Eco-Environment & Health 3 (2024) 11–20

Contents lists available at ScienceDirect

Eco-Environment & Health

journal homepage: www.journals.elsevier.com/eco-environment-and-health

Original Research Article

The development of local ambient air quality standards: A case study of Hainan Province, China

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ARTICLE INFO

Keywords:
Local ambient air quality standard
Statistical form
Feasibility
Health effects
Hainan province

ABSTRACT

The ambient air quality standard (AAQS) is a vital policy instrument for protecting the environment and human health. Hainan Province is at the forefront of China's efforts to protect its ecological environment, with an official goal to achieve world-leading air quality by 2035. However, neither the national AAQS nor the World Health Organization guideline offers sufficient guidance for improving air quality in Hainan because Hainan has well met the former while the latter is excessively stringent. Consequently, the establishment of Hainan's local AAQS becomes imperative. Nonetheless, research regarding the development of local AAQS is scarce, especially in comparatively more polluted countries such as China. The relatively high background values and significant interannual fluctuations in air pollutant concentrations in Hainan present challenges in the development of local AAQS. Our research proposes a world-class local AAQS of Hainan Province by reviewing the AAQS in major countries or regions worldwide, analyzing the influence of different statistical forms, and carefully evaluating the attainability of the standard. In the proposed AAQS, the annual mean concentration limit for $PM_{2.5}$, the annual 95th percentile of daily maximum 8-h mean (MDA8) concentration limit for O_3, and the peak season concentration limit for O_3 are set at 10, 120, and 85 μg/m^3, respectively. Our study indicates that, with effective control policies, Hainan is projected to achieve compliance with the new standard by 2035. The implementation of the local AAQS is estimated to avoid 1,526 (1,253–1,789) and 259 (132–501) premature deaths attributable to long-term exposure to $PM_{2.5}$ and O_3 in Hainan in 2035, respectively.

1. Introduction

Air pollution is a great threat to human health [1,2], with research indicating that long-term exposure to $PM_{2.5}$ leads to almost 4.2 million deaths in 2019 worldwide [3,4]. To address the air pollution problem, ambient air quality standards (AAQSs) have been established as crucial policy tools worldwide [5,6]. In 2021, the World Health Organization (WHO) strengthened its Air Quality Guidelines (AQG) to better protect human health [7,8]. The air quality in China has been improving continuously in recent years [9,10]. Hainan Province, the national ecological civilization pilot zone in China, generally exhibits excellent air quality among all provinces [11]. According to the official assessment methods [12], the annual mean concentrations of SO_2, NO_2, $PM_{2.5}$, and PM_{10}, as well as the annual 95th percentile of the 24-h mean concentration of CO and the annual 90th percentile of the daily maximum 8-h mean (MDA8) concentration of O_3 in Hainan has already reached the

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https://doi.org/10.1016/j.eehl.2023.10.002
Received 29 July 2023; Received in revised form 15 September 2023; Accepted 2 October 2023

Chinese National Ambient Air Quality Standards (NAAQS, GB 3095-2012) Grade-II. Nevertheless, the pollutant levels in Hainan are far from the WHO-recommended levels, e.g., the $PM_{2.5}$ annual mean concentration in Hainan in 2020 was 13 μg/m^3, 8 μg/m^3 higher than the target of WHO AQG 2021 [13]. The air quality in Hainan urgently needs further improvement, and the Hainan government [14] proposes a goal that Hainan shall achieve world-leading air quality by 2035. It is obvious that the existing NAAQS GB 3095-2012 in China is insufficient in guiding Hainan to achieve the official goal, and this situation calls for a new world-class local AAQS that is in line with the current status and future target of air quality in Hainan.

Major developed countries or organizations usually make a comprehensive review when establishing or revising their AAQSs, including assessing the health risk caused by pollutants, evaluating the air quality situation, and assessing the achievability as well as benefits of new standards [15,16]. A number of studies have been conducted to support the development of NAAQS. For example, the National Environment Protection Council of Australia conducted research on the basic framework and the statistical form of the standards, the health effects of different pollutants, and the comparability of Australian air quality standards to AAQSs of other countries or regions before upgrading the NAAQS [15]. Besides, Vahlsing and Smith [17] have reviewed the NAAQS for SO_2 and $PM_{2.5}$ in 96 countries and concluded that the most commonly considered evidence for establishing standards was air quality observation data, followed by the AAQSs used in other countries, studies on environmental epidemiology, and the WHO AQG. Current research on the development of AAQSs has been concentrated on the national scale [15,17,18], yet limited literature exists concerning the development of local AAQS. However, for areas with relatively good air quality and in compliance with its NAAQS, there are no existing standards to guide further air quality improvement. Therefore, it is imperative to establish local AAQSs for areas with leading air quality in one country [19,20], thereby fostering better guidance in local air quality improvement and playing a pioneering role in protecting the national environment.

When developing local AAQSs, there are some extra challenges compared with developing NAAQSs. One of the main challenges of establishing local AAQSs is that the local AAQS should have continuity with the NAAQS to ensure the high efficiency of air quality management. Another challenge is that the influence of special natural, geographical, and climatic conditions on air quality should be evaluated thoroughly when designing the local AAQS, while the overall air quality in the whole country is a priority, and the special sites are usually ignored when developing the NAAQS. For example, the US EPA excludes measurement data from some high-altitude locations that are highly impacted by non-domestic sources, such as natural or international transport emissions, when setting O_3 standards [21]. In summary, difficulties remain in the establishment of local AAQS, especially in setting local standards for comparatively more polluted countries, such as China, where the air quality in an area is significantly impacted by regional transport.

For developing local AAQSs of Hainan Province in China, the main challenges are that the pollutant concentrations are greatly affected by regional transport, natural emissions, and meteorological conditions. Due to the relatively low local pollutant emissions, the background pollutant concentrations of Hainan are relatively high. The air quality is greatly influenced by the pollutants transported from mainland China and surrounding countries in Southeastern Asia, as it is reported that regional transport contributes to 41.6% of $PM_{2.5}$ in Hainan [13]. Besides, the high forest coverage rate of about 62% in Hainan leads to a large amount of biogenic volatile organic compounds emissions enhancing O_3 production, and sea salt contributes to 13% of the $PM_{2.5}$ mass concentration in Hainan [13]. Furthermore, the pollutants from regional transport and natural sources are very sensitive to meteorology condition changes, resulting in large interannual variations of air pollutant concentrations in Hainan along with interannual meteorology fluctuations. In all, the influencing factors affecting air quality in Hainan are complex. These factors lead to relatively high background values and large interannual fluctuations in pollutant concentrations, making it difficult to develop local AAQS that reflect the benefits of Hainan's anthropogenic emission reduction well.

Considering the aforementioned challenges in establishing local AAQSs for Hainan, this study aims to propose a world-class local AAQS for the province. By comparing domestic and international standards, selecting indicators, and selecting concentration thresholds while analyzing the influence of the assessment methods on air quality evaluated concentrations, we proposed this local AAQS. Furthermore, we evaluated the attainability and health benefits of the AAQS through scenario design and air quality simulation. In addition, we quantified the health benefits resulting from the implementation of the local AAQS. The introduction of these proposed AAQSs has the potential to encourage Hainan's government to adopt more stringent air pollution control policies while also serve as a valuable reference for other provinces and regions globally in upgrading their own AAQSs.

2. Design of the proposed world-class local AAQSs

2.1. *The technical route of developing AAQSs*

AAQSs encompass four fundamental components: pollutant indicators, threshold levels, averaging time, and statistical forms [22]. Prior to determining the main components of the AAQS, it is important to review AAQSs established in other countries or regions as well as WHO AQG 2021, which provides valuable references for the development of the local AAQS [18]. Furthermore, subsequent to establishing the core elements of the AAQS, an assessment of its feasibility and health benefits becomes indispensable.

In this study, the method of developing AAQS is compartmentalized into the following parts: (1) comparison of domestic and international standards, (2) selection of indicators, (3) setting of averaging time, statistical forms, and concentration thresholds, (4) attainability analysis, and (5) health benefits assessment. The first three parts are described in *Section 2*, while the attainability evaluation and health benefit assessment are expounded upon in *Section 3*.

2.2. *Comparison of domestic and international standards*

In accordance with the essential components of AAQS, the comparison of Chinese NAAQS and international AAQSs is divided into four aspects, i.e., pollutant indicators, threshold levels, averaging time, and statistical forms.

Although the pollutant indicators vary in different countries or organizations, six types of pollutants, i.e., $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3, are included in the AAQSs of most countries [23–30], with no exception in Chinese NAAQS [31]. Among the six pollutants, China has nearly the most stringent threshold level for CO in the world. However, the threshold level of NO_2 is at an intermediate level, and the threshold level of SO_2 is relatively loose compared with other AAQSs. The threshold values for $PM_{2.5}$, O_3, and PM_{10} of AAQSs in major countries or regions are summarized in Table S1, with the limits of these three kinds of pollutants in China looser than most developed countries.

Considering the short-term or long-term effects of pollutants on human health, the averaging time varies for different pollutants [7]. For instance, the averaging time for $PM_{2.5}$ and PM_{10} includes 24 h and 1 year in most AAQSs because both short-term and long-term exposure to $PM_{2.5}$ cause great damage to human health [32,33], while there is only short-term averaging time for CO because it mainly has acute effects on human health [34]. Notably, as shown in Table S1, no countries have added the peak season standard for O_3 (average of daily maximum 8-h mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration) so far, which was first proposed by WHO in 2021 [7].

The statistical form, namely the air quality ambient assessment method, defines the calculation method of monitoring data when determining whether an area meets the standard. All monitoring sites in an area meeting the standards represent the air quality attainment of the area in the United States and European Union, while China uses the average concentration of pollutants in an administrative region as a basis for attainment judgment [35]. Table S2 presents the statistical forms for the 24-h mean and annual mean concentrations of $PM_{2.5}$ and PM_{10}, as well as the 1-h mean, MDA8, and peak season concentration of O_3 in AAQSs of major countries or regions. The percentile-based method is usually adopted in the statistical form to relieve the impact of extreme values and missing observation data, which is sorting the daily concentration in one year from small to large and taking a specific percentile as the representative value for daily attainment evaluation, as shown in Table S2 [36]. For example, the annual 99th percentile (equivalent to three to four exceedance days per year) of daily mean concentration or MDA8 concentration is set in AQG 2021, and the percentile values in Chinese NAAQS are 90%, 95%, or 98% (Table S2). Moreover, the three-year moving-average method is used in the standards of the United States, Australia, and the Taiwan region, taking the interannual meteorological fluctuations into account [35], while the European Union set the three-year moving-average method only for O_3 standards [26].

Overall, the pollutant indicators and averaging time in the standards have no obvious difference among countries or regions, while the statistical forms and threshold levels are very different and closely related to the local conditions of individual countries or regions.

2.3. Selection of indicators

The air quality indicators in the proposed local AAQS are $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO. One of the reasons for selecting these indicators is that these six pollutants are of great concern globally, and are set in most international AAQSs. Besides, the six indicators are aligned with the Chinese NAAQS GB 3095-2012 [31], which is conducive to the management of local air quality.

2.4. Assessing the impact of statistical forms on evaluation concentrations

As highlighted in the *Introduction*, the special natural, geographical, and climatic conditions in Hainan result in Hainan's pollutant concentrations having high background values and large interannual fluctuations, which are the major challenges for developing the local AAQS. To address the two challenges, it is significant to set concentration thresholds that are feasible for Hainan's anthropogenic emission reduction. Given that the concentration thresholds of AAQSs are closely related to statistical forms, we first assessed the influence of statistical forms on pollutant evaluation concentration levels. Additionally, it is essential to set appropriate statistical forms that contribute to mitigating the interannual fluctuations of the air quality evaluation concentrations. Therefore, we evaluated the influence of statistical forms on the interannual fluctuations of evaluation concentrations. In all, assessing the influence of statistical forms on evaluation concentrations is crucial to tackling the challenges of developing the local AAQS.

We discuss three aspects of statistical forms in the assessment: (1) annual percentile values of 24-h mean or MDA8 concentration in the annual air quality attainment evaluation, (2) time periods of the moving-average method aimed at reducing interannual variation, and (3) regional attainment judgment by site-specific method (judging the air quality attainment of a region by the concentration of the most-polluted monitoring site) or regional average method (judging the air quality attainment of a region by the average concentration of all monitoring sites). In order to ensure the representativeness of the assessment, we selected two typical cities in Hainan: Haikou, with relatively high concentrations, and Sanya, with relatively low concentrations.

The impact of percentile values in the percentile-based evaluation method (ranging from 90% to 100%) on annual evaluation concentration levels of $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO is presented in Fig. S1 and Fig. S2. A higher percentile value in the evaluation method indicates a stricter limit on the number of days in a year that are allowed to exceed the threshold levels. Obviously, the evaluation concentrations increase with the higher percentiles. The growth levels of evaluation concentrations vary with different pollutants. It is shown that the evaluation values of the $PM_{2.5}$ and O_3 grow more sharply than others if adopting the annual percentile values of daily concentrations in WHO AQG 2021 (99% for $PM_{2.5}$, 99% for O_3) instead of Chinese NAAQS GB 3095-2012 (95% for $PM_{2.5}$, 90% for O_3). Specifically, $PM_{2.5}$ and O_3 have the highest increase in evaluation concentrations, rising by approximately 57.8% and 31.5% in Haikou, respectively. Besides, the evaluation concentrations increment of PM_{10}, NO_2, SO_2, and CO are about 21.0%, 20.7%, 17.0%, and 14.3% in Haikou.

Moreover, annual percentile values of 24-h mean or MDA8 concentrations also affect the interannual variability of evaluation concentrations. The analysis of the evaluation concentrations with different percentile values (90%, 95%, 98%, and 99%) is presented in Fig. 1. The evaluation concentrations exhibit larger interannual variation with larger percentiles. The annual 99th percentile of 24-h mean concentrations of $PM_{2.5}$ ranged from 45 to 78 $\mu g/m^3$ during 2015–2021 in Haikou, spanning a broad spectrum of 33 $\mu g/m^3$. However, the annual 90th percentile of the 24-h mean concentration of $PM_{2.5}$ span 19 $\mu g/m^3$ during 2015–2021 in Haikou, much less than the evaluation concentration of the 99th percentile. The concentration span during the years increases continuously as the percentile value increases, except for the MDA8 concentration of O_3 in Haikou. It implies that the smaller percentiles may mitigate the impact of meteorological fluctuations on the interannual variation of evaluation concentrations. To sum up, the looser percentile-based method has more advantages in eliminating the interannual meteorological fluctuations, while the effect of percentile values on the evaluated concentration levels varies with different pollutants, so the annual percentile values of the 24-h mean or MDA8 concentrations depend on pollutants when developing the new standards.

In addition to the influence of the annual percentile value of 24-h mean or MDA8 concentrations on the interannual fluctuation of pollutant estimation concentrations, the time interval of the moving average method also has an impact on the concentration fluctuations. The time intervals of 1 year (not adopting the moving-average

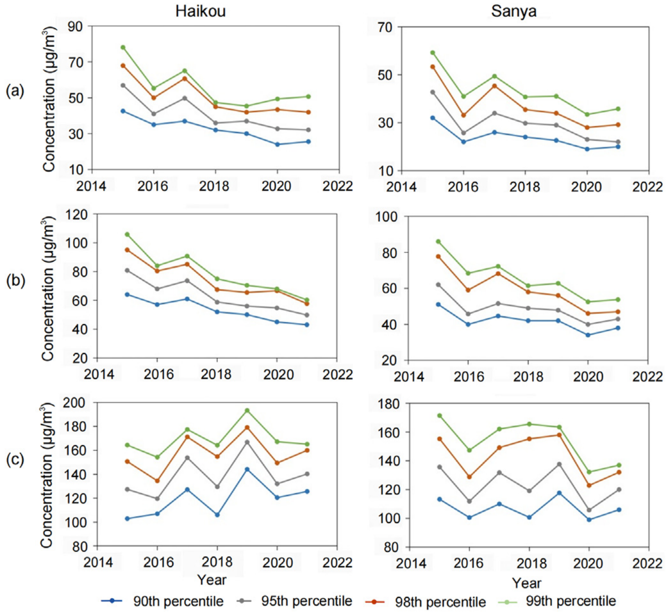

Fig. 1. Annual evaluation concentrations from 2015 to 2021 with 90th, 95th, 98th, and 99th percentile in the percentile-based evaluation method in Haikou and Sanya. (**a**) 24-h mean concentration of $PM_{2.5}$, (**b**) 24-h mean concentration of PM_{10}, (**c**) MDA8 concentration of O_3.

method), 2 years, 3 years, 4 years, and 5 years are chosen to explore the effect of time periods on interannual variations, as displayed in Fig. S3. Without adopting the moving-average method, the evaluation concentrations fluctuate sharply, especially for O_3. When using the 2-year moving-average method, it can be seen that there are also visible variations in the evaluation concentrations of $PM_{2.5}$, PM_{10}, and O_3 in Sanya. The fluctuation of evaluation concentrations with the 3-year moving-average method is reasonably small. Although a larger time interval has marginally larger benefits to reducing the variation of evaluation concentrations resulting from unstable meteorology, it is unfavorable for achieving timely assessment results. For these reasons, we set the 3-year moving-average method in the newly proposed standards, the same as the NAAQS of the US and Australia.

When determining whether an area meets the standards, the site-specific evaluation method is stricter than the regional average evaluation method. To select the attainment evaluation method that is more suitable for Hainan, the evaluation concentrations in Haikou and Sanya calculated by the two methods have been explored, respectively, as shown in Fig. S4. Compared with the regional average method, the evaluated concentrations of pollutants increase by 10.9% and 4.8% on average in Haikou and Sanya, respectively. It indicates that evaluation concentrations calculated by the two attainment judgment methods only slightly differ. Moreover, to be consistent with Chinese NAAQS, we use the evaluation method of regional average for all pollutants in the new standards.

2.5. Setting of averaging time, statistical forms, and concentration thresholds

Based on the above analysis and the local air quality conditions of Hainan, we set the averaging time, statistical forms, and concentration thresholds of the local AAQS, as shown in Table 1. When setting the concentration threshold, we tried to adopt the air quality and interim targets in WHO AQG 2021, as emphasized in research conducted by Hoffmann et al. [2] and Heresh Amini [8]. Additionally, the concentration threshold was also set with consideration of the attainability analysis in the following *Section 3.2*. Meanwhile, the statistical forms and concentration thresholds set in the AAQS should attain a globally pioneering level, aligning with Hainan's goal of achieving the world's leading air quality by 2035.

In the newly proposed local AAQS of Hainan Province, the 3-year moving-average method is used for the pollutants susceptible to meteorological fluctuations, i.e., $PM_{2.5}$, PM_{10}, and O_3. Besides, the regional average evaluation method is used for all pollutants in the local AAQS, the same as the Chinese NAAQS.

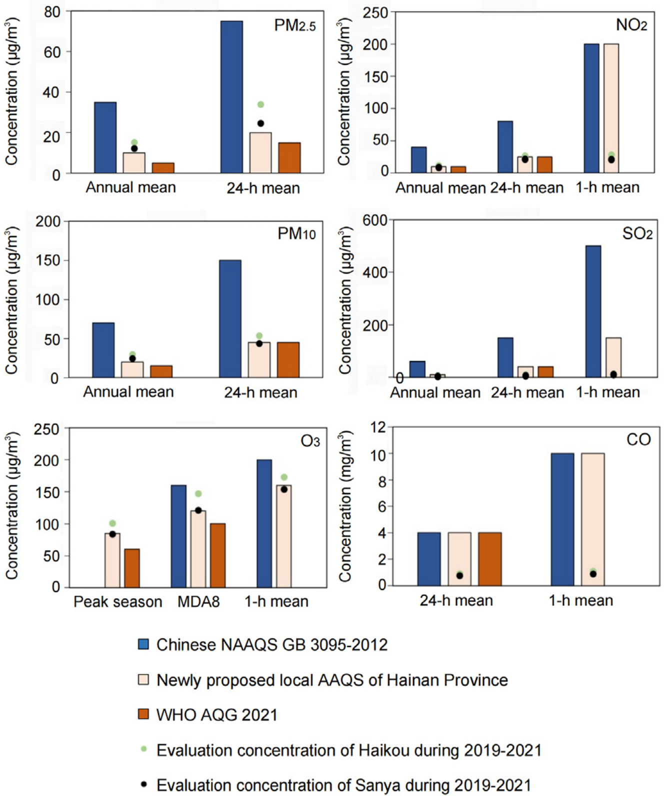

Fig. 2. The threshold levels for the six pollutants ($PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO) in the newly proposed local AAQS of Hainan Province, Chinese NAAQS GB 3095-2012, as well as WHO AQG 2021, respectively, and the air quality evaluation concentrations in Haikou and Sanya during 2019–2021 assessed by the statistical form in newly proposed local AAQS of Hainan Province. AAQS, ambient air quality standard; NAAQS, National ambient air quality standard.

Fig. 2 displays the comparison among pollutant evaluation concentrations during 2019–2021, Chinese NAAQS GB 3095-2012, the newly proposed local AAQS of Hainan Province, and WHO AGQ 2021. For SO_2, NO_2, and CO, the averaging time remains the same as the Chinese NAAQS GB 3095-2012. Besides, in view that only small growth levels of evaluation concentrations occur when using the statistical forms of WHO AQG 2021 rather than Chinese NAAQS (Fig. S2), and the evaluation concentrations in both Haikou and Sanya are lower than or close to the limits of WHO AQG 2021 (Fig. 2), statistical forms and threshold levels for the three pollutants in the local AAQS follow the WHO AQG 2021. Specifically, CO only has an annual 99th percentile of 24-h mean concentration standard of 4 mg/m^3 and an annual 99th percentile of 1-h

Table 1
The newly proposed local ambient air quality standards of Hainan Province.

Pollutant	Averaging time	Level	Statistical form	Unit
Sulphur dioxide (SO_2)	Annual mean	10	Not to be exceeded	μg/m^3
	24-h mean	40	Annual 99th percentile of 24-h mean concentration	
	1-h mean	150	Annual 99th percentile of 1-h mean concentration	
Nitrogen dioxide (NO_2)	Annual mean	10	Not to be exceeded	μg/m^3
	24-h mean	25	Annual 99th percentile of 24-h mean concentration	
	1-h mean	200	Annual 99th percentile of 1-h mean concentration	
Carbon monoxide (CO)	24-h mean	4	Annual 99th percentile of 24-h mean concentration	mg/m^3
	1-h mean	10	Annual 99th percentile of 1-h mean concentration	
Ozone (O_3)	Peak season	85	Average of daily maximum 8-h mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration, averaged over 3 years	μg/m^3
	Maximum daily 8-h mean	120	Annual 95th percentile of daily maximum 8-h mean concentration, averaged over 3 years	
	1-h mean	160	Annual 99th percentile of 1-h mean concentration, averaged over 3 years	
PM_{10}	Annual mean	20	averaged over 3 years	μg/m^3
	24-h mean	45	Annual 95th percentile of 24-h mean concentration, averaged over 3 years	
$PM_{2.5}$	Annual mean	10	Annual mean, averaged over 3 years	μg/m^3
	24-h mean	20	Annual 95th percentile of 24-h mean concentration, averaged over 3 years	

mean concentration standard of 10 mg/m^3, while the other two pollutants involve an extra annual mean standard. The thresholds for annual, 24-h, and 1-h averaging time in the new standards are 10, 40, and 150 μg/m^3 for SO_2, and 10, 25, and 200 μg/m^3 for NO_2, respectively. To sum up, the standards for SO_2, NO_2, and CO in the newly proposed local AAQS in Hainan are benchmarked against the latest WHO guideline values.

For $PM_{2.5}$ and PM_{10}, their averaging time encompasses both 24-h mean and annual mean concentrations, the same as the Chinese NAAQS GB 3095-2012 and WHO AQG 2021, as shown in Fig. 2. With regard to the statistical forms of $PM_{2.5}$ and PM_{10}, the annual 95th percentile of 24-h mean concentration is adopted in the local AAQS, retaining the form of Chinese NAAQS. One of the main reasons is that the analysis in *Section 2.4* reveals the vast growth of evaluation concentrations for particulate matters when tightening the annual percentile value of daily mean evaluation concentrations from 95% to 99% (Fig. S1). Adopting a smaller percentile in the evaluation method is also beneficial for reducing interannual variation of evaluation concentrations. Another reason is that the evaluation method of the annual 95th percentile of daily average concentrations for $PM_{2.5}$ and PM_{10} is at a comparable level with major developed countries (the percentiles ranging from 90% to 99%), as shown in Table S2.

Concerning the threshold levels of annual mean standards, the guideline limits in WHO AQG 2021 are 5 μg/m^3 and 15 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively. WHO has such stringent values that few countries reach the targets by 2021 [37], and currently, no NAAQS is stricter than the guideline limits, as shown in Table S1. In Hainan Province during 2019–2021, the annual mean concentration of $PM_{2.5}$ (15.3 μg/m^3 in Haikou and 12.2 μg/m^3 in Sanya) is about three times the limit of WHO AQG 2021 (5 μg/m^3) and the annual mean concentration of PM_{10} (29.6 μg/m^3 in Haikou and 24.4 μg/m^3 in Sanya) is about twice the limit of WHO AQG 2021 (15 μg/m^3), as shown in Fig. 2. It is obvious that the concentration targets for the particle matter in WHO AQG 2021 are too strict for Hainan's AAQSs, but loose standards are not instructive to the air quality improvement. As a compromise, the interim target 4 levels of WHO AQG 2021 are adopted in the proposed standards, namely, an annual mean level of 10 μg/m^3 for $PM_{2.5}$ and 20 μg/m^3 for PM_{10}.

In terms of threshold levels for 24-h mean standards, the 24-h mean concentration limit of $PM_{2.5}$ in the new standards is 20 μg/m^3, tighter than that in major developed countries as well as the interim target 4 level (25 μg/m^3) of WHO AQG 2021, but looser than the limit of WHO AQG 2021 (15 μg/m^3). One of the reasons is that the annual 95th percentile of daily mean concentrations for $PM_{2.5}$ in Hainan in 2021 is about twice the limit of WHO AQG 2021, so the WHO AQG 2021 is difficult for Hainan to attain. Another reason is that higher concentration levels like interim target 4 may not work for cities with relatively good air quality like Sanya, where the annual 95th percentile of daily mean concentration for $PM_{2.5}$ is 24.7 μg/m^3 in 2021. For PM_{10}, as shown in Fig. 2, the annual 95th percentile of daily mean concentrations in Sanya and Haikou in 2021 (53.5 and 43.6 μg/m^3, respectively) have met or been near the target of WHO AQG 2021. Hence, the 24-h mean concentration limit of PM_{10} in the local AAQS has the same level as WHO AQG 2021 of 45 μg/m^3.

Compared with the other five pollutants, O_3 is the most challenging pollutant for air quality improvement in Hainan [38]. In the newly proposed AAQSs, in addition to the existing averaging time of 1-h mean and MDA8 in the Chinese NAAQS GB 3095-2012, we have incorporated the averaging time of peak season for O_3 based on the WHO AQG 2021. The statistical forms and limits of O_3 in Chinese NAAQS Grade-II are loose (Tables S1–S2). The annual percentile values of MDA8 concentrations in AAQSs of the EU and US are 93% and 99%, respectively, stricter than the Chinese AAQS for O_3 (90%). It is necessary for the new world-class standards to tighten the statistical form of O_3. However, the O_3 concentration in Hainan shows a noticeable increase as the percentile increases (Fig. S1) and has a large fluctuation with interannual meteorology changes when a large percentile is used (Fig. 1). Therefore, to strike a balance between the world-leading level and feasibility of the standards, as well as to mitigate the interannual fluctuations of annual evaluation concentrations, the newly proposed local AAQS adopts a percentile value of 95% for O_3 MDA8 concentration. The percentile value for O_3 MDA8 concentration aligns with the percentile used in the annual assessment method for $PM_{2.5}$ and PM_{10}. Moreover, to mitigate the acute health impacts of short-term O_3 exposure on the population and ensure consistency with current Chinese NAAQS, the newly proposed AAQSs include the annual 99th percentile of 1-h mean concentration for O_3. This percentile value is consistent with the percentiles employed in the 1-h mean standards for SO_2, NO_2, and CO.

The MDA8 concentration limit of O_3 in the local AAQS is 120 μg/m^3, the same as the interim target 2 level of WHO AQG 2021 and stricter than that in the US (140 μg/m^3). The MDA8 concentration limit of O_3 is mainly determined due to two aspects, except for the feasibility evaluation results of the new standards in *Section 3.2*. On the one hand, the 95th percentile of MDA8 concentration of O_3 is 147.0 μg/m^3 in Haikou and 121.0 μg/m^3 in Sanya during 2019–2021 (Fig. 2), difficult for Hainan to achieve the target of WHO AQG 2021 (100 μg/m^3) in 2035. On the other hand, a higher limit, like 140 μg/m^3, may not guide air quality improvement in lighter-polluted cities like Sanya.

The peak season concentration of O_3 in Hainan during 2019–2021 is intermediate between the interim target 1 level (100 μg/m^3) and interim target 2 level (70 μg/m^3) in WHO AQG 2021, with 101.0 μg/m^3 in Haikou and 84.0 μg/m^3 in Sanya, as shown in Fig. 2. In order to protect public health to the greatest extent possible, the peak season standard of O_3 was set as 85 μg/m^3 with consideration of the feasibility evaluation results in *Section 3.2*.

The 1-h mean concentration limit for O_3 is 160 μg/m^3 in the newly proposed local AAQS of Hainan Province, the same as Chinese NAAQS Grade-I and stricter than Chinese NAAQS Grade-II (200 μg/m^3). It is because the annual 99th of 1-h mean concentration for O_3 in Hainan during 2019–2021 (173.0 μg/m^3 in Haikou and 154.0 μg/m^3 in Sanya) is far below the threshold level in Chinese NAAQS Grade-II, as shown in Fig. 2. Therefore, we tightened the limit to meet the stringent criteria set in Chinese NAAQS Grade-I, rendering the newly proposed AAQSs not only globally leading but also highly instructive in enhancing air quality in Hainan Province.

3. Attainability analysis and health benefits assessment

3.1. Scenarios designed for evaluating the new standards

In order to assess the achievability and health benefits of the newly proposed AAQS, this study set 3 future scenarios for pollutant emission control in Hainan Province until 2035, with the year 2019 being the baseline. The pollutants emission inventory in the baseline year is described in *Section S1.1* of the Supplementary Material.

The three future scenarios include “business as usual” (BAU), “maximum technically feasible reduction” (MTFR), and “enhanced control policies” (ECP). In the three scenarios, emission pollutants are categorized into ten sectors, as seen in Fig. 3. The BAU scenario was set mainly based on the 13th Five-Year Plan in China [39]. The MTFR scenario was designed to explore the maximum potential anthropogenic emission reduction in Hainan, where we consider all the technically feasible control measures, including structural adjustment, energy efficiency improvement, and end-of-pipe control. The ECP scenario was designed with enhanced control measures according to the policies released after 2019, such as the 14th Five-year Plan for Economic and Social Development and the Outline of Long-term Objectives for the Year 2035 in Hainan Province [40], the Implementation Plan of Carbon Peak in Hainan Province [41], as well as the advice from Academy of Environmental Sciences of Hainan Province and other governmental departments in Hainan. Besides, the ECP scenario was finally determined by repeated adjustments of pollution control measures and model simulation to make Hainan Province just attain the newly proposed world-class

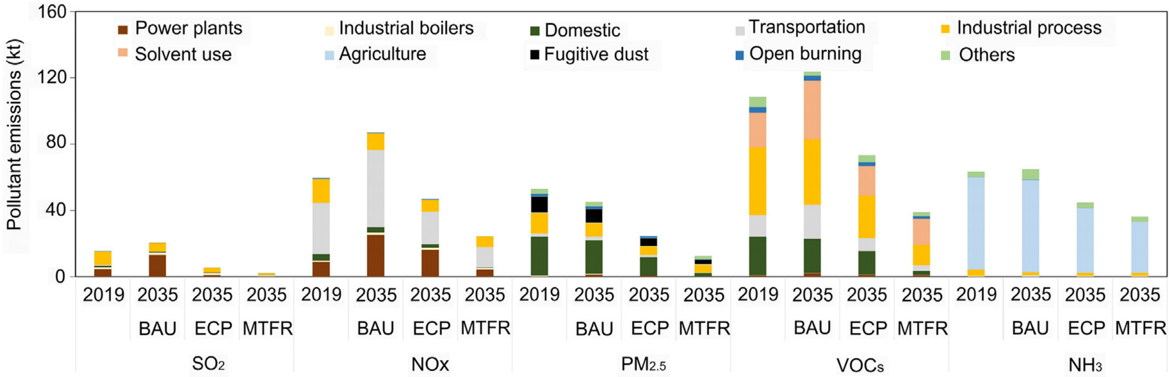

Fig. 3. Emissions of SO_2, NO_x, primary $PM_{2.5}$, VOCs, and NH_3 in 2019 and 2035 under the BAU, ECP, MTFR scenarios for ten sectors: power plants sector, industrial boilers sector, domestic sector, transportation sector, industrial process sector, solvent use sector, agriculture sector, dust sector, open burning sector, and "others" sector. BAU, business as usual; ECP, enhanced control policies; MTFR, maximum technically feasible reduction; VOC, volatile organic compound.

local AAQS in 2035. Detailed settings are described in *Section S1.1* and Table S3 of the Supplementary Material.

Fig. 3 shows the sectoral emissions for five pollutants in 2019 and 2035 under three scenarios in Hainan, and the total amounts of each pollutant are summarized in Table S6. Under the BAU scenario, $PM_{2.5}$ declines by 14.5%, while the other five pollutants increase during 2019–2035. The ECP scenario achieves remarkable emission reduction compared with the BAU scenario, where the largest reduction occurs in SO_2 (74%). The pollutant emissions in the MTFR scenario show a significant decrease of 44%–90% compared to the BAU scenario. The concrete analysis of pollutant emissions under the three scenarios is described in *Section S1.1* of the Supplementary Material.

3.2. Attainability analysis

We used the Community Multiscale Air Quality (CMAQ) model to predict the air quality under the BAU, ECP, and MTFR scenarios. The detailed configuration and performance evaluation of the model system is shown in *Section S1.2* of the Supplementary Material. It shows that the model simulation performs reasonably well for the concentration levels and variation trends of both $PM_{2.5}$ and O_3, and thus, our model system is applicable to evaluating the attainability and health benefits of the local AAQS.

We evaluated the achievability of the six pollutants in the newly proposed standards under the ECP scenario and MTFR scenario for 18 cities of Hainan Province. According to the evaluation methods of air quality attainment in SMAT-CE [42] of ABaCAS, the future assessed value in a city is calculated by multiplying the observed value with the ratio of simulated value in 2035 to the simulated value in 2019, expressed as follows:

$$(C_{2035})_I = (C_{obs\_2019})_I \times \frac{(C_{sim\_2035})_I}{(C_{sim\_2019})_I} \qquad (1)$$

Where C_{2035} is the air quality assessed value of city I in 2035, C_{obs_2019} is the air quality observed value of city I in 2019 or averaged from 2019 to 2021, depending on the statistical form in Table 1; C_{sim_2019} is the air quality simulated value in 2019 predicted by CMAQ; C_{sim_2035} is the air quality simulated value in 2035 predicted by CMAQ; the units of four variables are μg/m^3 or mg/m^3.

By comparing the air quality assessed values with threshold values in the new standards, it can be easy to tell whether a city meets the standard. We define Hainan Province attaining the newly proposed world-class local AAQS as: the mean concentration in 18 cities under the MTFR/ECP scenario meets the threshold value. Meanwhile, at least 70% of the 18 cities all meet the threshold value, and cities that fail to meet the new standards only exceed the threshold level by less than 10%. The feasibility of the local AAQS proposed in our study means that air quality in Hainan under the MTFR scenario meets the new standards. Besides, the air quality under the ECP scenario is expected to just meet the new standards.

Fig. 4 displays the comparisons of evaluation concentrations for $PM_{2.5}$, PM_{10}, and O_3 under the ECP scenario and MTFR scenario with limits in the proposed standards, respectively. It is obvious that the annual mean evaluation concentrations for both $PM_{2.5}$ and PM_{10} in the 18 cities under the two scenarios all meet the threshold values in the new standards. Besides, the annual 95th percentile of 24-h mean concentrations of $PM_{2.5}$ and PM_{10} in each city are all lower than the limits. It indicates that the level of $PM_{2.5}$ and PM_{10} in Hainan under the ECP scenario and MTFR scenario can attain the local AAQS in 2035.

The average peak season concentrations of O_3 in 18 cities under the ECP scenario and MTFR scenario are 76.95 μg/m^3 and 74.98 μg/m^3, respectively, less than the threshold values, as shown in Fig. 4. Two cities (Haikou and Dongfang) are out of the limit for the peak season concentration of O_3 under the ECP scenario and MTFR scenario, while Lingao meets the standards under the MTFR scenario but is beyond the limit under the ECP scenario. Among the 18 cities, Haikou has the highest peak season concentration of O_3, exceeding the threshold level by less than 10%. As for the annual 95th percentile of MDA8 concentrations for O_3, the average concentrations of the 18 cities under the two scenarios are less than the limits in the local AAQS. For the evaluation concentration in each city, five cities fail to achieve the standards under the ECP scenario, and two cities do not attain the standards under the MTFR scenario, where Haikou still has the largest concentration under both scenarios, exceeding the threshold level by less than 5%. Regarding the annual 99th percentile of 1-h mean concentration for O_3, evaluation concentrations in the 18 cities are all below the prescribed limits in the local AAQS. In summary, the O_3 levels in Hainan under the two scenarios are capable of meeting the newly proposed local AAQS.

Fig. S8 illustrates the comparisons between assessed concentrations and the corresponding limits in the proposed standards for SO_2, CO, and NO_2 under the ECP scenario and MTFR scenario, respectively. It is evident that all three pollutants in Hainan successfully achieve the proposed standards for each air quality evaluation indicator since each of the 18 cities meets the threshold values in the standards under the two scenarios.

In conclusion, the world-class local AAQS proposed in our study demonstrates its feasibility for implementation in Hainan. Moreover, Hainan can approximately attain the newly proposed local AAQS by taking control measures outlined in the ECP scenario, which indicates that the ECP scenario is suitable for evaluating health benefits resulting from the implementation of the local AAQS.

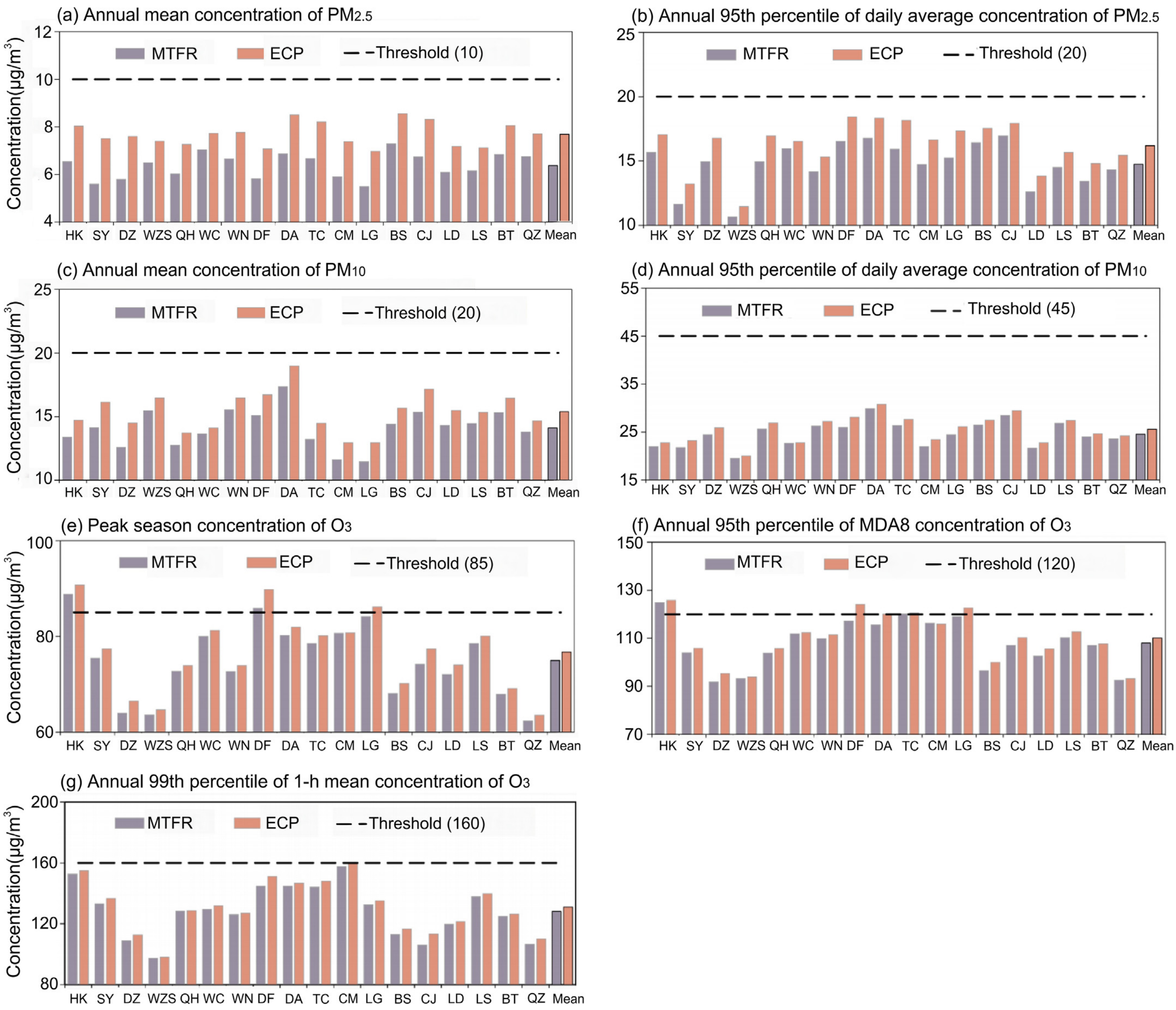

Fig. 4. The evaluation concentration of $PM_{2.5}$ (**a-b**), PM_{10} (**c-d**), and O_3 (**e-g**) compared with threshold concentration in the proposed standards under the ECP scenario and MTFR scenario for 18 cities of Hainan Province: Haikou (HK), Sanya (SY), Danzhou (DZ), Wuzhishan (WZS), Qionghai (QH), Wenchang (WC), Wanning (WN), Dongfang (DF), Ding'an (DA), Tunchang (TC), Chengmai (CM), Lingao (LG), Baisha (BS), Changjiang (CJ), Ledong (LD), Lingshui (LS), Baoting (BT) and Qiongzhong (QZ), as well as the mean concentration of the 18 cities (Mean).

3.3. *Health benefits assessment*

We used BenMAP-CE [43] to quantify the avoided deaths attributable to long-term exposure to $PM_{2.5}$ and O_3 if implementing the newly proposed AAQS. The key parameters and main processes for calculating the avoided deaths are displayed in *Section S1.3* of the Supplementary Material. The avoided deaths associated with long-term exposure resulting from the implementation of the local AAQS were calculated by the number of attributable deaths in the BAU scenario minus the number of attributable deaths in the ECP scenario.

Fig. 5a gives the avoided deaths related to long-term exposure to $PM_{2.5}$ in Hainan Province. The newly proposed local AAQS is estimated to avoid 1,526 (95% confidence interval: 1,253–1,789) premature deaths caused by long-term $PM_{2.5}$ exposure in 2035. Among the five specific causes of death due to $PM_{2.5}$, the number of premature deaths caused by ischemic heart disease (IHD) are the largest, and those caused by stroke, chronic obstructive pulmonary disease (COPD), lung cancer (LC), and lower respiratory infections (LRI) are successively smaller, accounting for 31%, 18%, 8%, 3%, and 7% of the deaths from all diseases, respectively. This pattern may be caused by the high level of baseline mortality in IHD. The avoided deaths attributable to long-term exposure to O_3 in Hainan Province are presented in Fig. 5c. It shows that 259 (132–501) premature deaths caused by long-term O_3 exposure can be avoided in 2035. With regard to the specific causes of death related to O_3, COPD is the leading cause with a proportion of 57%, and respiratory takes the proportion of 11%.

Fig. 5b and d present the spatial distribution of avoided deaths due to long-term $PM_{2.5}$ exposure and O_3 exposure, respectively. It is apparent that $PM_{2.5}$-attributable deaths and O_3-attributable deaths have similar features of spatial distribution. The decreased deaths vary substantially across Hainan, depending on the pollutant concentration and population density. It shows that Haikou and Sanya exhibit more considerable health effects compared to other cities in Hainan, possibly due to their large population and concentration reduction.

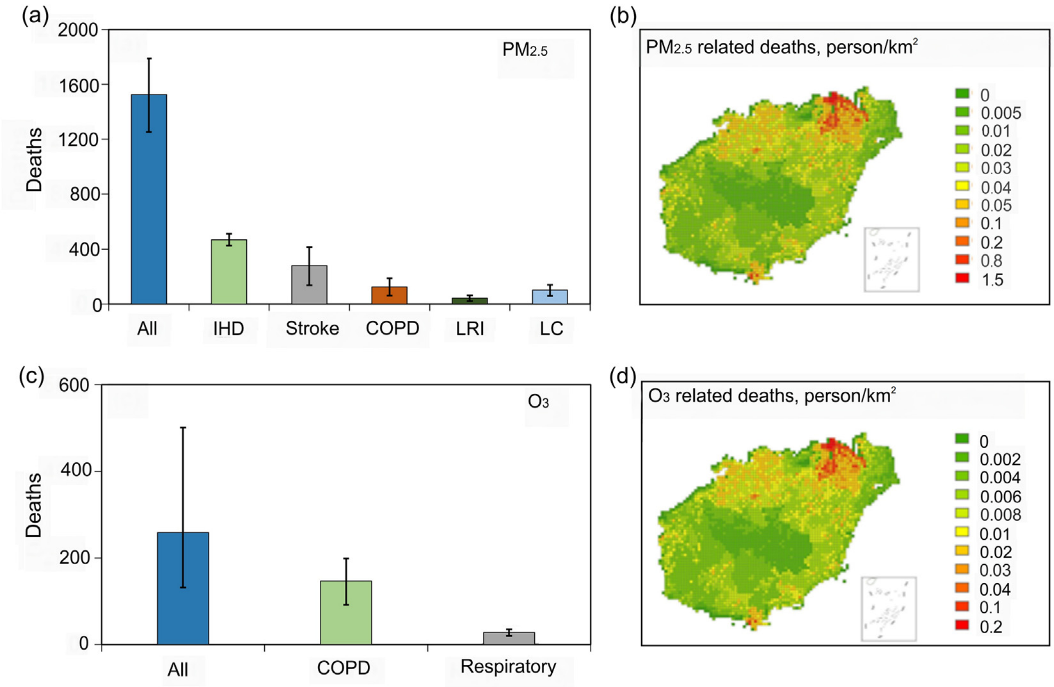

Fig. 5. Avoided deaths in 2035 attributable to long-term $PM_{2.5}$ exposure (**a**) and long-term O_3 exposure (**c**) and their spatial distributions (**b**, **d**). Error bars in (a, c) indicate the 95 % confidence intervals.

4. Conclusions and policy implications

4.1. Summary

Hainan Province takes a leading role in China's endeavors to improve its ecological environment, but the national AAQS and WHO guidelines provide limited direction for enhancing the current air quality in Hainan. Hence, our study develops a local AAQS for Hainan, filling the research gap regarding limited exploration into establishing local AAQS. Considering the relatively high background concentration and large interannual fluctuation of pollutant levels in Hainan, we first investigated the impact of statistical form on the evaluated concentrations and their interannual variations prior to setting concentration thresholds and statistical forms. Besides, in the process of developing the local AAQS, we also considered local air quality conditions, domestic and international AAQSs, and proposed the local AAQS. Moreover, we verified Hainan's ability to achieve the local AAQS by 2035, through designing the MTFR emission scenario and conducting CMAQ simulation. Finally, we quantified the potential reduction in mortality associated with long-term exposure if the standards were to be approximately just met (under the ECP scenario). The summary of this study is as follows:

1) The proposed local AAQS of Hainan Province contains six pollutant indicators: $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO. In the local AAQS, the limits of annual mean concentration for $PM_{2.5}$ and PM_{10} are 10 and 20 μg/m^3, respectively. The limits of the annual 95th percentile of 24-h mean concentrations for $PM_{2.5}$ and PM_{10} are 25 and 45 μg/m^3, respectively. It is noteworthy that the peak season standard of O_3 with the limit of 85 μg/m^3 is added to the new standards. Additionally, the annual 95th percentile of O_3 MDA8 concentration limit of 120 μg/m^3 and the annual 99th percentile of O_3 1-h mean concentration limit of 160 μg/m^3 are set in the local AAQS. Besides, the three-year moving-average method is adopted for $PM_{2.5}$, PM_{10}, and O_3 to reduce interannual variation, and the regional average evaluation method is used for air quality attainment evaluation in the local AAQS.

2) By implementing effective control measures, Hainan is projected to achieve compliance with all the standards specified in the local AAQS by 2035. For example, the annual mean concentration of $PM_{2.5}$, the annual mean concentration of PM_{10}, and the annual 95th percentile of the daily maximum 8-h average concentration of O_3 can meet the respective targets of 10 μg/m^3, 20 μg/m^3, and 120 μg/m^3.

3) The implementation of the newly proposed local AAQS is projected to yield significant health benefits in Hainan. Putting the standards into implementation may contribute to reducing 1,526 (1,253–1,789) premature deaths attributable to long-term exposure to $PM_{2.5}$ and 259 (132–501) premature deaths owing to long-term exposure to O_3 in 2035, respectively. Among all the cities in Hainan, Haikou and Sanya have the most remarkable health effects.

4.2. Policy implications

1) It is strongly recommended that Hainan Province promptly issue and enforce the newly proposed word-class local AAQS. This proactive action will not only enhance air quality management in Hainan Province but also make a substantial contribution to the development of Hainan Province as a national ecological civilization pilot zone and to Hainan's vision of achieving world-leading air quality by 2035.

2) It is suggested that the government of Hainan Province should implement more stringent policies to attain the new AAQS. Hainan Province has already issued some policy documents aimed at the 14th Five-Year period or beyond the period, and strict adherence to these policy documents forms the foundation for Hainan to meet the new standards by 2035. Furthermore, according to the ECP scenario, to meet the local AAQS by 2035, the government needs to formulate and implement more specific and more stringent control policies for the 2025–2035 period. These control policies include enhancing efforts in promoting energy-efficient buildings, employing low-VOC solvents, and encouraging green dining practices; strengthening energy-saving renovations in the industrial sector; intensifying control measures for open biomass burning; and advancing the rectification of small-scale livestock and poultry farming practices among rural households.

3) Our research offers valuable insights into the development of local AAQSs for regions worldwide. In countries with large territorial areas, the significant variations in geography, climate, and air quality across

different regions make it challenging to achieve effective environmental management through unified NAAQS. Therefore, the establishment of local AAQSs becomes necessary to better guide air quality improvement. When formulating these local AAQSs, in addition to referring to the leading AAQSs globally and WHO AQG, careful consideration should be given to determining appropriate statistical forms and threshold values based on the local air quality conditions. Threshold values should be set lower than the current pollutant concentrations but not excessively low, to ensure that the new standards offer guidance for improving local air quality while remaining feasible. Moreover, both the threshold values and statistical forms should strive to align with the WHO AQG or global AAQSs so that the assessment results can be readily interpreted by the international community. Finally, the feasibility and health benefits of the new standards should be verified through scenario design and air quality simulations.

Author contributions

Q.S.: conceptualization, data curation, methodology, formal analysis, visualization, validation, writing–original draft, writing–review & editing. N.N.Z.: data curation, methodology, formal analysis. Y.N.Z.: data curation, formal analysis, writing–review & editing. D.J.Y.: data curation, methodology, writing–review & editing. J.M.H., S.X.W.: conceptualization, methodology, formal analysis, supervision, funding acquisition, project administration. S.Y.L.: data curation, methodology. W.S.X., W.J.Y., X.X.M., X.H.X.: data curation, formal analysis, writing–review & editing, project administration. X.C.W.: writing–review & editing, project administration. D.H.X.: methodology, writing–review & editing, project administration. Y.Z.: methodology, writing–review & editing. Q.P.Q., X.H.: formal analysis, investigation. Y.Q.J., Z.X.D., H.T.Z., Y.S.S.: data curation. Z.Q.L.: writing–review & editing. B.Z.: conceptualization, methodology, formal analysis, supervision, writing–review & editing, funding acquisition, project administration.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research is supported by the National Key R&D Program of China (2022YFC3700702), the Energy Foundation, and the Tsinghua-Toyota Joint Research Institute Inter-disciplinary Program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eehl.2023.10.002.

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