Estimating Mortality Related to O$_3$ and PM$_{2.5}$ under Changing Climate and Emission in Continental Southeast Asia

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ABSTRACT

Air pollution causes adverse effects not only on the environment but also on human health. This study evaluated the excess mortalities in continental Southeast Asia that are related to future O$_3$ and PM$_{2.5}$ ambient concentration changes attributed to future climate change and emission change. The Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE) was applied as a health impact assessment tool. In BenMAP-CE simulations, baseline scenarios presenting for the present year (2014) were compared against the control scenarios presenting for the future year (2050). The air pollutant concentrations for the simulations were collected from modeled data. The future population data and baseline incidence rates were as same as the 2014 levels. In four calculating countries namely Laos, Cambodia, Thailand, and Vietnam, on average, impacted by climate change alone, the avoided mortalities of –1164 and –3358 under Representative Concentration Pathway (RCP) 4.5 scenario and the additional mortalities of +758 and +2562 under RCP8.5 scenario were calculated for O$_3$ and PM$_{2.5}$, respectively. Future emission change alone under Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants current legislation (ECLIPSE CLE) scenario induces +7113 and +11072 additional O$_3$ and PM$_{2.5}$ related mortalities, respectively. Combined change in climate and emission produces additional O$_3$ and PM$_{2.5}$ related mortalities of +6067 and +7830 under RCP4.5 and ECLIPSE CLE combined scenario and +8763 and +14580 under RCP8.5 and ECLIPSE CLE combined scenario, respectively. The results of this study provided meaningful information for understanding the public health attributed to air pollution in the region.

Keywords: Fine particulate matter, Ozone, BenMAP-CE, Mortality

1 INTRODUCTION

Southeast Asia has been faced with air pollution issues largely caused by rapid population growth and economic development. Its annual rate of population change was 1.1% during the period 2015–2020 (UN, 2019) and its gross domestic product was 5.0% during the period 2013–2017 (OECD, 2019). Regional air quality varies widely across space and time (Nguyen et al., 2019a). Ambient concentrations of ozone (O$_3$) and particle with an aerodynamic diameter smaller than and equal to 2.5 µm (PM$_{2.5}$) have continued to increase. Open biomass burning and inappropriate land-use practices cause transboundary smoke haze pollution which has become a serious air quality problem in Southeast Asia (UNEP, 2016). As well-known, along with environmental effects, air pollution produces harmful effects on human health. Exposure to air pollution might increase the risk of heart disease, chronic respiratory diseases, lung infections, and cancer (HEI, 2019). Of the pollutants in the atmosphere, O$_3$ and PM$_{2.5}$ are believed to be the most detrimental to public health (Boldo et al., 2011; EEA, 2012; Stowell et al., 2017; Yang et al., 2019). Studies have shown a link between O$_3$ and PM$_{2.5}$ exposures and a variety of adverse health outcomes.
Breathing to PM$_{2.5}$ in long-term is related to irregular heartbeat, heart attacks, premature death, and respiratory symptoms (U.S. EPA, 2019). Breathing to O$_3$ in long-term is associated with cardiovascular, respiratory, reproductive, metabolic, and central nervous system effects (U.S. EPA, 2020). According to HEI (2019), in 2017, air pollution ranked fifth among the global mortality risk factors. It caused nearly 5 million early deaths, of which, ambient PM$_{2.5}$ accounted for about 2.9 million deaths and O$_3$ accounted for about 472,000 early deaths.

Assessing the health effects of air pollution can not only inform about air pollution-related public health, but also consider the possible air pollution control (Sacks et al., 2020). To calculate the public health impact related to air pollution, various tools have been developed such as AirCounts, AIRQ2.2, GMAPS, EBD, LEAP-IBC, IOMLIFET, TMS-FASST, SIM-Air (Anenberg et al., 2016). Among these tools, the Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE) developed by U.S. EPA is one of the best well-known programs. BenMAP-CE has been used extensively at local, regional, national, and global scales and reported in a large number of publications. The range of countries where BenMAP-CE was applied covers all continents, the most common use are in North America, South America, Europe, and Asia (Chen et al., 2017; Li et al., 2019; Sacks et al., 2018; 2020).

Generally, many studies applied the health impact assessment tools to quantify the harmful effects on health caused by O$_3$ and PM$_{2.5}$ using the monitoring/modeled concentrations or to evaluate the health benefits from an air pollution control implementation. However, there are few studies that addressed the link between human health and air quality in the context of future changing climate and emission. Climate change can impact the pollutants in the atmosphere through several mechanisms including air stagnation conditions, deposition rates, natural emissions, and photochemical reactions (Jacob and Winner, 2009; Fiore et al., 2015; Nguyen et al., 2019b). Moreover, future change in anthropogenic emission will directly change the air quality (Nguyen et al., 2020). So far, some researches have quantified health effects attributed to air pollution change resulting from the changes in future climate and emission (Fang et al., 2013; Fann et al., 2015; Stowell et al., 2017; Tagaris et al., 2009; Yang et al., 2019; Zhang et al., 2017). One of these studies was by Stowell et al. (2017). The study assessed the excess mortalities associated with O$_3$ concentrations impacted by future climate change and emission control policies in the United States. It indicated that, by 2050, under Representative Concentration Pathway (RCP) 4.5 scenario, increased O$_3$ levels could contribute to an annual increase of about 50 premature deaths. Under RCP8.5 scenario, increased O$_3$ level was calculated to cause over 2200 additional premature deaths annually. However, in continental Southeast Asia, this kind of research is still lacking while estimation of impacts of future air pollution on public health is necessary because this data is useful for the development of air pollution control and public health protection plans.

This study evaluated the excess mortalities resulting from the changes in the future O$_3$ and PM$_{2.5}$ ambient concentrations impacted by the future climate change and emission change. BenMAP-CE health impact assessment tool was applied for this estimation. In BenMAP-CE calculation, baseline scenarios presenting for the present year (2014) were compared against the control scenarios presenting for the future year (2050). The year 2050 was chosen for the projected year because the IPCC generally uses the year 2050 as the threshold for major global temperature divergence (IPCC, 2013). The evaluation accounted for the health impacts related to O$_3$ and PM$_{2.5}$ changes produced by future climate change alone, future emission change alone, and changes in both future climate and emission. The future climate was according to RCP4.5 and RCP8.5 scenarios. The future emission was according to the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants current legislation (ECLIPSE CLE) scenario. The calculation of mortality was carried out for Laos, Cambodia, Thailand, and Vietnam considering annual and seasonal trends. Seasons of the year were defined as the dry season and the wet season. The dry season is from November to April. The wet season is from May to October. To our best knowledge, this is the first study that investigated the indirect impacts of climate and emission changes on mortality via their direct impacts on O$_3$ and PM$_{2.5}$ concentrations in continental Southeast Asia. It is because of the limited studies currently addressing the air quality impacted by future climate and emission changes in the region.
2 MATERIALS AND METHODS

2.1 Air Quality Modeling Data

The Weather Research and Forecasting (WRF) model version 3.4 (Skamarock et al., 2008) was online coupled with Community Multiscale Air Quality (CMAQ) model version 5.0.2 (CMAS, 2012) to provide the current and future O3 and PM2.5 levels in continental Southeast Asia. The modeling domain (Fig. 1) had a horizontal resolution of 24 km. It had 98 × 98 grid cells covering 4°N to 26°N and 94°E to 116°E. The number of its vertical grid cells was 30, from the surface up to 100 hPa. In the CMAQ model, the gas-phase chemistry and the aerosol process were based on the Carbon Bond mechanism developed in 2005 (CB05) (Whitten et al., 2010) and the sixth-generation CMAQ aerosol module (AERO6) (Appel et al., 2013), respectively. The clear-sky photolysis rates were calculated using the method that calculates the rates online using O3 and aerosol concentrations projected within a simulation (Binkowski et al., 2007). Comprehensive model evaluations were performed by comparing the model results of baseline simulation with the observations at monitoring sites (Fig. 1). The correlation coefficients between the modeled concentrations and observed concentrations were 0.69 and 0.36 for O3 and 0.80 and 0.69 for PM2.5 in Thailand and Vietnam, respectively. The modeled PM2.5 concentrations were found to be underestimated in Thailand but overestimated in Vietnam. The modeled O3 concentrations were overestimated in both countries. The detailed WRF-CMAQ model configuration and evaluation can be found in Nguyen et al. (2019a).

In order to project the future air pollution levels attributed to the impacts of climate change alone, emission change alone, and the changes in both climate and emission in future year (2050) relative to the present year (2014), WRF-CMAQ simulations were carried out which were different in using the meteorological and emission input data. The first simulation, a baseline simulation, was used the present meteorology condition and present anthropogenic emission. The next two simulations were used future meteorology condition and present anthropogenic emission. The future climate was calculated following the two popular RCP4.5 and RCP8.5 climate scenarios developed by Intergovernmental Panel on Climate Change (IPCC). The fourth simulation was used present meteorology condition and future anthropogenic emission. Future anthropogenic emission was produced based on the projection of ECLIPSE CLE scenario. The last two simulations were used future meteorology condition under RCP4.5 and RCP8.5 scenarios and future anthropogenic emission under ECLIPSE CLE scenario. Description of key input of the simulations is summarized in Table 1. More details about simulation design together with simulation input data were reported in our previous studies (Nguyen et al., 2019b, 2020). The O3 and PM2.5 concentration results of all the above WRF-CMAQ simulations were used for BenMAP-CE simulations which were described in Section 2.3.

The detail future changes in O3 and PM2.5 levels due to future climate and emission changes can be found in Nguyen et al. (2019b, 2020). Table 2 and Figs. 2 and 3 show O3 and PM2.5 average...
Table 1. Description of air quality simulations.

| Simulation                                                                 | Meteorological conditions                                                                                     | Anthropogenic emission                                      |
|----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| Present climate and present emission simulation (baseline simulation)      | 2014 National Centers for Environmental Prediction/final analysis (NCEP/FNL) and real time global high resolution sea surface temperature (RTG_SST_HR) meteorological conditions | 2010 Hemispheric Transport of Air Pollution (HTAP) emission data |
| Future climate and present emission simulation (under RCP4.5 scenario)     | 2050 meteorological conditions obtained by taking the sum of the differences between future (2046–2055) and present (2006–2015) climate conditions which were generated by Community Earth System Model (CESM) that participated in phase 5 of the Coupled Model Intercomparison Experiment (CMIP5) under RCP4.5 scenario and 2014 NCEP/FNL and RTG_SST_HR meteorological conditions | 2010 HTAP emission data                                     |
| Future climate and present emission simulation (under RCP8.5 scenario)     | 2050 meteorological conditions obtained by taking the sum of the differences between future (2046–2055) and present (2006–2015) CMIP5 CESM climate conditions under RCP8.5 scenario and 2014 NCEP/FNL and RTG_SST_HR meteorological conditions | 2010 HTAP emission data                                     |
| Present climate and future emission simulation (under ECLIPSE CLE scenario) | 2014 NCEP/FNL and RTG_SST_HR meteorological conditions                                                       | 2050 emission data produced by multiplying 2010 HTAP emission with the ratio of 2050 ECLIPSE CLE emission to 2010 ECLIPSE CLE emission |
| Future climate and future emission simulation (under RCP4.5 and ECLIPSE CLE scenarios) | 2050 meteorological conditions obtained by taking the sum of the differences between future (2046–2055) and present (2006–2015) CMIP5 CESM climate conditions under RCP4.5 scenario and 2014 NCEP/FNL and RTG_SST_HR meteorological conditions | 2050 emission data produced by multiplying 2010 HTAP emission with the ratio of 2050 ECLIPSE CLE emission to 2010 ECLIPSE CLE emission |
| Future climate and future emission simulation (under RCP8.5 and ECLIPSE CLE scenarios) | 2050 meteorological conditions obtained by taking the sum of the differences between future (2046–2055) and present (2006–2015) CMIP5 CESM climate conditions under RCP8.5 scenario and 2014 NCEP/FNL and RTG_SST_HR meteorological conditions | 2050 emission data produced by multiplying 2010 HTAP emission with the ratio of 2050 ECLIPSE CLE emission to 2010 ECLIPSE CLE emission |

Concentrations and concentration changes under the impacts of changes in climate and emission. Positive values mean concentration increase, negative values mean concentration decrease. Briefly, our previous study (Nguyen et al., 2019b) found that climate change has a non-negligible impact on O₃ and PM₂.₅ concentrations since it changes O₃ and PM₂.₅ concentrations in four targeted countries up to 4.62% and 22.52%, respectively. Under RCP4.5 scenario, O₃ and PM₂.₅ concentrations appear to be reduced in the future atmosphere which indicated a potential benefit for air quality. The largest O₃ decrease occurs in Vietnam during the dry season and in Laos during the wet season. The largest PM₂.₅ decrease is in northern Cambodia and northern Vietnam. Under RCP8.5 scenario, climate change causes increases in O₃ and PM₂.₅ concentrations in most areas in the dry season. In the wet season, there are more areas that have O₃ and PM₂.₅ decreases compared to the dry season. The large O₃ increase is located in northern Vietnam and the large PM₂.₅ increase is located in areas surrounding northern Cambodia and southern Laos in the dry season. O₃ decrease was found in Laos and Vietnam and PM₂.₅ decrease was found in Cambodia, Laos, and Vietnam in the wet season. Under these two scenarios, O₃ decrease is attributed to water vapor increase, and O₃ increase is driven mainly by the stagnant condition, biogenic emission increase, and temperature increase; PM₂.₅ decrease is mostly due to the precipitation increase, and PM₂.₅ increase is caused largely by the more stagnant condition in the future climate (Nguyen et al., 2019b). Comparing to the impacts of climate change alone, the impacts of emission change alone on regional air quality are larger (Nguyen et al., 2020). Overall, attributable to emission growth separately under
Table 2. \(O_3\) and \(PM_{2.5}\) average concentrations in baseline simulation and concentration changes under the impacts of changes in climate and emission.

| Country       | \(O_3\) concentration, ppb | \(PM_{2.5}\) concentration, \(\mu g/ m^3\) |
|---------------|-----------------------------|---------------------------------------------|
|               | Entire year | Dry season | Wet season | Entire year | Dry season | Wet season |
| Baseline      |             |            |            |             |            |            |
| Cambodia      | 28.08       | 36.12      | 20.25      | 23.26       | 40.94      | 6.27       |
| Laos          | 32.09       | 39.78      | 24.57      | 23.26       | 36.85      | 9.88       |
| Thailand      | 32.24       | 40.23      | 24.42      | 19.43       | 29.40      | 9.56       |
| Vietnam       | 32.11       | 37.50      | 26.80      | 24.08       | 32.73      | 15.46      |
| RCP4.5        |             |            |            |             |            |            |
| Cambodia      | –0.64       | –0.79      | –0.51      | –0.88       | –1.56      | –0.23      |
| Laos          | –0.91       | –0.92      | –0.90      | –1.16       | –1.32      | –1.00      |
| Thailand      | –0.64       | –0.72      | –0.56      | –0.75       | –0.76      | –0.73      |
| Vietnam       | –0.92       | –1.05      | –0.80      | –1.18       | –1.36      | –1.01      |
| RCP8.5        |             |            |            |             |            |            |
| Cambodia      | +0.20       | +0.39      | +0.02      | +1.26       | +2.67      | –0.16      |
| Laos          | +0.11       | +0.54      | –0.30      | +0.90       | +1.85      | –0.04      |
| Thailand      | +0.31       | +0.40      | +0.22      | +1.14       | +2.13      | +0.16      |
| Vietnam       | +0.32       | +0.71      | –0.05      | +0.50       | +1.46      | –0.46      |
| ECLIPSE CLE   |             |            |            |             |            |            |
| Cambodia      | +4.43       | +4.13      | +4.74      | +1.26       | +1.68      | +0.88      |
| Laos          | +6.19       | +5.44      | +6.97      | +4.12       | +5.00      | +3.30      |
| Thailand      | +6.51       | +7.09      | +5.95      | +4.54       | +5.58      | +3.55      |
| Vietnam       | +4.09       | +2.40      | +5.77      | +3.54       | +4.04      | +3.08      |
| RCP4.5 and ECLIPSE CLE |   |            |            |             |            |            |
| Cambodia      | +3.74       | +3.34      | +4.15      | +0.35       | +0.09      | +0.61      |
| Laos          | +5.32       | +4.64      | +6.02      | +2.89       | +3.58      | +2.25      |
| Thailand      | +5.90       | +6.51      | +5.33      | +3.80       | +4.93      | +2.72      |
| Vietnam       | +3.25       | +1.43      | +5.05      | +2.30       | +2.52      | +2.11      |
| RCP8.5 and ECLIPSE CLE |         |            |            |             |            |            |
| Cambodia      | +4.81       | +4.82      | +4.84      | +2.63       | +4.63      | +0.68      |
| Laos          | +6.92       | +6.87      | +7.01      | +5.48       | +7.47      | +3.56      |
| Thailand      | +7.35       | +8.36      | +6.36      | +6.25       | +8.70      | +3.87      |
| Vietnam       | +4.95       | +3.77      | +6.15      | +4.15       | +5.65      | +2.69      |

ECLIPSE CLE scenario, \(O_3\) and \(PM_{2.5}\) increases were projected for continental Southeast Asia excepting part of northern Vietnam in the dry season for \(O_3\) and areas in and surrounding Phnom Penh (PP), Hanoi Metropolitan Region (HNMR), and Ho Chi Minh City Metropolitan Region (HCMCMR) (Fig. 1) all year round for \(PM_{2.5}\). The \(O_3\) decrease in part of northern Vietnam could be explained as follows. The ratio of NMVOCs/NOx in the area was very low compared to those of the other areas. Therefore, the lower this ratio decreases under the effects of projected anthropogenic emission change, the more favorable the titration is in this area than in the other areas, causing a greater \(O_3\) loss. Reduction in \(PM_{2.5}\) was observed in areas in and surrounding PP, HNMR, and HCMCMR because there are anthropogenic primary \(PM_{2.5}\) EC and \(PM_{2.5}\) OC emission decreases implying a success of air quality control activities in these areas (Nguyen et al., 2020). In comparison with Cambodia and Vietnam, Laos and Thailand suffer more \(O_3\) increases. The annual average \(O_3\) increases are +6.19 and +6.51 ppb in Laos and Thailand while they are +4.43 and +4.09 ppb in Cambodia and Vietnam, respectively (Table 2). A significant \(O_3\) increase was found in the wet season in northern Laos. For \(PM_{2.5}\), areas in and surrounding Bangkok Metropolitan Region (BMR), Mae Moh power plant (MMPP), and part of northern Vietnam receive significant increases. Climate change and emission change in combination mostly produce the rises in \(O_3\) and \(PM_{2.5}\) concentrations. \(O_3\) and \(PM_{2.5}\) rises are larger in RCP8.5 and ECLIPSE CLE combined scenario than that in RCP4.5 and ECLIPSE CLE combined scenario. The spatial patterns of concentration changes in these two scenarios were quite similar to those of ECLIPSE CLE scenario.
Fig. 2. (a) O₃ baseline concentration and concentration change between current and future under (b) RCP4.5 scenario, (c) RCP8.5 scenario, (d) ECLIPSE CLE scenario, (e) RCP4.5 and ECLIPSE CLE combined scenario, and (f) RCP8.5 and ECLIPSE CLE combined scenario.
Fig. 3. (a) PM$_{2.5}$ baseline concentration and concentration change between current and future under (b) RCP4.5 scenario, (c) RCP8.5 scenario, (d) ECLIPSE CLE scenario, (e) RCP4.5 and ECLIPSE CLE combined scenario, and (f) RCP8.5 and ECLIPSE CLE combined scenario.
2.2 Population Data

The population exposed to O3 and PM2.5 for the year 2014 in four calculated countries was calculated by scaling the 2015 gridded population using a population growth rate. The 2015 gridded population with 10 km² resolution was obtained from Regional Datasets on the U.S. EPA website for BenMAP-CE which originated from the UN, Socioeconomic Data and Applications Center (SEDAC) Gridded Population of the World (GPW) v4. The growth rate of each country for the year from 2010 to 2015 was calculated from annual population data provided by the Population Division, Department of Economic and Social Affairs, UN (UN, 2019). The estimated 2014 population distribution is shown in Fig. 4. In general, Vietnam and Thailand had high population and population densities than Cambodia and Laos. The population was highly concentrated in areas in and surrounding BMR, HNMR, HCMCMR, and PP. At area surrounding MMPP, where has a high PM2.5 concentration increase, also had a dense population.

2.3 Health Impact Assessment

The BenMAP-CE health impact assessment tool version 1.5 released in May 2021 was employed to estimate excess mortalities related to O3 and PM2.5 changes in the future period due to changes in climate and emission. BenMAP-CE is an open source software that is powerful in estimating health impacts resulting from changes in air pollution concentrations (U.S. EPA, 2021). To quantify health impacts associated with air pollution, BenMAP-CE first estimates the air pollution change using user-specified air quality data. The change in air pollutant concentration is the difference between the starting pollutant concentration in a baseline scenario and the pollutant concentration after some change in a control scenario. Next, this pollutant concentration change is related to certain health effects. The relationship between concentration change and health effect is referred to as the health impact function (HIF). These functions are derived from epidemiology studies relating pollutant concentrations with health outcomes. BenMAP-CE utilizes HIFs to the population experiencing the air pollution change to calculate health impacts. The expression for HIF is defined as shown in Eq. (1) (U.S. EPA, 2021).

\[ \Delta Y = (1 - e^{(-\beta \times \Delta AQ)}) \times Y_0 \times POP \]

where \( \Delta Y \) represents the rate of adverse health effects due to the change of pollutant concentration. The statistical coefficient \( \beta \), which is unitless, is determined from the epidemiological analysis measuring the response of a health effect to one-unit change in pollutant concentration. \( \Delta AQ \) represents the concentration difference between the control scenario and the baseline scenario. \( Y_0 \) is the baseline incidence rate for the health endpoint per unit population, and \( POP \) represents the population exposed to the air pollution.

In BenMAP-CE, there is a library of HIFs which is used for different health endpoints including work loss days, morbidity, and mortality. In this study, the selected health effect was mortality from all-cause. Table 3 summarizes the HIFs embedded in BenMAP-CE that were selected to apply in this study. The HIF for O3 (Bell et al., 2005) was selected since it represents the entire age groups.

![Image](https://example.com/image.png)

**Fig. 4.** Estimated spatial population distribution in year 2014.
### Table 3. Summary of the main characteristics of the selected HIFs.

| Health effect | Author     | Year | Location      | Age | $\beta$  | Standard error | Form     |
|---------------|------------|------|---------------|-----|----------|----------------|----------|
| $O_3$ Mortality, all-cause | Bell et al. | 2005 | US and non-US | 0–99 | 0.001500 | 0.000401 | Log-linear |
| PM$_{2.5}$ Mortality, all-cause | Turner et al. | 2016 | Nationwide | 30–99 | 0.005827 | 0.000963 | Log-linear |

and is the only choice for the health endpoint of all-cause mortality related to daily 24 (D24) hour mean $O_3$ within in datasets of BENMAP-CE. The selected all-cause mortality HIF for PM$_{2.5}$ (Turner et al., 2016) is the most recent HIF which covers larger numbers of locations and age groups compared to the others in the datasets.

To calculate $O_3$ and PM$_{2.5}$ related excess mortality, the key input data was obtained as follows. Air quality changes, $\Delta AQ$, were calculated by using two sets of pollutant concentrations: future pollutant concentrations minus present concentrations. The future and present pollutant concentrations were simulated as documented in Section 2.1. The exposed population, $POP$, was estimated as shown in Section 2.2. All-cause baseline mortality rates, $Y_0$, in 2014 were calculated from crude death rates collected from Work Bank Open Data (https://data.worldbank.org/). All the data inputs were adjusted according to formats that BenMAP-CE recognizes. All other options and parameters were set as default within the tool.

In order to estimate the health impacts produced by the change of $O_3$ and PM$_{2.5}$ concentrations caused by climate change alone, emission change alone, and combined climate change and emission change, five simulations were performed. The present and future air quality (AQ) data were referred to as the baseline scenario and the control scenario in each simulation, respectively. In all simulations, the future exposed population and baseline mortality rates were kept constant as in the present levels so that the estimated mortalities were affected only by pollutant concentration changes between present and future air quality. In the first and second simulations, the $O_3$ and PM$_{2.5}$ levels caused by climate change alone under RCP4.5 and RCP8.5 scenarios, respectively, were used as the future air quality data, therefore, these mortality assessments can quantify the air pollution-related health impacts due to climate change alone. Similarly, in the third simulation, the $O_3$ and PM$_{2.5}$ levels caused by emission change alone under ECLIPSE CLE scenario were used as the future air quality data, so that, this assessment estimated mortality attributed to air quality change due to future emission change alone. In the fourth and fifth simulations, the $O_3$ and PM$_{2.5}$ levels caused by both climate change under RCP4.5 and RCP8.5 scenarios, respectively, and emission change under ECLIPSE CLE scenario were used as the future air quality data, and these assessments provided mortality attributed to climate change along with emission change. This type of simulation design has been carried out in several previous works (Knowlton et al., 2004; Sun et al., 2015; Yang et al., 2019). Table 4 summarizes the simulation design of this study.

### 3 RESULTS AND DISCUSSION

#### 3.1 Mortality Related to $O_3$

Table 5 summarizes annual and seasonal all-cause mortality findings caused by future changes in $O_3$ attributable to climate change and emission change. The additional mortalities are presented by positive values, the avoided mortalities are presented by negative values. The mean values were given together with median values, and 90% confidence intervals (CI). National mortality was gained by adding up all the estimates of the nation’s cells. In response to the decrease in future $O_3$ in Cambodia, Laos, Thailand, and Vietnam, BenMAP-CE estimated −53, −30, −242, −419 avoided mortalities in the dry season, −29, −28, −140, −226 avoided mortalities in the wet season, and −82, −58, −382, −642 avoided mortalities all year round in average under RCP4.5 scenario, respectively. On the other hand, the predicted increase in future $O_3$ under RCP8.5 scenario results in additional mortalities except in Laos in the wet season. Cambodia has +23, +4, +27 additional mortalities, Thailand has +197, +136, +339 additional mortalities, Vietnam has +349, +38, +383 additional mortalities in the dry season, the wet season, and all year round, respectively. Lao has
Table 4. Simulation design.

| Simulation | ΔAQ | AQBaseline scenario | POP | Y0 |
|------------|-----|---------------------|-----|----|
| S1         | +16  | 2014 climate and 2010 emission | 2014 | 2014 |
| S2         | +17  | 2014 climate and 2010 emission | 2014 | 2014 |
| S3         | +18  | 2014 climate and 2010 emission | 2014 | 2014 |
| S4         | +19  | 2014 climate and 2010 emission | 2014 | 2014 |

Table 5. Annual and seasonal excess mortalities due to projected O₃ concentration changes.

| Country     | Number of excess mortalities, death |
|-------------|-------------------------------------|
|             | Mean  | Median | 90% CI | Mean  | Median | 90% CI | Mean  | Median | 90% CI |
| RCP4.5      |       |        |        |       |        |        |       |        |        |
| Cambodia    | −82   | −81    | −38    | −113  | −53    | −52    | −25    | −74    | −29    | −28    | −13    | −40    |
| Laos        | −58   | −57    | −27    | −81   | −30    | −30    | −14    | −42    | −28    | −27    | −13    | −38    |
| Thailand    | −382  | −376   | −178   | −529  | −242   | −238   | −113   | −335   | −140   | −137   | −65    | −193   |
| Vietnam     | −642  | −631   | −298   | −888  | −419   | −412   | −195   | −580   | −226   | −222   | −105   | −313   |
| RCP8.5      |       |        |        |       |        |        |       |        |        |
| Cambodia    | +27   | +27    | +13    | +37   | +23    | +23    | +11    | +32    | +4     | +4     | +2     | +6     |
| Laos        | +9    | +9     | +4     | +13   | +17    | +16    | +8     | +23    | −7     | −6     | −3     | −9     |
| Thailand    | +339  | +334   | +158   | +469  | +197   | +194   | +92    | +273   | +136   | +133   | +63    | +187   |
| Vietnam     | +383  | +376   | +178   | +529  | +349   | +343   | +162   | +483   | +38    | +37    | +17    | +52    |
| ECLIPSE CLE |       |        |        |       |        |        |       |        |        |
| Cambodia    | +582  | +572   | +271   | +805  | +292   | +287   | +136   | +404   | +292   | +287   | +136   | +403   |
| Laos        | +410  | +403   | +191   | +567  | +188   | +185   | +88    | +260   | +223   | +219   | +104   | +308   |
| Thailand    | +3888 | +3824  | +1813  | +5372 | +2177  | +2142  | +1016  | +3008  | +1722  | +1694  | +803   | +2380  |
| Vietnam     | +2233 | +2196  | +1041  | +3087 | +304   | +300   | +143   | +419   | +1919  | +1887  | +894   | +2651  |
| RCP4.5 and ECLIPSE CLE |       |        |        |       |        |        |       |        |        |
| Cambodia    | +498  | +490   | +232   | +689  | +240   | +236   | +112   | +332   | +260   | +256   | +121   | +359   |
| Laos        | +355  | +349   | +165   | +490  | +162   | +160   | +76    | +224   | +193   | +190   | +90    | +267   |
| Thailand    | +3560 | +3501  | +1660  | +4918 | +2006  | +1973  | +936   | +2771  | +1567  | +1541  | +731   | +2165  |
| Vietnam     | +1654 | +1627  | +771   | +2287 | −90    | −88    | −40    | −126   | +1731  | +1702  | +807   | +2392  |
| RCP8.5 and ECLIPSE CLE |       |        |        |       |        |        |       |        |        |
| Cambodia    | +631  | +621   | +294   | +872  | +336   | +330   | +156   | +464   | +298   | +293   | +139   | +412   |
| Laos        | +460  | +452   | +214   | +635  | +234   | +230   | +109   | +323   | +227   | +223   | +106   | +314   |
| Thailand    | +4563 | +4488  | +2129  | +6302 | +2701  | +2657  | +1261  | +3730  | +1867  | +1837  | +871   | +2580  |
| Vietnam     | +3109 | +3057  | +1449  | +4296 | +937   | +922   | +437   | +1295  | +2168  | +2132  | +1011  | +2995  |

+17 additional deaths in the dry season but −7 avoided mortalities in the wet season. All year round, it has +9 additional mortalities. Under the impact of climate change alone, larger health effects occur in the dry season compared to the wet season that was consistent with the higher projected O₃ changes found in this season (Fig. 2). Future emission under ECLIPSE CLE scenario mostly increases (Nguyen et al., 2020) causing high additional mortalities significantly compared to climate change impact under RCP8.5 scenario. Additional mortalities were estimated to be +292, +188, +2177, +304 in the dry season, +292, +223, +1722, +1919 in the wet season, and +582, +410, +3888, +2233 all year round in Cambodia, Laos, Thailand, Vietnam, respectively. The combined impacts of climate change under RCP4.5 scenario and emission change under ECLIPSE CLE scenario produce +240, +162, +2006 additional mortalities in the dry season, +260, +193, +1567 additional mortalities in the wet season, and +498, +355, +3560 additional mortalities all year round at Cambodia, Laos, Thailand. Different from these countries, Vietnam has −90 avoided mortalities.
mortalities in the dry season but +1731 additional mortalities in the dry season. For the entire year, it suffers +1654 additional mortalities. RCP8.5 scenario together with ECLIPSE CLE scenario brings out more additional mortalities compared to RCP4.5 scenario in combination with ECLIPSE CLE scenario as RCP8.5 scenario causes O₃ concentration increase while RCP4.5 scenario causes the decrease in O₃ concentration (Nguyen et al., 2019b). The additional mortalities are +336, +234, +2701, +937 in the dry season, +298, +227, +1867, +2168 in the wet season, and +631, +460, +4563, +3109 all year round in Cambodia, Laos, Thailand, Vietnam, respectively. In general, among countries, it turned out that Vietnam and Thailand have higher excess mortality numbers than Cambodia and Laos because of their higher population.

The national mortality increases or decreases corresponding to the increase or decrease of national average O₃ concentration. However, in Vietnam, under RCP8.5 scenario, the national average O₃ concentration was projected to decrease −0.05 ppb (Table 2) while mortality was estimated to increase in the wet season. As shown in Fig. 2 and Fig. 4, parts of Vietnam where have O₃ increase also have high population density, causing large additional mortality compared to the avoided mortality from the parts of Vietnam where have O₃ decrease and lower population density. The additional mortality is +91 deaths and the avoided mortality is −54 deaths. It results in net mortality of +38 deaths. Similarly, under RCP4.5 and ECLIPSE CLE combined scenario, there is the O₃ increase of +1.43 ppb over Vietnam in the dry season (Table 2). However, the mortality decreases. It was because the large O₃ decrease, that is up to −8.03 ppb, in part of northern Vietnam (Fig. 2) where has a high population density (Fig. 4) causes high mortality reduction. The avoided mortality is −747 deaths. In the areas where have O₃ increase, the additional mortality is +657 deaths. Thus, the net result is −90 avoided deaths.

Fig. 5 shows the annual and seasonal spatial distributions of the all-cause mortalities. Overall, the mortality patterns are relevant to the corresponding patterns of O₃ concentration changes, the mortality increases or decreases along with the rising or reducing O₃ concentration. The spatial distribution of O₃ related mortality showed high mortality in areas where have dense populations. It indicated the dominant influence of the population on mortality results that was also found in Sun et al. (2015). Significant additional mortality was observed in areas in and surrounding PP, HCMCMR, MMPP, and BMR all year round and in areas in and surrounding HNMR in the wet season under ECLIPSE CLE scenario, RCP4.5 and ECLIPSE CLE combined scenario, RCP8.5 and ECLIPSE CLE combined scenario (Figs. 5(c), 5(d), and 5(e)). It was due to the significant effect of the population as mentioned since the O₃ concentration changes in these areas were not so large in comparison with those of the other areas in most scenarios. Large avoided mortality from future O₃ reduction occurs in areas in and surrounding HNMR in the dry season in all scenarios except RCP8.5 scenario (Fig. 5(b)). The largest avoided mortality was found under RCP4.5 and ECLIPSE CLE combined scenario.

### 3.2 Mortality Related to PM₂.₅

Table 6 summarizes the annual and seasonal PM₂.₅ related all-cause mortality attributed to climate and emission changes. Resulting from the future PM₂.₅ decrease under RCP4.5 scenario, the avoided mortalities are −116, −58, −778, −782 in the dry season, −19, −46, −628, −943 in the wet season, and −132, −104, −1407, −1715 all year round at Cambodia, Laos, Thailand, and Vietnam, respectively. Under RCP8.5 scenario, results show +248, +95, +848 additional mortalities in the dry season, −29, −4, −820 avoided mortalities in the wet season, and +221, +90, +32 additional mortalities all year round in Cambodia, Laos, Vietnam, respectively. Thailand has additional mortalities in both seasons due to PM₂.₅ concentration increase. The mortalities are +1984, +231, and +2219 in the dry season, the wet season, and all year round, respectively. For ECLIPSE CLE scenario, a high increase in mortality was observed in the four target countries compared to RCP8.5 scenario. It was found +192, +6111 additional mortalities in the dry season, +151, +4276 additional mortalities in the wet season, and +341, +10369 additional mortalities all year round in Laos, Thailand, respectively. In Cambodia and Vietnam, mortalities increase by +70, +391 in the dry season and decrease by −45, −28 in the wet season, resulting in the additional mortalities of +22, +340 all year round. Under RCP4.5 and ECLIPSE CLE combined scenario, results showed mortality decrease in Cambodia and Vietnam but mortality increase in Laos and Thailand. The avoided mortalities are −52, −529 in the dry season, −71, −858 in the wet season, and −124, −1406
Fig. 5. Projected changes in annual and seasonal O₃ all-cause mortalities in (a) S1 simulation, (b) S2 simulation, (c) S3 simulation, (d) S4 simulation, and (e) S5 simulation.
### Table 6. Annual and seasonal excess mortalities due to projected PM$_{2.5}$ concentration changes.

| Country         | RCP4.5 | ECLIPSE CLE | RCP8.5 | ECLIPSE CLE |
|-----------------|--------|-------------|--------|-------------|
|                 | Entire year | Mean | Median | 90% CI | Mean | Median | 90% CI | Mean | Median | 90% CI | Mean | Median | 90% CI |
| Cambodia        | −132   | −131       | −89    | −164   | −116   | −114   | −77    | −143   | −19    | −18    | −12    | −23    |
| Laos            | −104   | −103       | −70    | −129   | −58    | −57    | −39    | −72    | −46    | −46    | −31    | −57    |
| Thailand        | −1407  | −1392      | −941   | −1741  | −778   | −770   | −520   | −963   | −628   | −621   | −420   | −777   |
| Vietnam         | −1715  | −1697      | −1146  | −2123  | −782   | −774   | −522   | −968   | −943   | −933   | −630   | −1168  |
| RCP8.5          |        |            |        |        |        |        |        |        |        |        |        |        |
| Cambodia        | +221   | +219       | +148   | +273   | +248   | +245   | +166   | +306   | −29    | −29    | −19    | −36    |
| Laos            | +90    | +89        | +60    | +111   | +95    | +94    | +64    | +117   | −4     | −4     | −3     | −5     |
| Thailand        | +2219  | +2197      | +1488  | +2743  | +1984  | +1964  | +1332  | +2451  | +231   | +229   | +155   | +286   |
| Vietnam         | +32    | +32        | +22    | +39    | +848   | +840   | +569   | +1047  | −820   | −811   | −548   | −1015  |
| ECLIPSE CLE     |        |            |        |        |        |        |        |        |        |        |        |        |
| Cambodia        | +22    | +21        | +15    | +26    | +70    | +70    | +47    | +87    | −45    | −45    | −30    | −56    |
| Laos            | +341   | +337       | +229   | +420   | +192   | +190   | +129   | +237   | +151   | +149   | +101   | +186   |
| Thailand        | +10369 | +10271     | +7004  | +12758 | +6111  | +6054  | +4135  | +7512  | +4276  | +4235  | +2886  | +5264  |
| Vietnam         | +340   | +342       | +265   | +379   | +391   | +390   | +285   | +458   | −28    | −25    | −2     | −53    |

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all year round in Cambodia, Vietnam, respectively. The additional mortalities are +130, +5483 in the dry season, +101, +3666 in the wet season, and +229, +9131 all year round in Laos, Thailand, respectively. RCP8.5 and ECLIPSE CLE scenarios in combination lead to the largest health impact associated with PM$_{2.5}$. Laos and Thailand have +312 and +8838 additional mortalities in the dry season, +156 and +4677 additional mortalities in the wet season, and +465 and +13519 additional mortalities all year round. Cambodia and Vietnam have +328 and +1146 additional mortalities in the dry season, and −78 and −786 avoided mortalities in the wet season, and +248, +348 additional mortalities all year round.

The mortality increases or decreases in accordance with the increase or decrease of the PM$_{2.5}$ concentration as for O$_3$ except in the following cases. Even the average national PM$_{2.5}$ concentrations in Cambodia and Vietnam increase by +0.88 and +3.08 µg m$^{-3}$ in the wet season under ECLIPSE CLE scenario, and +0.09 and +2.52 µg m$^{-3}$ in the dry season and +0.61 and +2.11 µg m$^{-3}$ in the wet season under RCP8.5 and ECLIPSE CLE combined scenario, and +0.68 and +2.69 µg m$^{-3}$ in the wet season under RCP8.5 and ECLIPSE CLE combined scenario (Table 2), respectively, the corresponding mortalities decrease across these two countries. The large PM$_{2.5}$ decrease together with high population density in areas in and surrounding PP, HNMR, and HCMCMR (Figs. 3 and 4), results in largely avoided mortalities. The avoided mortalities in Cambodia, Vietnam are −119, −1814 in the wet season under ECLIPSE CLE scenario, −96, −2110 in the dry season and −127, −2314 in the wet season under RCP4.5 and ECLIPSE CLE combined scenario, and −138, −2358 in the wet season under RCP8.5 and ECLIPSE CLE combined scenario, respectively. On the other hand, the increase of PM$_{2.5}$ concentration in the other areas of the countries where had lower population density produces fewer additional mortalities compared to avoided mortalities. The additional mortalities are +74, +1787 in the wet season under ECLIPSE CLE scenario, +45, +1581 in the dry season and +56, +1455 in the wet season under RCP4.5 and ECLIPSE CLE combined scenario, and +60, +1573
in the wet season under RCP8.5 and ECLIPSE CLE combined scenario in Cambodia, Vietnam, respectively. Thus, the avoided mortalities dominated the estimated net results of –45, –28 deaths in the wet season under ECLIPSE CLE scenario, –52, –529 deaths in the dry season, and –71, –858 deaths in the wet season under RCP4.5 and ECLIPSE CLE combined scenario, and –78, –786 deaths in the wet season under RCP8.5 and ECLIPSE CLE combined scenario in Cambodia and Vietnam, respectively.

Comparing among target countries, Thailand was estimated to suffer the highest additional mortality resulting from both high population size and PM2.5 increase. Between the two seasons, the excess mortality related to PM2.5 is mostly higher in the dry season than that in the wet season because of a larger change in the future PM2.5 concentration in the dry season (Fig. 3). Comparing to O3, PM2.5 has larger health impacts. One of the potential reasons was that the $\beta$ coefficient of the PM2.5 related all-cause mortality is higher than that of the O3 related one (Table 3) (Sun et al., 2015).

Fig. 6 shows the spatial distributions of annual and seasonal all-cause mortalities related to PM2.5. The spatial distributions of PM2.5 related mortality outcomes correspond to those of trends of future PM2.5 concentration changes (Fig. 2). The major health impacts occur in areas where have large future PM2.5 change and dense populations. Having a large increase in PM2.5 concentration together with the dense population, areas in and surrounding BMR showed high additional mortalities except under RCP4.5 scenario. RCP8.5 and ECLIPSE CLE combined scenario produces the largest additional mortality in these areas. The major health benefits would be observed in areas in and surrounding HNMR and HCMCMR except under RCP8.5 scenario in the dry season, resulting from the large reductions in future PM2.5 and the great number of inhabitants that congregate in these areas as mentioned. The highest PM2.5 related avoided death occurs in areas in and surrounding HNMR under RCP4.5 and ECLIPSE CLE combined scenario. In addition, in northern Cambodia and southern Laos with a large increase of PM2.5 in the dry season under RCP8.5 scenario, the health impact is not high. It was because of the low population distribution within the area.

4 CONCLUSIONS

In this study, BenMAP-CE health impact assessment tool was utilized to quantify O3 and PM2.5 related health impacts due to the changes in climate and emission. The results indicated that health benefit in term of avoided deaths was calculated for RCP4.5 scenario. By contrast, under other scenarios, additional mortalities related to O3 and PM2.5 were mostly found. Change in emission causes higher impacts on mortalities in comparison with change in climate. Between the two seasons, the dry season has more excess mortalities than the wet season. Among four countries, Thailand and Vietnam undergo higher excess mortalities than Laos and Cambodia mainly contributed by the high population size. PM2.5 change contributes greater mortality than O3 change which was consistent with that of Yang et al. (2019).

The BenMAP-CE estimate reliability depends on the precise and relevance of data used in calculations. The input data includes air pollutant concentrations, baseline incidence rates, and estimated populations. The BenMAP-CE results are also affected by used HIFs. Each of them may be uncertain that leads to having impacts on the final estimates of mortality changes. Uncertainties may exist in modeled air pollutant concentrations coming from the uncertainties in the air quality model configurations, formulations, and inputs (Yang et al., 2019). As stated in the previous study (Nguyen et al., 2019a), WRF-CMAQ modeling system that produced the air quality data for this study was evaluated comprehensively. The model performance showed that the model system could reasonably reproduce the observations. The estimated population data and baseline incidence rates in this study were calculated using data from reliable sources. The HIFs used in this study may produce several uncertainties since they were gained from studies that were carried out in a limited number of locations (Yang et al., 2019). The assessment of this study relied on the results from these epidemiological studies because of the absence of robust Asia HIFs for exposure to ambient PM2.5 and O3. Despite these limitations, the results of this study could provide meaningful information for air quality control and public health protection.

The limitation of the health impact analyses of this study was that O3 and PM2.5 related cause-specific mortalities were not included because of the lack of health data in the region. The existing
Fig. 6. Projected changes in annual and seasonal PM$_{2.5}$ all-cause mortalities in (a) S1 simulation, (b) S2 simulation, (c) S3 simulation, (d) S4 simulation, and (e) S5 simulation.
HIFs tend to be generic. They are applied commonly to both sexes, and do not differentiate well across age groups, although the effects on these subgroups may not be the same (Sun et al., 2015). In addition, this study just focused on the impacts of climate and emission changes on O₃ and PM₂.₅ related mortalities in the future period. Hence, it did not consider the influences of population growth and future baseline incidence rate on the changes of mortalities related O₃ and PM₂.₅. Therefore, combining these facts in further studies can give more information for understanding the public health impacts and developing proper policies in the region.

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