the industry and transportation sectors, the corresponding emission ratios for BC were 0.87 (Indonesia) and 0.6 (Thailand). Under BAU2030, the emissions of which BC was rising steadily from the BY2007 with higher rates as compared to RED2030 (Fig. S2, SI).

For other countries in the domain, the RCP8.5 was used to project the emissions under RED2030. The same ratios between 2030 and 2007 emissions for different species estimated for Asia were applied for the rest countries in the domain to obtain their RED2030 emissions. As discussed above, the RED2030 featured the emission reductions from BY2007 for several species presented in Table 1, i.e. with the RED2030/BY2007 ratios of 0.84-0.88 for PM species, 0.69 for SO_2 and 0.98 for CO. The emissions of NOx, NH_3 and NMVOC were however increased by 1.05-1.3 times (Table 1). Due to the insufficient information on air quality and climate policies of other countries in the domain, this study focused primarily on the emission reduction measures for 2 countries of Indonesia and Thailand. Nevertheless, as highlighted in our accompanying paper (Permadi et al., 2017a), collectively these two countries had the large contributions in the domain, i.e. sharing 25-66 % of the total SEA emission and 17-44% to the study domain total (SEA + southern part of China) for most of the species in 2007. This justified the importance of the emission reduction measures of these 2 countries for the region. Note that the reductions for NH_3, CH_4 and N_2O were relatively small in both countries because the major sources of these species were not addressed in the four source sectors considered for mitigation in this study. On the opposite, the reductions PM species and CO were relatively more significant for both countries because the mitigation measures addressed the key sources of the species.

3.2 Black carbon direct radiative forcing for base year of 2007

Black carbon DRF in SEA is of interest to understand the impacts of BC emission on the climate warming effects. Therefore, BC AOD (τ_{ab}) was first calculated as the difference between the total AOD (scattering + absorbing) and scattering AOD following the same method presented in literature (Landi and Curci, 2011). In our accompanying paper (Permadi et al., 2017a), the results of BC AOD for the BY2007 were used for the model evaluation. The BC AOD results for all scenarios were used to calculate the BC DRF using Eq. 2. The monthly averages of BC DRF for the base year 2007 are presented in Figure 1 for selected months of August (wet season in the northern domain but dry season in the southern domain) and January, February, December (dry season in the northern domain but wet season in southern part of the domain). Note that the BC DRF values represent the forcing at the top of the model layer and not that at the Earth surface. In the following discussion, we focused on the results for the SEA countries which excluded the southern part of China in the domain.

Among of the selected months, December had the highest BC DRF with the maximum monthly average value in the SEA countries of 1.4 W m^{-2} while January and August had the lowest values of only 0.9 W m^{-2}. In August, the SEA part of the domain had the maximum monthly average seen at the border between Thailand and Myanmar and in Riau Province of Sumatera Island, Indonesia. In December, the maximum monthly average in the SEA countries was seen at the Malaysian peninsular and western part of Java Island, Indonesia. In January, higher values BC DRF were seen at western part of Malaysian peninsular and eastern part of Java Island, Indonesia. The monthly highest values in February were seen in the western part of Malaysian peninsular and western part of Kalimantan Island, Indonesia. Note that, the influence of the emissions from the up-wind part of the SEA domain was more pronounced in the months when the northeast monsoon was predominant (January, February and December). In these months, the highest monthly values were simulated outside the SEA countries, i.e. above the southern part of China and Taipei (maximum of 1.4 – 1.9 W m^{-2}).

The monthly distributions of BC DRF were consistent to the simulated monthly BC AOD. Note that in this study we assumed the internally mixed state for BC when calculating AOD by AODEM and this may overestimate the light absorption of BC (Jacobson, 2001). Our estimated BC DRF values are comparable to a previous study by Kim et al. (2012) who estimated the monthly BC DRF values for Korean peninsula of 1.2 – 1.5 W m^{-2} but higher than the global average BC DRF suggested by Jacobson (2000) of 0.55 W m^{-2}.

3.3 Co-benefits analysis of emission reduction measures in 2030

Our co-benefit analysis covered the health benefit in term of the avoided number of premature deaths due to the reduced $PM_{2.5}$ pollution and climate benefit by the reduction in BC DRF. The results of RED2030 were compared to those of BAU2030 to quantify the impacts of the emission reduction measures.

3.3.1 Air quality and premature deaths

1) $PM_{2.5}$ and BC

A summary of the maximum BC and $PM_{2.5}$ (air quality) along with BC DRF (climate) and premature deaths under the scenarios is given in Table 2 for SEA countries only, i.e. excluding the southern China part of the modeling domain. Annual average concentrations of BC and $PM_{2.5}$ for BY2007 and two different scenarios of BAU2030 and RED2030 are presented in Figure 2, which shows similar patterns of BC and $PM_{2.5}$ for all scenarios but their maximum values were much higher under BAU2030 as compared to other scenarios. Over the SEA countries, the maximum BC and $PM_{2.5}$ were shown over eastern part of Java Island (Indonesia) in all scenarios. The maximum BC values simulated for BAU2030 of 7.2 µg m^{-3} appeared over eastern part of Java Island that featured an increase by 1.2 µg m^{-3} from the BY2007. Under RED2030, the maximum of BC in SEA countries was 4.3 µg m^{-3} which is 2.9 µg m^{-3} lower than that under BAU2030. For $PM_{2.5}$, there was an increase of the maximum level over SEA countries, from 32 µg m^{-3} in BY2007 to 36 µg m^{-3} in BAU2030. However, the emission reduction measures under RED2030 would reduce the SEA maximum $PM_{2.5}$ to 21 µg m^{-3} (Table 2).

The changes in total BC and $PM_{2.5}$ emissions in the domain were consistent to the emission changes in the domain under different scenarios. As discussed above, the BAU2030 featured a total emission increase in the $PM_{2.5}$ emissions (primary particles) in the SEA domain by 1.6 times as compared to BY2007 as well as for BC (1.6 times). In 2030, as compared to BAU2030 the RED2030 would reduce the emissions of $PM_{2.5}$ (primary) by 2.4 times and BC emission by 2.1 times. The ambient $PM_{2.5}$ should compose also of secondary particles hence would be also affected by the changes in the precursors' emissions. The magnitude of changes in $PM_{2.5}$ and BC emissions were not similar to the changes in their simulated ambient concentrations suggesting influences of atmospheric processes of dispersion, removal/wet scavenging as well as the boundary conditions used for 2007 and 2030. Overall, the emission reduction measures implemented in four anthropogenic source sectors under RED2030 could maintain the $PM_{2.5}$ and BC levels in 2030 quite close to or even lower than those in 2007 while under BAU2030 their levels would substantially increase.

2) Number of premature death

The impacts of the two emission scenarios on the number of the premature deaths in 2030, i.e. BAU2030 vs. BY2007, and RED2030 vs. BAU2030, were quantified based on ambient $PM_{2.5}$ and the results are presented in Figure 3. The increase in $PM_{2.5}$ levels under BAU2030 compared to BY2007 would bring in the total number of additional premature deaths in the SEA countries of around 201,000 cases (average 30/100,000 population). In Indonesia, the total number of premature death under BAU2030 would be 52,628 cases (26/100,000 population) while in Thailand it would be 13,420 cases (23/100,000). Spatially, the maximum value of 7/100,000 per grid was seen in the populated areas over the eastern part of Java Island, Indonesia.

The RED2030 would avoid a total number of premature deaths in the SEA countries of 401,000 cases (63/100,000 population) from that estimated for BAU2030. In Indonesia, the number of avoided premature death would be 103,448 (49/100,000 population) while in Thailand it would be around 21,235 (36/100,000 population). More than 50% the total number of avoided premature deaths in SEA countries would be realized in Indonesia and Thailand, where the mitigation measures were considered. The values estimated in this study were lower than those by Shindell et al. (2012) for both Indonesia (74/100,000 population) and Thailand (68/100,000 population) (http://www.giss.nasa.gov/staff/dshindell/Sci2012/FS5/). This is because our study considered a smaller set of emission reduction measures as compared to Shindell et al. (2012) who considered 7 BC measures and 7 methane measures in different sectors. In addition, the health effects in this study were quantified only for $PM_{2.5}$ while Shindell et al. (2012) also included effects of ground level ozone as well as other co-emitting species of BC.

3.3.2 BC direct radiative forcing

The spatial distributions of the simulated annual average BC DRF of BY2007, BAU2030 and RED2030 scenarios are presented in Figure 4. In this section, we discussed only the values estimated for SEA countries in the modeling domain. The maximum simulated BC DRF for SEA countries under BAU2030 (2.0 W m^{-2}), appeared over Riau province, Sumatera Island of Indonesia, and this is about 1 W/m^2 higher than that in BY2007 (0.98 W m^{-2}). Under RED2030, the highest BC DRF would be 1.4 W m^{-2} (appeared above Riau province, Indonesia) i.e. about 0.6 W m^{-2} lower than that of BAU2030. In Thailand, the maximum BC DRF was 0.40 W m^{-2} in 2007, appeared at Chonburi province and increased by two times under BAU2030. Under RED2030, the maximum BC DRF in Thailand would be 0.48 W/m^2, appeared at the same place, i.e. only a slight increase as compared to BY2007. Note that, the highest BC DRF values for all scenarios in the modeling domain were actually seen in the southern part of China.

Apart from Indonesia and Thailand for which the mitigation measures were simulated, other countries in the domain following the RCP8.5 emission pathway also gained benefits because the pollutants (i.e. SLCPs) were also mitigated in this scenario (Riahi et al., 2011) but not the long-lived GHGs (Table 1). Other parts of the modeling domain, i.e. the southern part of China and other SEA countries, also gained quite similar ranges of the BC DRF reduction and the health benefits as Indonesia and Thailand. Our study thus clearly demonstrated that the measures implemented to reduce BC (and PM) may bring in substantial benefit to human health and climate. The benefits to crops and materials, for example, in the region should also be considered and the monetary values of the benefits should be presented in future studies to better inform policy makers and to promote mitigation measures for the SLCPs.

4. Conclusions

This study developed two emission scenarios for SEA in 2030, BAU2030 and RED2030. BAU2030 assumed a linear increase of activity levels of the key anthropogenic sectors in Thailand and Indonesia, and featured a BC emission increase by 1.6 times in Thailand and 1.3 times in Indonesia as compared to BY2007. For other countries in the domain the projection was done using the average GDP growth rate and the emission growth rate was 2.2 times of the BY2007 for all species. RED2030 considered the emission reduction measures in four major anthropogenic sources for Indonesia and Thailand (on-road traffic, residential combustion, industry, open burning), the two large contributors to SEA emissions, and featured a cut in BC emission by 45% in Indonesia and 51% in Thailand as compared to BAU2030. With other countries in the domain would follow RCP8.5 emissions, the collective BC emissions from the modeling domain total under RED2030 would reduce by 16% from the BY2007 amount or 22%. For the SEA domain, the BAU2030 featured a total emission increase in the $PM_{2.5}$ emissions by 1.6 times as compared to BY2007 as well as for BC (1.6 times). The RED2030 $PM_{2.5}$ and BC would reduce by 2.4 times and BC emission by 2.1 times of the BAU2030.

WRF/CHIMERE/AODEM modelling system simulation results provided $PM_{2.5}$ ambient concentrations and BC DRF under different scenarios which showed substantial co-benefits of the emission reduction under RED2030. Under BAU2030, assuming "no intervention", the increase in annual $PM_{2.5}$ levels would induce an additional number of premature deaths of 30/100,000 population above the BY2007 in the SEA domain. The reduction measures implemented under RED2030 would help to cut down (avoided) the total number of the premature deaths by 63/100,000 population as compared to BAU2030. For the two countries where specific measures were to be implemented, RED2030 would help to avoid 49 premature deaths in Indonesia and 36 in Thailand per every 100,000 population. RED2030 would also slow down the increase in the BC DRF over the SEA domain, i.e. lowering the maximum annual average BC DRF from 2.0 W m^{-2} under BAU2030 to 1.4 W/m^2 under RED2030.

Future studies should assess the potential impacts of the emission reduction on agricultural crops (mainly via ozone formation) to better quantify the co-benefit and this is important because agriculture is the major economic sector in SEA. Other pollutants (beside PM and BC) should be included in the assessment of health co-benefits. Likewise, for the long-term climate effects, the induced emission reduction of GHGs by the measures should also be included.

Acknowledgements

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Table caption

Table 1: Emissions of BY2007, BAU2030 and RED2030 for Indonesia, Thailand and other countries in the domain

Table 2: Summary of the co-benefits of emission reduction scenarios for the SEA domain

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Table 1: Emissions of BY2007, BAU2030 and RED2030 for Indonesia, Thailand and other countries in domain

Emission (Gg y^{-1})	SO_2	NOx	NH_3	PM_1	$PM_{2.}$	BC	OC	NMVOC	CO	CO_2	CH_4	N_2O
Indonesia												
BY2007[a]	997	3,282	1,258	2,046	1,644	226	674	3,840	24,169	508,022	3,950	180
BAU2030	1,944	5,251	2,214	2,844	2,252	305	903	5,760	29,003	810,413	5,530	324
RED2030	1,785	4,923	2,151	859	904	167	506	4,608	17,885	378,193	3,792	157
Ratio BAU2030/BY2007	1.95	1.6	1.76	1.39	1.37	1.35	1.34	1.5	1.2	1.5	1.4	1.8
Ratio RED2030/BY2007	1.79	1.5	1.71	0.42	0.55	0.74	0.75	1.2	0.74	0.7	0.96	0.87
Ratio RED2030/BAU2030	0.92	0.94	0.97	0.3	0.4	0.55	0.56	0.8	0.62	0.47	0.69	0.48
Thailand												
BY2007	827	701	469	782	607	47	240	1,120	9,095	260,988	1,053	84
BAU2030	1,613	995	727	1,298	953	77	341	1,725	9,186	287,087	1,685	151
RED2030	1,340	925	661	712	498	38	127	1,366	6,730	219,230	853	80
Ratio BAU2030/BY2007	1.95	1.42	1.55	1.66	1.57	1.63	1.42	1.54	1.01	1.1	1.6	1.8
Ratio RED2030/BY2007	1.62	1.32	1.41	0.91	0.82	0.8	0.53	1.22	0.74	0.84	0.81	0.95
Ratio RED2030/BAU2030	0.83	0.93	0.91	0.55	0.52	0.49	0.37	0.79	0.73	0.76	0.51	0.53
Other countries in the domain												
BY2007	8,940	6,886	3,900	5,522	4,184	528	1,287	10,416	55,308	2,291,381	29,186	677
BAU2030[b]	19,668	15,149	8,580	12,148	9,205	1,162	2,831	22,915	121,678	5,041,038	64,209	1,489
RED2030[c]	6,169	7,781	5,070	4,915	3,640	444	1,133	10,937	54,202	2,749,657	34,439	785
Ratio BAU2030/BY2007	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Ratio RED2030/BY2007	0.69	1.13	1.3	0.89	0.87	0.84	0.88	1.05	0.98	1.2	1.18	1.16
Ratio RED2030/BAU2030	0.31	0.51	0.59	0.41	0.4	0.38	0.4	0.48	0.45	0.55	0.54	0.53

Note: [a] Permadi and Kim Oanh (2017b). [b] - GDP average growth rates from 2000 – 2007 for other countries were obtained from http://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG. Population weighted average GDP for other SEA countries and southern part of China was calculated to construct BAU2030/BY2007 ratio. [c] -2030/2007 ratio was extracted from RCP8.5 pathways taken from (http://tntcat.iiasa.ac.at:8787/RcpDb/)

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Table 2: Summary of co-benefits of emission reduction scenarios for the SEA domain.

Emission scenario	Remarks	BY2007	BAU2030	RED2030
Emission of $PM_{2.5}$ (Gg y^{-1})	SEA domain	3,171	5,230	2,203
Emission of PM_{10} (Gg y^{-1})	SEA domain	5,036	9,001	3,537
Emission of BC (Gg y^{-1})	SEA domain	373	603	289
$PM_{2.5}$ in SEA (µg m^{-3})	Hourly maximum	189	296	146
	Highest annual average[a]	32.0	36.4	21.1
	Highest monthly average[b]	82	97	58
PM_{10} in SEA (µg m^{-3})	Hourly maximum	327	472	247
	Highest annual average[a]	50	58	34
	Highest monthly average[b]	127	150	88
BC in SEA (µg m^{-3})	Hourly maximum	39	59	32
	Highest annual average[a]	6.0	7.2	4.3
	Highest monthly average[b]	21	22	11
BC AOD in SEA	Highest monthly average[b]	0.08	0.24	0.11
BC DRF in SEA (W m^{-2})	Highest annual average[a]	0.98	2	1.4
Mortality cases per 100,000 of population[c]	Total number of additional mortality cases in the SEA domain compared to BY2007		(+) 30[d]	(-)63[e]
	Total number of additional mortality cases in Indonesia		(+)26[d]	(-)49[e]
	Total number of additional mortality cases in Thailand		(+)23[d]	(-)36[e]

Note: this table does not include the values simulated for southern China part of the modeling domain total.
[a] Highest annual average value observed in the SEA domain, [b] Highest monthly average value observed in the SEA countries, and [c] Sum of all value in the SEA/country, (+) addition, and (-) reduction (avoided), [d] compared to BY2007, [e] compared to BAU2030.

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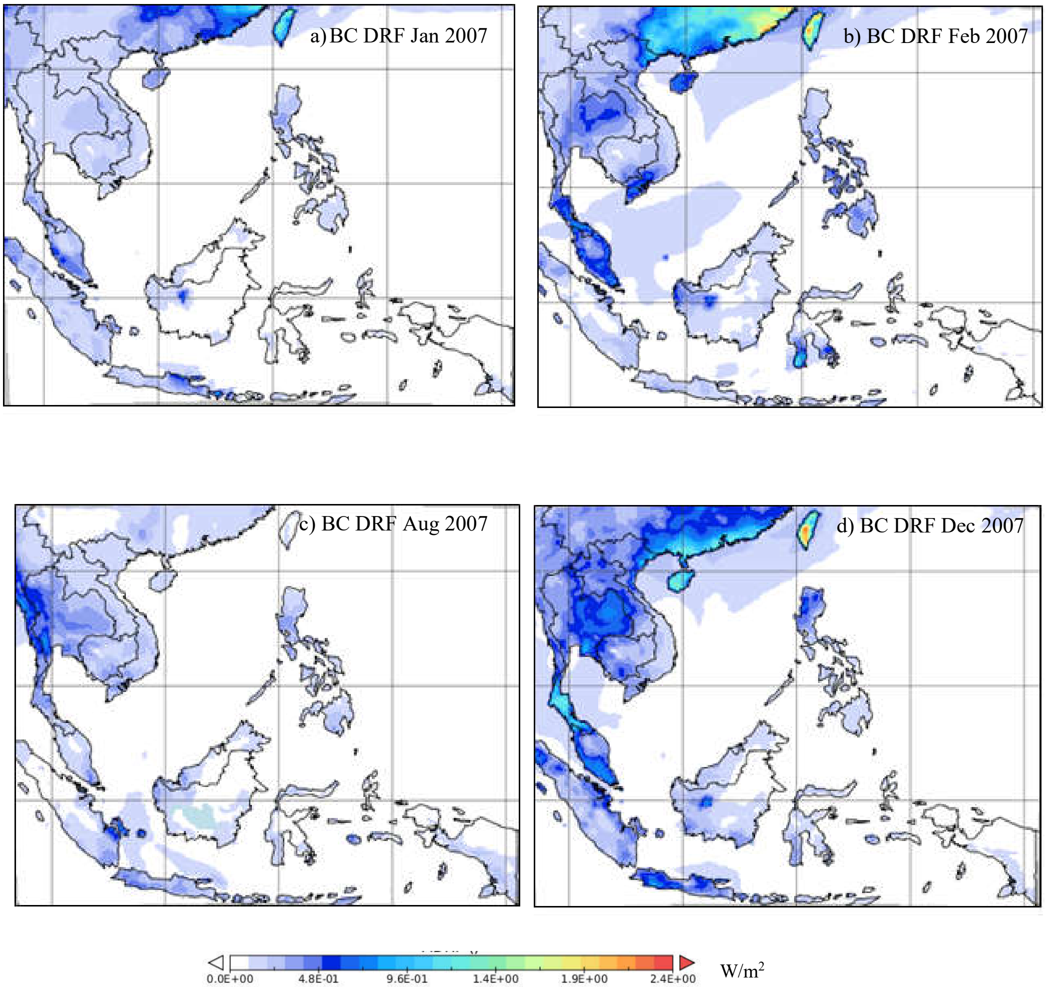
Figure captions

Figure 1: Spatial distribution of monthly average BC direct radiative forcing for the selected months, 2007
Figure 2: Simulated annual average concentrations of BC and $PM_{2.5}$ for BY2007, BAU2030 and RED2030 in $\mu g/m^3$
Figure 3: Change in the number of mortality cases between BAU2030 and BY2007, and between BAU2030 and RED2030 (cases/100,000 population)
Figure 4: Spatial distribution of annual average BC DRF under BY2007, BAU2030 and RED2030 scenario.



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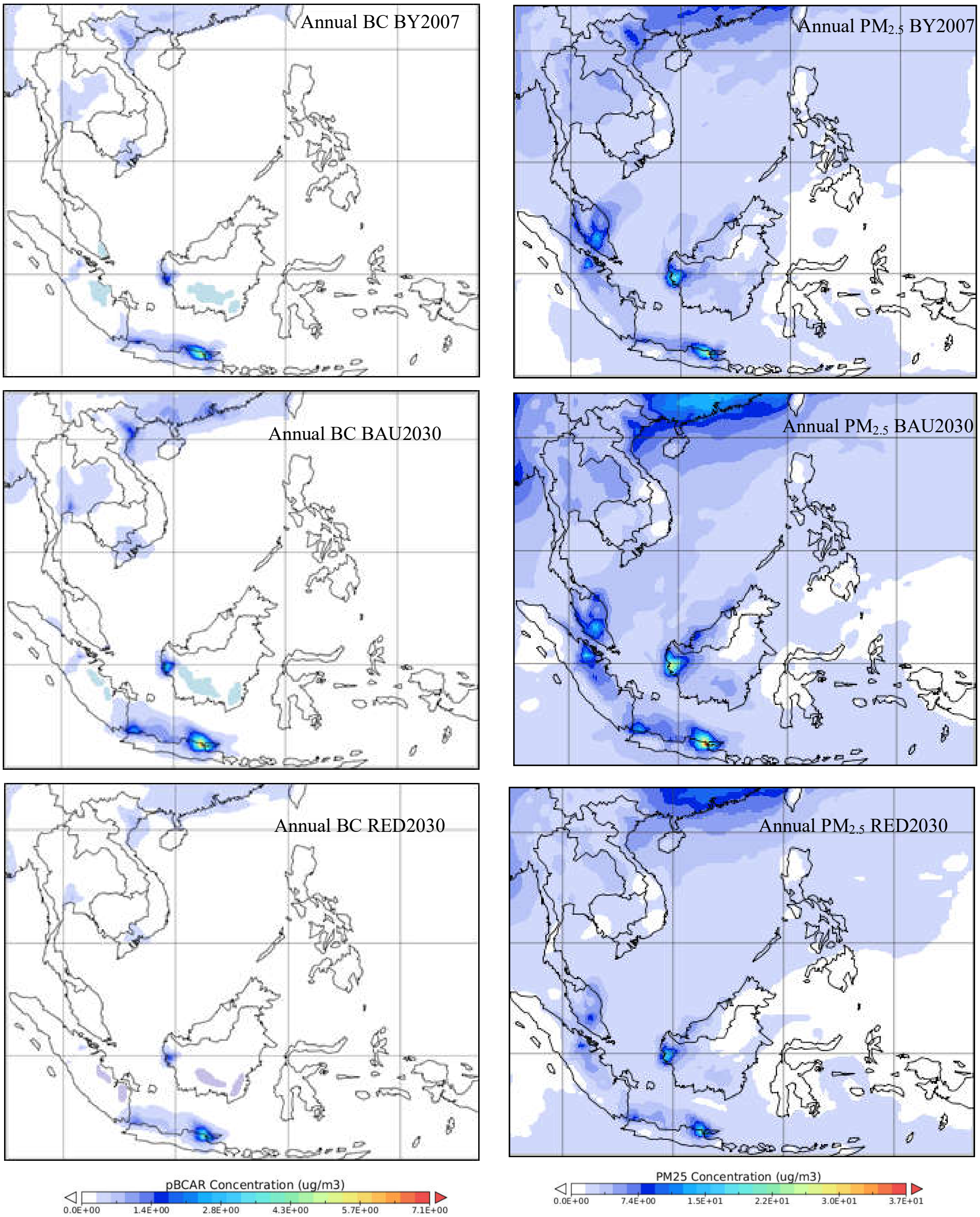

Figure 2: Simulated annual average concentrations of BC and $PM_{2.5}$ for BY2007, BAU2030 and RED2030 in µg/m^3

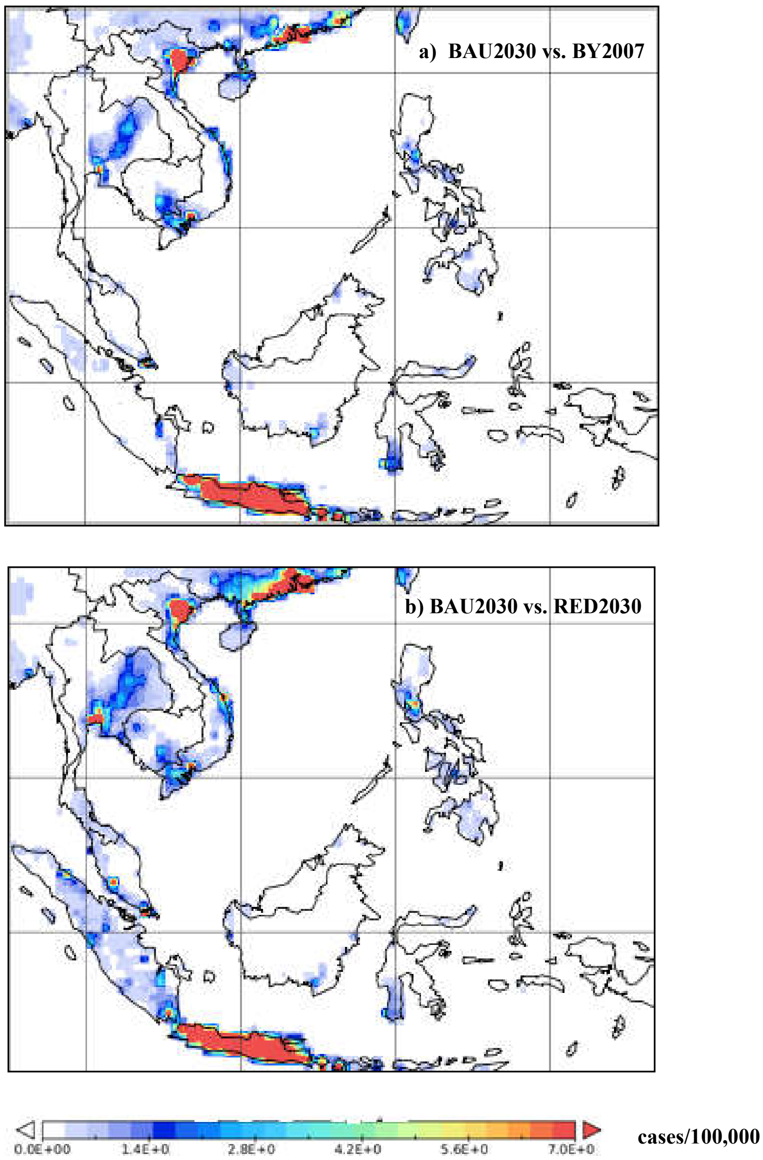

Figure 3: Change in the number of mortality cases between BAU2030 and BY2007, and between BAU2030 and RED2030 (cases/100,000 population)

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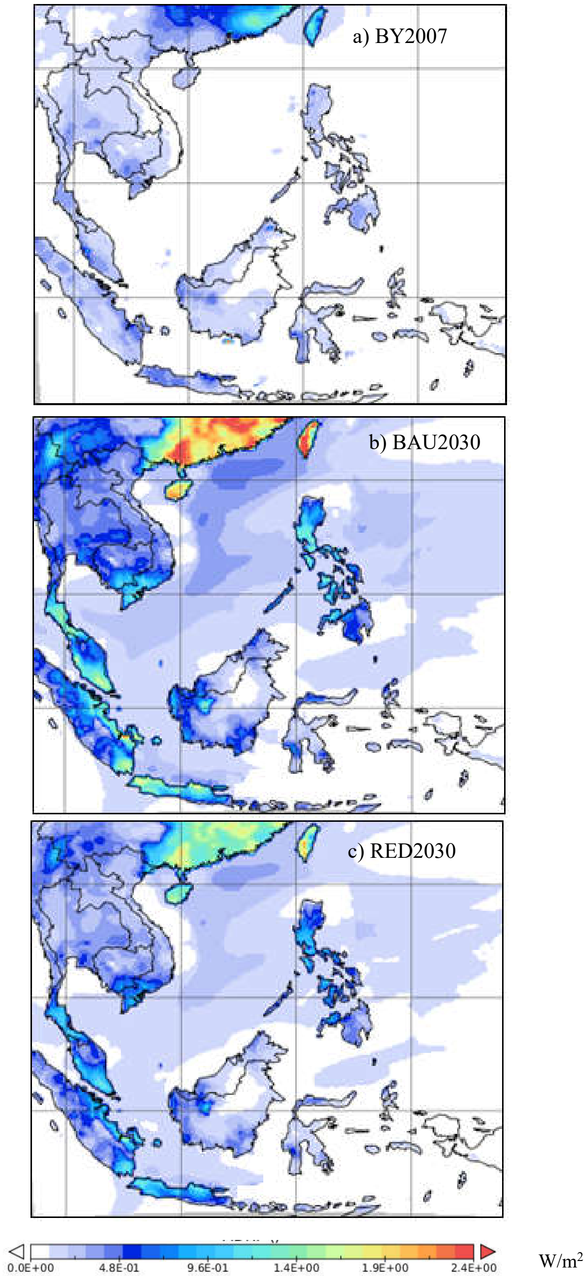

Figure 4: Spatial distribution of annual average BC DRF under BY2007, BAU2030 and RED2030 scenario.