Airborne and Satellite Investigation of Asian Air Quality

Thailand Rapid Science Synthesis Report

Geo-Informatics and Space Technology Development Agency (Public Organization) and Many More

Introduction to the ASIA-AQ Rapid Science Synthesis Report for Thailand

In Thailand, concerns about air pollution remain a pressing issue, driven by the high levels of fine particle pollution associated with haze observed across the country. To address this, the Thai government is currently moving closer to the implementation of a Clean Air Act (CAA). Thailand has a strong history of environmental law and monitoring programs that are detailed in the Appendix to this report. The Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) provides an opportunity for valuable feedback on current conditions in Thailand and detailed observations to identify the causes of unhealthy air quality conditions.

ASIA-AQ assembled a large team of experts to focus on air quality in Thailand under the leadership of the Geo-Informatics and Space Technology Development Agency (GISTDA) of Thailand in collaboration with the National Aeronautics and Space Administration (NASA) of the United States and the National Institute of Environmental Research (NIER) of South Korea. The study connected international researchers with local experts from GISTDA and the academic community in Thailand as well as Thailand's Pollution Control Department (PCD) and the National Astronomical Research Institute of Thailand (NARIT).

The overarching goal of the study was to improve understanding of the factors contributing to poor air quality in Thailand. To accomplish this, NASA's DC-8 and G-III aircraft collected detailed measurements during research flights in late March of 2024. A research team from Korea University also established a ground-based research site in Chiang Mai during the study period. Observations were guided by model forecasts of meteorology and air quality, and comparison with these models serves as an important evaluation of air pollutant emissions and understanding of air quality chemistry and transport.

The detailed report that follows provides a set of early high-level findings that are intended to be useful for policy makers to consider in the development of ongoing air quality mitigation strategies and the verification of contributions from specific emission sources that could be targeted for reduction.

The ASIA-AQ study collected observations across Asia. In addition to Thailand, flights were conducted over the Philippines, South Korea, and Taiwan. Flights in each location provided unprecedented comprehensive measurements of pollutants for both gaseous and fine particle pollution with extensive spatial and vertical sampling coverage. It is important to recognize that the brief ASIA-AQ measurement period is insufficient to address all of the air quality issues confronting Thailand. This introduction is provided to summarize both the value and limitations of the ASIA-AQ observations.

The ASIA-AQ observation period in Thailand was specifically chosen to target the impact and extent of burning in northern Thailand during peak pollution season with the understanding that drivers of air pollution impacts in Bangkok are more persistent over a longer period each year.

Thailand has a well-established air quality monitoring program with valuable observations on air pollution trends. Air quality standards for ozone and $PM_{2.5}$ (fine particle pollution less than 2.5 micrometers in diameter) focus on the two pollutants that are primarily responsible for respiratory health effects. Other measured criteria pollutants include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and PM_{10} (particle pollution less than 10 micrometers in diameter). Historical monitoring data played an essential role in selecting the most useful period to target for research flights. Specifically, when NASA and NIER scientists visited in 2022, PCD provided multi-year data for $PM_{2.5}$ and ozone at two monitoring sites, the Public Relations site in Bangkok and the City Hall site in Chiang Mai.

Hourly measurements of $PM_{2.5}$ at the two sites over the 2017-2021 time period (see Figure 1) show clear seasonal cycles. Pollution is heavier to the north in Chiang Mai, peaking in March. This peak is coincident with annual crop burning practices and associated wildfire activity that is well documented in satellite observations. While the peak in $PM_{2.5}$ comes earlier in Bangkok, the urban sources regulating local pollution impacts are more sustained and seasonal changes are less pronounced. For this reason, March was selected as the best time of year to observe both urban air quality in Bangkok and the extent to which burning activity impacts air quality across northern Thailand.

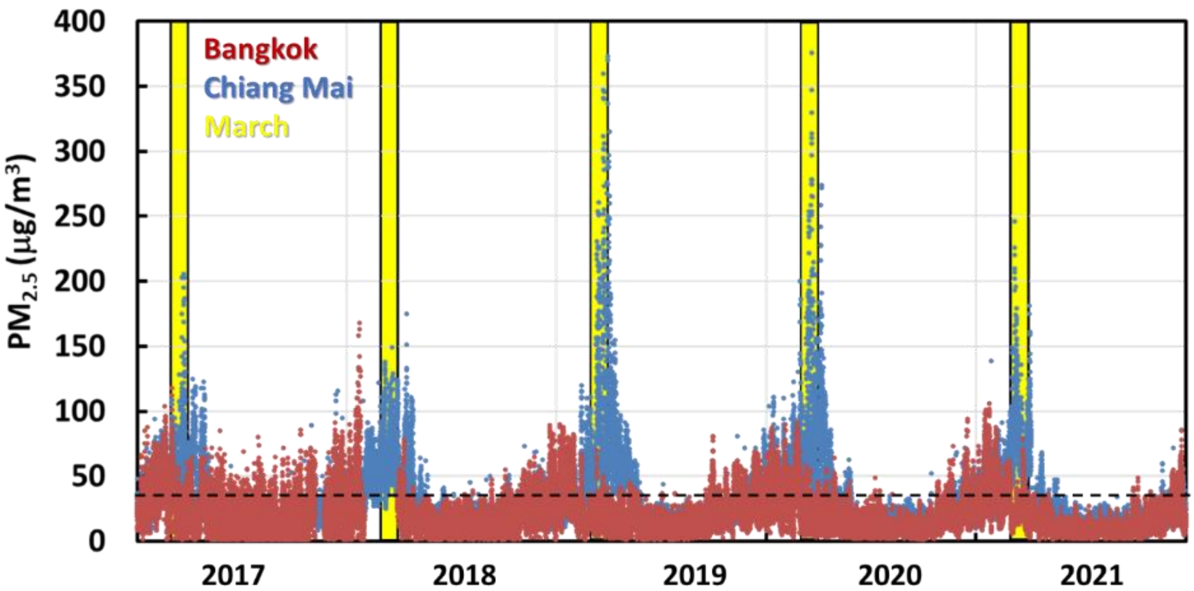


Figure 1. Timeline of hourly $PM_{2.5}$ measured in Bangkok (Public Relations site, red data) and in Chiang Mai (City Hall site, blue data) over the 2017-2021 time period. Peak pollution in March of each year is highlighted in yellow. The $PM_{2.5}$ daily standard of 36.5 mg/m^3 is shown by the dashed line.

Looking at the two most recent years before the ASIA-AQ study, the link between fire activity and $PM_{2.5}$ is more clearly demonstrated (see Figures 2 and 3). Air quality monitoring sites in northern Thailand show that increases in $PM_{2.5}$ levels coincide with the satellite detection of fire hotspots over Thailand and neighboring countries. They also demonstrate interannual variability with lower peak pollution in 2022 as heavier rainfall led to less burning activity compared to 2023 and 2024 (during ASIA-AQ). Additional evidence for the link between burning and $PM_{2.5}$ in the ASIA-AQ observations will be discussed in more detail in the section on $PM_{2.5}$ sources and composition.

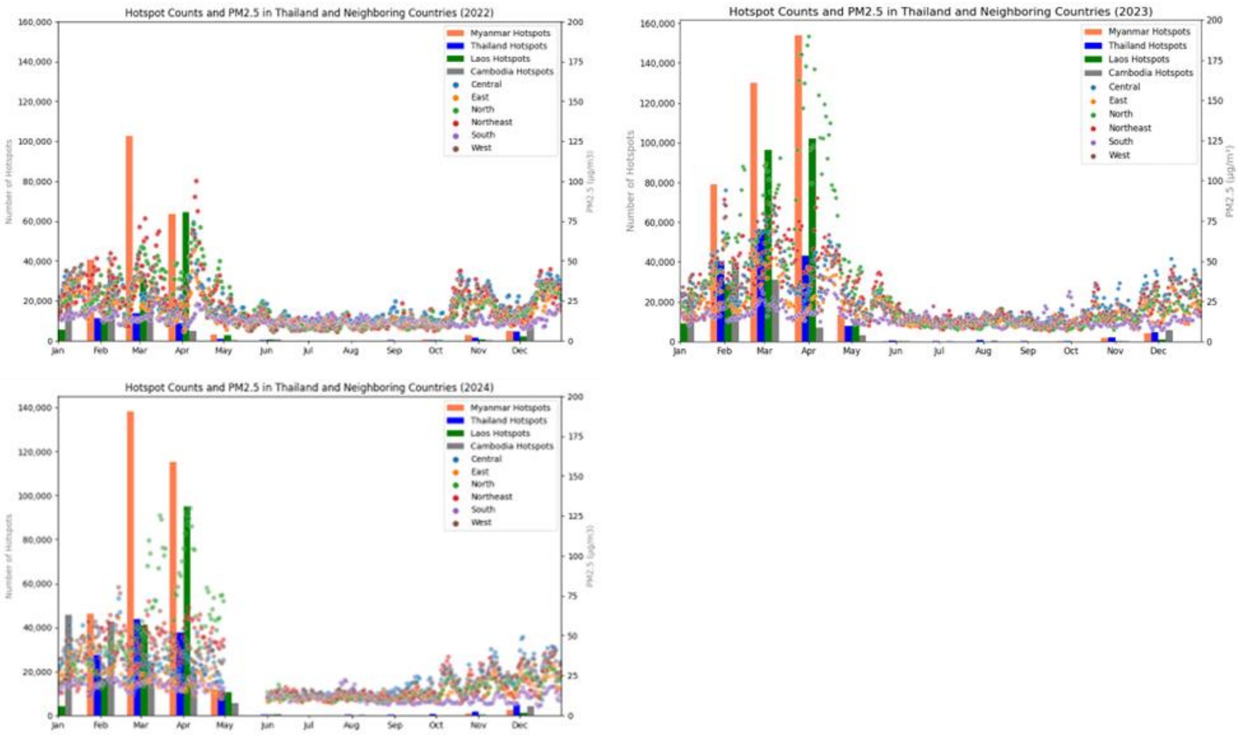


Figure 2. Seasonal cycle of average daily $PM_{2.5}$ levels across each region of Thailand and number of hotspots detected across Thailand and neighboring countries in 2022, 2023, and 2024.

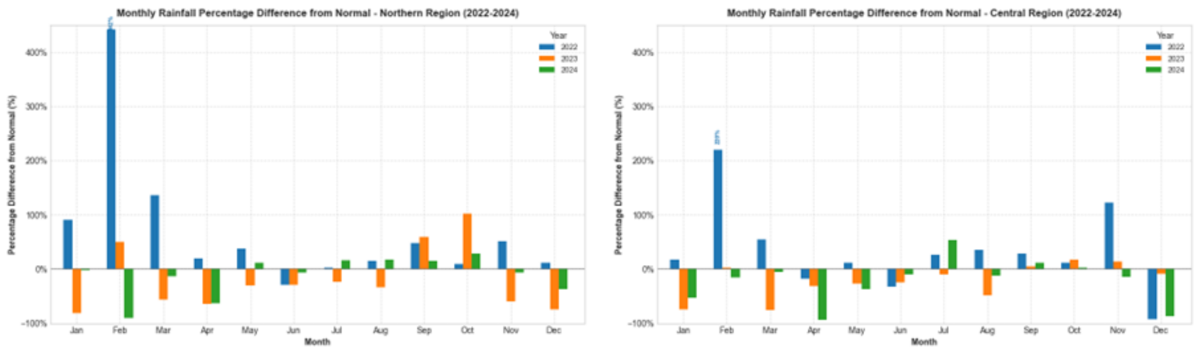


Figure 3. Monthly percent difference in rainfall from normal for 2022-2024 for the Northern and Central Regions of Thailand.

Public awareness is most influenced by visible haze associated with PM2.5, but attention is also needed for ozone pollution.

From a public awareness perspective, visible light scattering by fine particle pollution ($PM_{2.5}$) is most easily noticed, especially when conditions exceed the air quality standard. Judging pollution levels by the naked eye, however, is still imperfect and often misleading since the amount of light scattering is a complex function of relative humidity and particle properties such as size, shape, and composition. For ozone (O_3), there are no visible cues, leaving the population unaware of unhealthy conditions without consulting PCD measurements and alerts. Thus, increased awareness of Thai air quality monitoring observations and alerts for both $PM_{2.5}$ and ozone is essential to bringing more informed public attention to the timing and aspects of air quality most important to public health. Additional impacts on crop yields provide additional emphasis on the need for systematic monitoring of ozone.

Historical monitoring data for ozone (2011-2021) also shows distinct differences between Bangkok and Chiang Mai (see Figure 4). Since ozone undergoes rapid changes throughout the day, the air quality standard is based on a daily calculated value for the maximum 8-hour average (MDA8). MDA8 ozone in Chiang Mai shows a very consistent seasonal trend with values exceeding the standard of 70 ppb mainly during the spring (Feb-Apr) coincident with burning activity. By contrast, ozone in Bangkok can exceed the standard at almost any time from September to May (dry season) with a greater probability of extreme values of 90 ppb or more. This can be attributed to the much greater abundance of nitrogen oxides in Bangkok. This is discussed in more detail in the section on analysis of ozone production sensitivity to precursors.

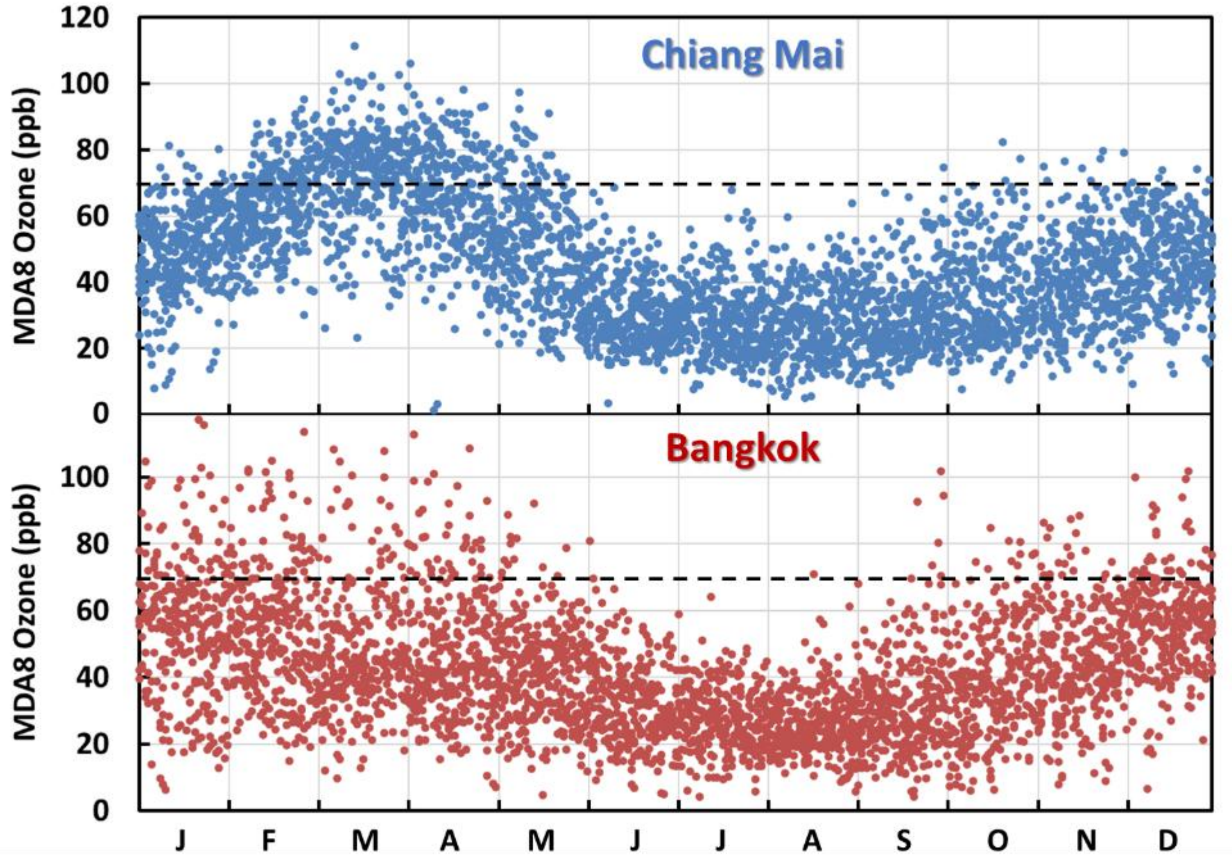


Figure 4. Seasonal trends in MDA8 ozone measured in Bangkok (Public Relations site, red data) and in Chiang Mai (City Hall site, blue data) over the 2011-2021 time period. The MDA8 ozone standard of 70 ppb is shown by the dashed line.

ASIA-AQ conducted sampling flights on four days during a time when air quality standards were exceeded for both PM2.5 and ozone. Large pollution shifts were also documented due to heavy burning activity during the first two flights (16 and 18 March) and reduced burning during the second two flights (21 and 25 March). However, burning influence was present throughout all flights.

As expected, ASIA-AQ research flights were able to successfully document air quality conditions in Thailand that exceeded air quality standards. More importantly, the good fortune of sampling during a period of changing conditions provided a better opportunity to assess pollution sources. In Chiang Mai, $PM_{2.5}$ far exceeded air quality standards during the first half of the study period (see Figure 5), and even when $PM_{2.5}$ was sharply reduced after the disruption of burning due to heavy precipitation, conditions mainly met or exceeded the $PM_{2.5}$ standard along with a slow increase as burning activity began to increase again. In Bangkok, conditions only briefly exceeded the standard for $PM_{2.5}$ with the shift in wind patterns after the precipitation event. In the section of this report addressing $PM_{2.5}$ sources, flight observations of fine particle chemical composition and tracers of burning provide ample evidence for the dominant role of burning to the peak $PM_{2.5}$ pollution in northern Thailand as well as persistent evidence of burning influence throughout the study across the entire flight area from Bangkok to Chiang Mai.

For MDA8 ozone, ozone values tend to be larger in Chiang Mai, although the highest ozone was observed in Bangkok on 22 March. These differences are consistent with the seasonal behaviors seen in Figure 4 showing that the higher ozone in Chiang Mai is linked to burning and is more sustained. By contrast, ozone conditions in Bangkok are more variable and driven by urban emissions and meteorology. In the section of this report addressing ozone, these differences will be discussed in more detail.

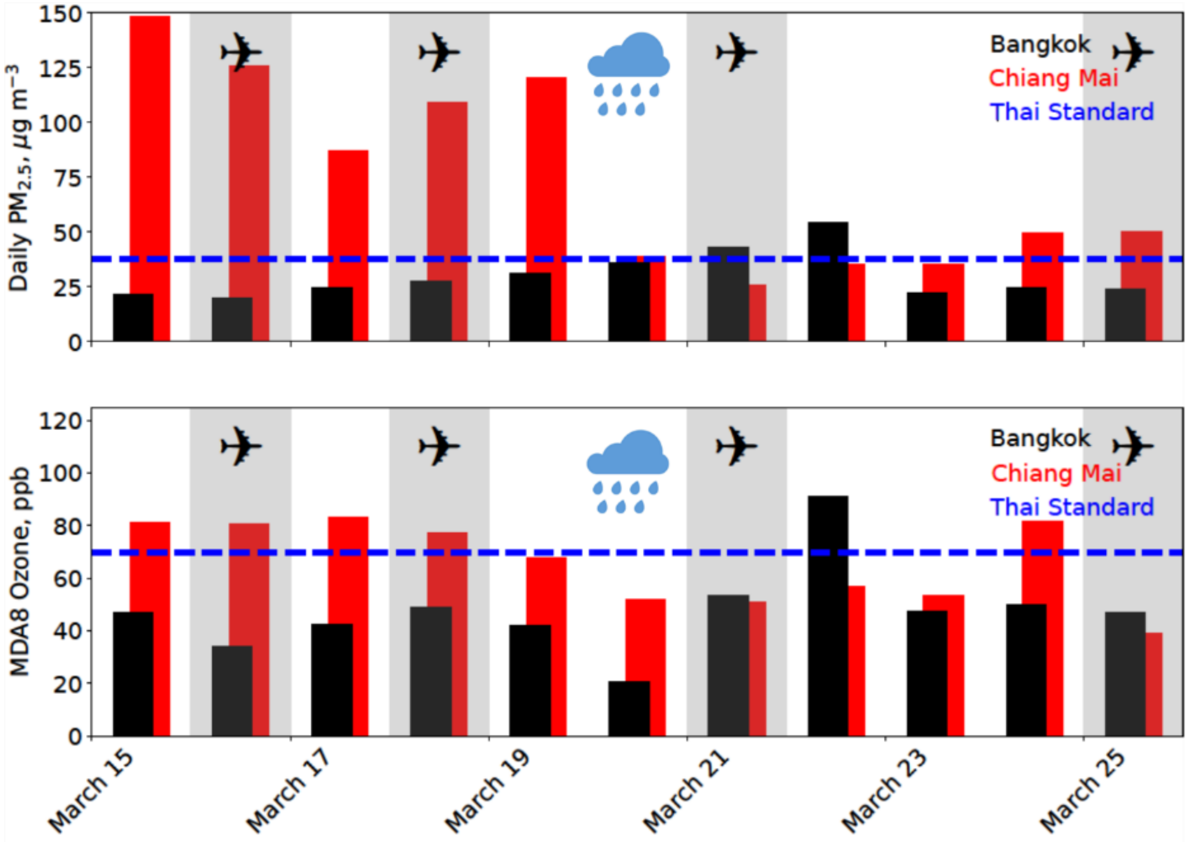


Figure 5. Air quality conditions observed by the Thai ground monitoring network during the ASIA-AQ study. Bars indicate daily average $PM_{2.5}$ (top) and MDA8 ozone (bottom) for sites in and around Bangkok (black) and Chiang Mai (red). The Thai air quality standards are indicated by a dashed blue line. Days sampled by DC-8 research flights are shaded gray and are marked with an aircraft symbol. The rain cloud marks a shift in conditions brought about by heavy precipitation across northern Thailand and a shift in wind patterns.

The ASIA-AQ sampling strategy used the NASA DC-8 to directly observe the detailed composition of the lower atmosphere between Bangkok and Chiang Mai, while the G-III used remote sensing to map air quality conditions in Bangkok.

Sampling on four flight days was methodically executed by both aircraft to provide a comparison of air quality under changing meteorological conditions. The aircraft were based in Utapao and used repetitive sampling. The DC-8 flew a circuit from the operational base in Utapao to Chiang Mai twice per day (see Figure 6). Constantly changing altitudes to profile the composition of the lower atmosphere, low approaches at several airports were used to sample all the way to the surface. These included Utapao, Don Mueang, Phitsanulok, Sukothai, Phrae, and Chiang Mai. The G-III flew only over Bangkok, mapping distributions of $PM_{2.5}$, ozone, NO_2, and CH_2O below the aircraft three times per day. Examples of G-III mapping are shown in Figure 6. The G-III was able to sample on two additional days (19 and 23 March) without the DC-8.

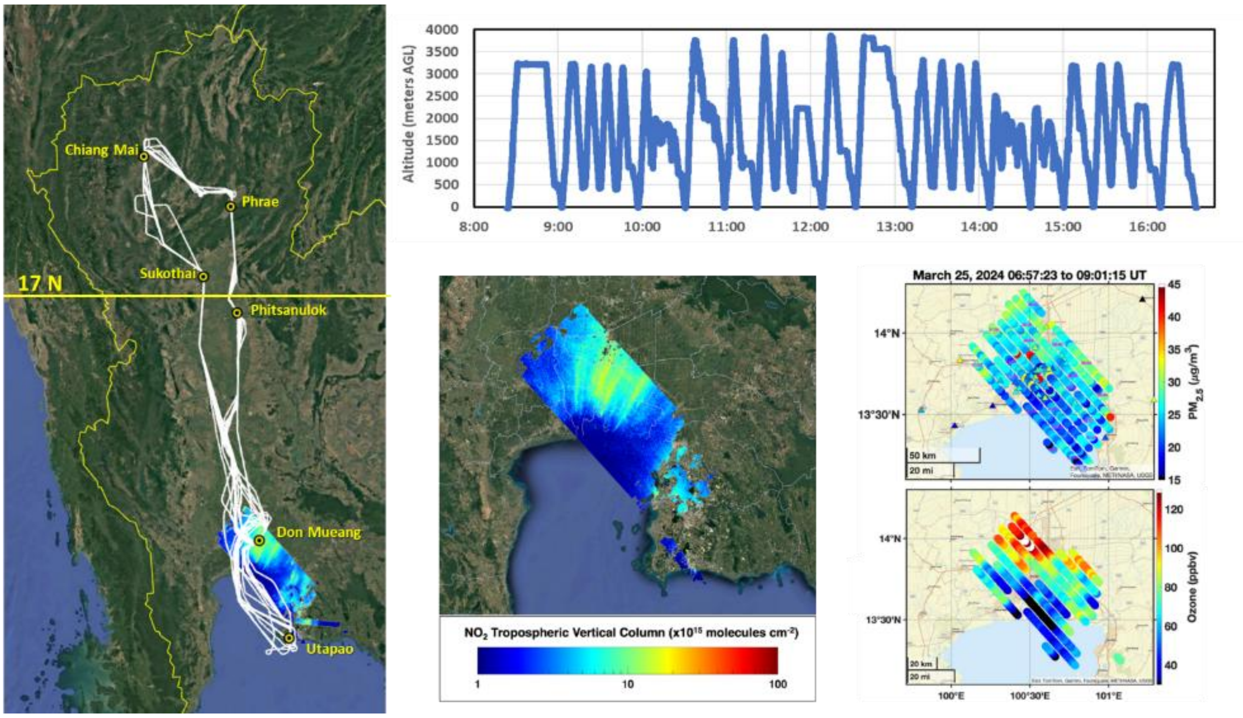


Figure 6. (Left) Map showing NASA DC-8 and G-III sampling strategies. The white line shows the DC-8 flight circuit from Utapao to Chiang Mai. The colored area shows the mapping of the G-III over Bangkok. Areas of heavy smoke were north of 17° N, and airports where the DC-8 conducted low approaches are labeled. (Top right) An example of the altitude changes of the DC-8. (Bottom right) Examples of remote sensing over Bangkok by the G-III for NO_2, $PM_{2.5}$, and ozone.

While more detailed discussion will be offered in later sections, it is noteworthy that pollution gradients in Bangkok can be very strong. In particular, the NO_2 distribution in Figure 6 shows evidence for transport of pollution northward, likely due to onshore sea breeze winds. This results in an ozone distribution that shows high values exceeding 100 ppb in the north and values as low as 40 ppb in southern parts of the city closer to the coast. These large shifts in air quality within the urban environment call for careful consideration of the placement and number of air quality monitors in Bangkok.

The value of the DC-8 observations to examine vertical, horizontal, and temporal changes is shown in Figure 7. The example is for sampling carbon monoxide (CO), but the DC-8 observations include many more compounds as well as particle composition measurements that aid in the interpretation of sources. As reflected in the ground monitoring of Figure 5, the strong shift in conditions between the first two flights and second two flights is also seen in the DC-8 flight observations. The regional nature of burning emissions is seen in the enhanced carbon monoxide up to 3000 m due to a combination of local and transported emissions. The shift to much cleaner conditions in the north on 21 March is also shown to be not only at the surface but throughout the lower atmosphere. The value of low approaches at airports is evident in observations that were collected at the lowest altitudes below 300 m (marked by the dashed line in Figure 6) that are normally inaccessible to airborne sampling.

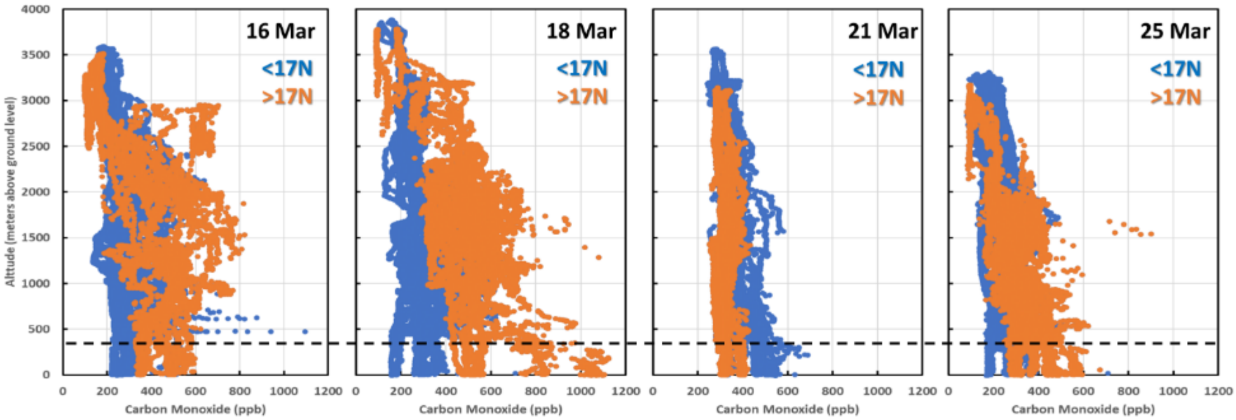


Figure 7. NASA DC-8 observations of carbon monoxide (CO) during the four ASIA-AQ sampling flights. Data are shown for sampling south (blue) and north (orange) of 17° N latitude (see Figure 6). The black dashed line at 300 m (1000 feet) indicates the lowest flight altitude allowable without conducting low approaches at airports.

The strong influence of burning on air quality in Thailand reinforces the need for documenting burning activity not only for Thailand but also for neighboring countries.

Annual inventories of hotspots and burned area for Thailand are an extremely valuable product for assessing the impact of fires to air quality. Currently, GISTDA provides information of exceptional quality on hotspots and burnt area for Thailand. The burnt area maps shown in Figure 8 indicate similar amounts of burning in 2023 and 2024. When highlighting the month of March 2024, the highest concentration of burned land overlaps with the northernmost portion of the DC-8 flight path including Chiang Mai, Lampang, and Phrae.

Analysis of land use reveals that forests have been most affected by fires, with over 11,000 square kilometers burned in 2023, accounting for approximately 61.4% of the total burned area. This correlation is also evident in hotspot data. As of March 2024, forest fires continue to be the primary cause of burning in Thailand, contributing to 43.8% of the total burned area and aligning with hotspot activity.

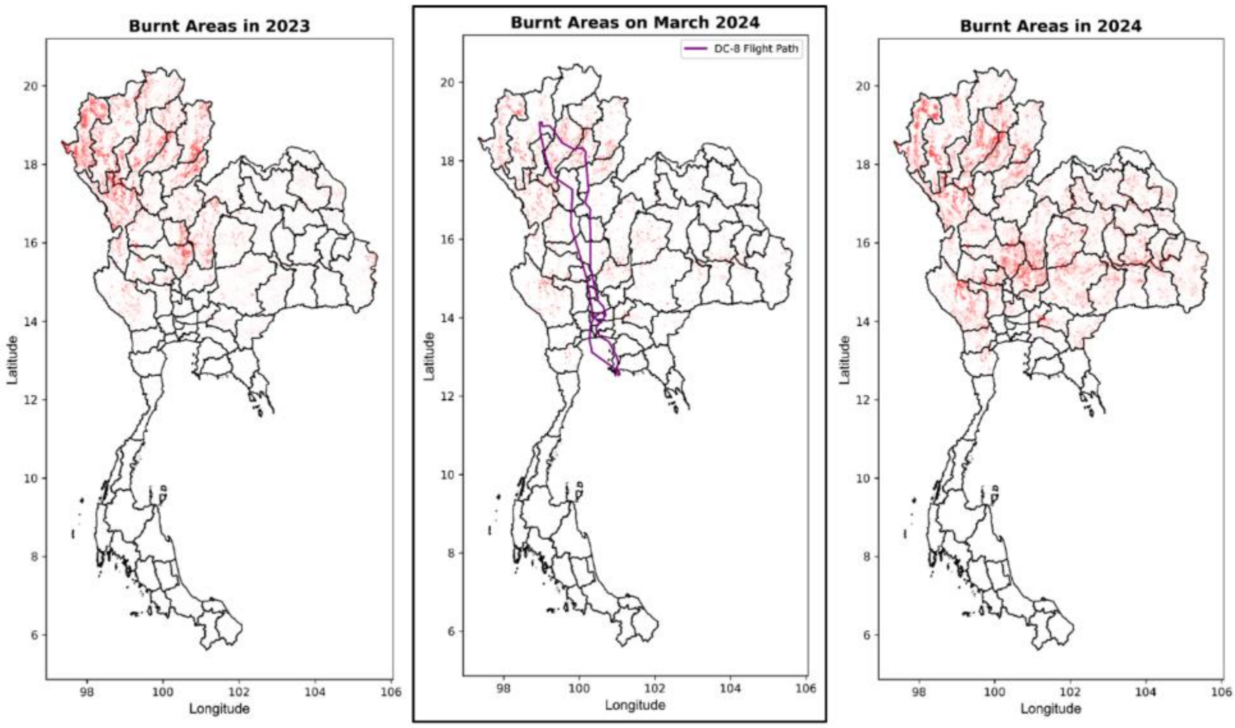


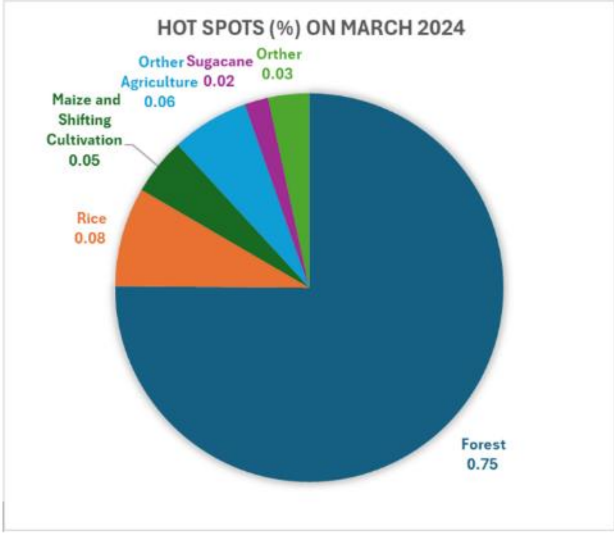
Figure 8. Burnt area in Thailand for 2023 (annual), March 2024, and 2024 (annual). Greatest overlap between the DC-8 flight path and burned area are in Chiang Mai, Lampang and Phrae (shaded gray).

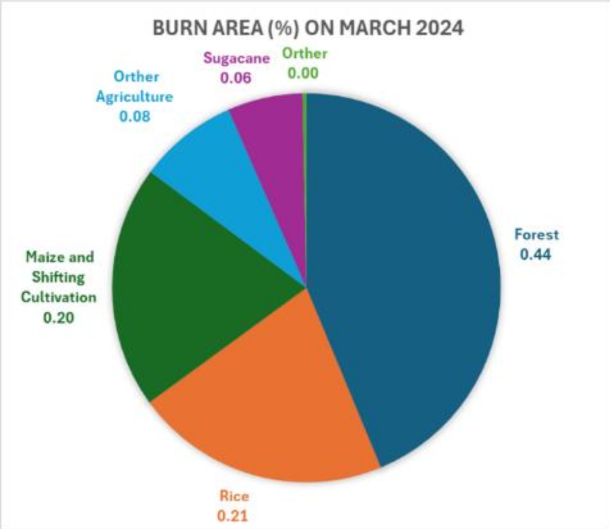
Statistics coincident with the ASIA-AQ study in March 2024 are provided in Table 1. Based on area burned, fire impacts in Thailand are roughly divided between forest and agricultural burning of different types. When evaluating satellite hotspots instead of burned area, the balance is shifted significantly towards forest burning. This can be related to both the persistence of burning and the amount of fuel available to burn. Fires associated with agricultural burning can be very short in duration such that they may escape hotspot detection from satellites, but they are still accounted for in burned area methods. Forest fires are longer in duration, making hotspot detection more likely, but they also lead to more fuel consumption, making both the hotspot and burned area statistics useful for understanding emissions.

While hotspots are easily obtained for neighboring countries, burned area products are much more resource intensive. Even so, based on the larger number of hotspot detections in Myanmar and Laos (see Figure 2), efforts to expand the production of burned area products outside of Thailand would provide valuable information on the controllable impacts of regional burning.

Table 1. Burnt area in Thailand during March 2024, categorized by different land use types. Results are also summarized in the pie charts below.

Land Use	Hot Spots (Points)	Percentage	Burn Area (km²)	Percentage
Forest	34,576	75.1%	3,615	43.7%
Rice	3,811	8.3%	1,754	21.2%
Maize and Shifting Cultivation	2,184	4.7%	1,669	20.2%
Other Agriculture	2,978	6.5%	682	8.3%
Sugarcane	907	2.0%	517	6.3%
Other	1,570	3.4%	27	0.3%
Grand Total	**46,026**	**100.00**	**8,264**	**100.00**





Questions addressed by this report of preliminary findings

This report is structured into chapters and a summary. Each chapter addresses current progress in answering a specific question for which ASIA-AQ observations provide valuable insight. Although the findings presented are preliminary, they are considered to be highly reliable. However, further scientific analysis is necessary to more precisely quantify these conclusions. These additional studies will be published in peer-reviewed scientific journals in the coming years. Importantly, the need for ongoing research should not delay discussions around strategies for emission reductions and their potential impact on improving air quality in Thailand.

The questions are as follows:

1. What are the key sources contributing to $PM_{2.5}$ in Thailand?

2. What are the sources and factors controlling ozone production in Thailand?

3. What is the role of local and regional meteorology in driving air pollution patterns in Thailand?

Question 1: What are the key sources contributing to $PM_{2.5}$ in Thailand?

Summary findings: Biomass burning is the dominant source of air pollution in northern Thailand, with higher $PM_{1.5}$ and biomass burning markers observed in Chiang Mai and surrounding areas. Urban emissions contribute significantly to pollutants like toluene in Bangkok. A rain event on March 21 temporarily reduced pollution levels, showing the role of weather in clearing the air. While both burning and urban sources need attention, peak pollution in Thailand will not improve without addressing burning practices both in Thailand and neighboring countries.

Air pollution remains a critical environmental and public health challenge in Thailand, with $PM_{2.5}$ and other pollutants reaching hazardous levels, particularly during the dry season. One of the highest priorities in Thailand is to understand the sources and factors controlling the $PM_{2.5}$ abundance. As demonstrated in the introduction, ground monitors show that $PM_{2.5}$ is much greater in Chiang Mai than in Bangkok, and temporal changes in $PM_{2.5}$ closely follow burning activity. Observations from the NASA DC-8 aircraft further reinforce this picture. Measurements from the aircraft are limited to smaller sizes up to only 1.5 micrometers in diameter ($PM_{1.5}$) but this includes valuable information on the chemical composition of the fine particle pollution. Analysis of the $PM_{1.5}$ concentrations and composition along with key chemical tracers (e.g., levoglucosan, acetonitrile, benzene, and toluene) provide important evidence for the role of burning and urban sources in the trends and factors influencing $PM_{2.5}$ pollution across different regions of Thailand. Flying a route between Utapao in the south to Chiang Mai in the north twice daily, $PM_{1.5}$ in the lower atmosphere was broadly sampled on each flight day (see Figure 9).

The scatter plots in Figure 9 show $PM_{1.5}$ concentrations in Thailand at altitudes below 1000 meters above ground level across the four flight days in March 2024. The x-axis represents latitude, ranging from southern locations (e.g., Utapao, Don Mueang) to northern areas (e.g., Chiang Mai). On the first two days (top panels for 16 and 18 March), $PM_{1.5}$ levels are lower in central Thailand, including Bangkok, and increase toward the north due to seasonal biomass burning. However, on 21 March, this pattern deviates, with much less variability and a weaker trend with latitude. This change is coincident with heavy regional rainfall on the previous day, which both helped clear particulate matter from the atmosphere and reduced burning activity, temporarily lowering pollution levels. A few days later on 25 March, the latitude trend with higher particulate matter in the north begins to be reestablished with the resumption of burning activity and accumulated smoke emissions. The trend lines in each graph reinforce this, showing a weaker or slightly reversed trend on 21 March compared to the other days.

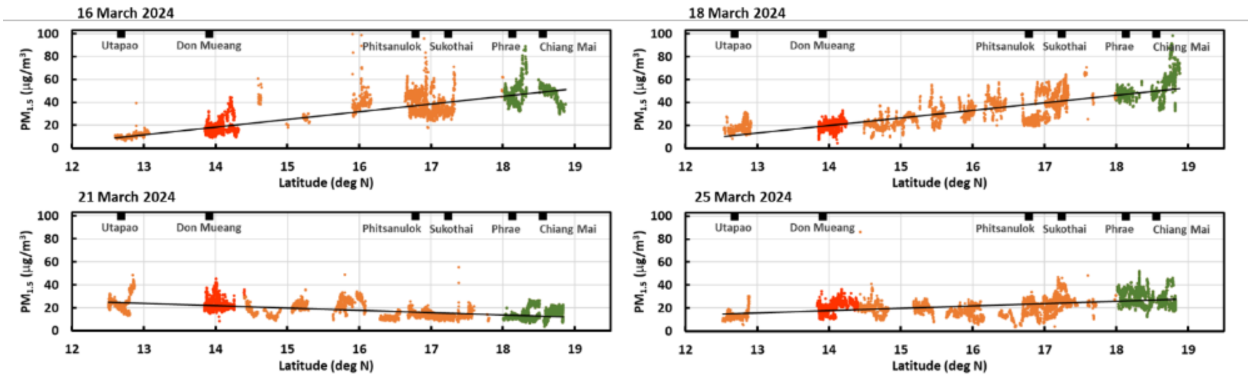


Figure 9. Latitudinal distribution of DC-8 observations of $PM_{1.5}$ in the lowest km over the four ASIA-AQ research flights. Location of airports for low approaches are annotated along with coloring to indicate measurements in Bangkok (red) and Chiang Mai (green) with other locations in orange.

Latitude trends in $PM_{1.5}$ composition further corroborate the importance of burning (see Figure 10). Across all locations and dates, Organic Aerosol (green) consistently dominates $PM_{1.5}$ composition, followed by Sulfate (red) and smaller fractions of other components. The distribution appears relatively stable across the different days, though important variations are visible that are consistent with biomass burning and other organic emissions playing a major role in $PM_{1.5}$ pollution in these areas, particularly in northern Thailand, where higher pollution levels were observed in previous analyses.

Consistent with Figure 9, the size of each pie chart in Figure 10 reflects the relative difference in total $PM_{1.5}$ concentrations. On 16 and 18 March, the organic fraction of aerosol composition increases for samples further north, consistent with greater impact of burning emissions. This changes on 21 March, when overall abundance of $PM_{1.5}$ is lower, organic contributions are reduced, and differences in composition across the region are minimal. By March 25, increasing $PM_{1.5}$ in the north is accompanied by increased organic aerosol contributions associated with increased burning activity. Unfortunately, it is difficult to fully attribute the burning contribution to organic aerosol since chemical oxidation quickly erases markers that would differentiate burning from other organic aerosol sources. The DC-8 instruments, however, measures other useful tracers that are related to burning emissions.

In Figure 11, acetonitrile (CH_3CN), a long-lived marker of biomass burning emissions shows a strong increase going north on 16 and 18 March. The northernmost values are five to six times greater than in the south, corroborating the strong influence of burning emissions on those two days when satellite observations indicated heavy burning activity and particulate pollution in the north was heavy. Acetonitrile is lowest on 21 March when $PM_{1.5}$ is lowest. By 25 March, when burning activity is being reestablished, the trend returns with acetonitrile in the north being factors of two to three higher than in the south. In the south, acetonitrile on 21 March is slightly elevated compared to other days, and evidence for a change in wind patterns shows that some burning emissions from Laos may have been transported into the vicinity of Bangkok and Utapao.

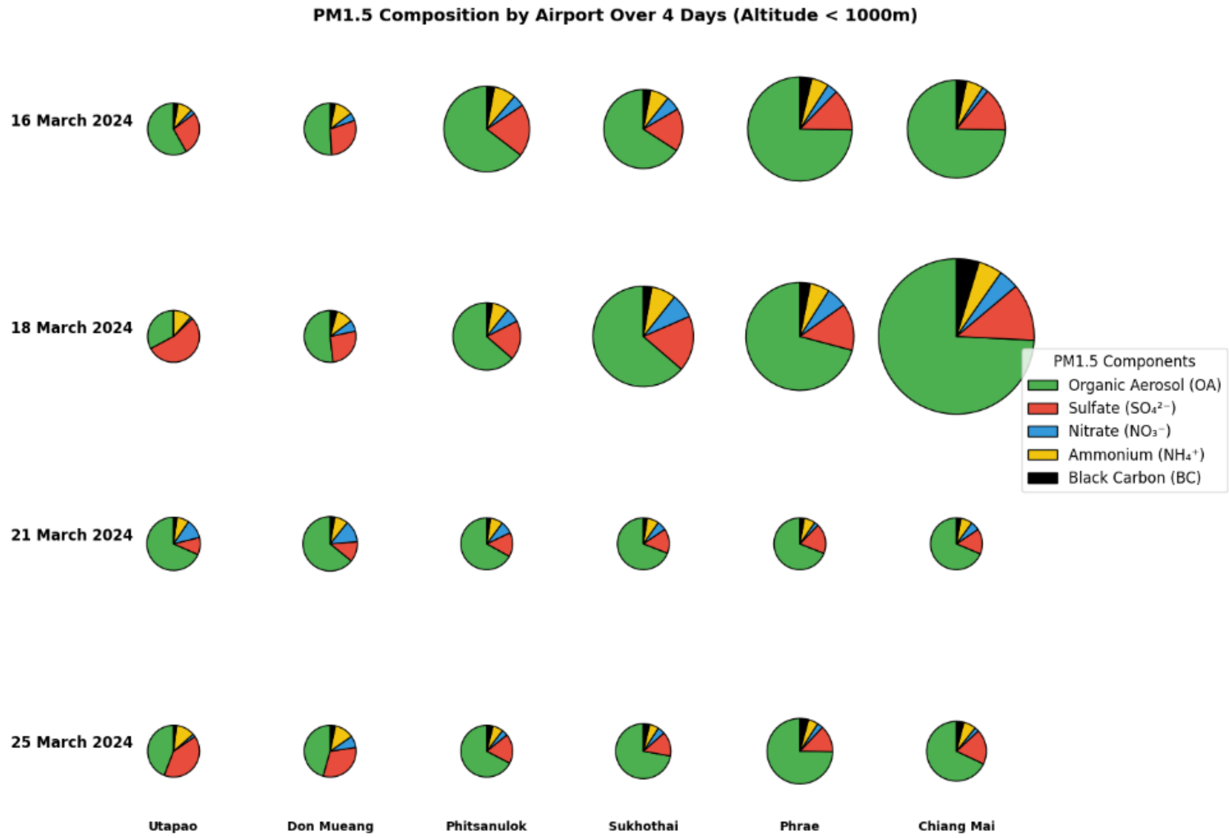


Figure 10. DC-8 measurements of $PM_{1.5}$ composition in the lowest km during low approaches over six airports during the four ASIA-AQ flights. The size of each pie is scaled to indicates the relative abundance of PM1.5 on each day. Airports are arranged from southernmost on the left to northernmost on the right.

It is important to clearly state that burning activity in Thailand and neighboring countries was never entirely suppressed and that smoke from fires was a persistent aspect of conditions in Thailand during ASIA-AQ, even in the southern portion of the sampling region. This is emphasized by a comparison of acetonitrile observed during flights in other ASIA-AQ countries with average values observed in Bangkok and Chiang Mai (see Figure 12). Even in Bangkok, acetonitrile in the lowest kilometer was two to three times greater than what was observed in other countries. These differences align with satellite observations of burning and smoke from fires in Southeast Asia in spring each year.

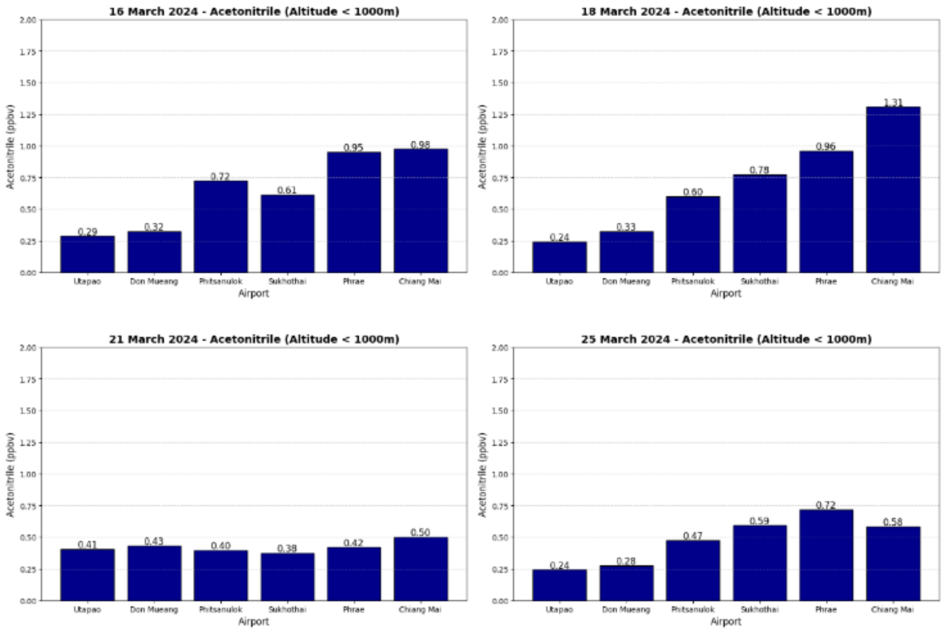


Figure 11. Average DC-8 observations of acetonitrile in the lowest km during low approaches over six airports during the four Thailand ASIA-AQ flights.

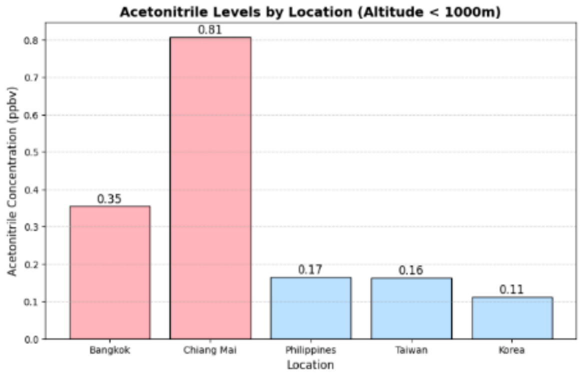


Figure 12. Average acetonitrile observed in the lowest km over Bangkok, Chiang Mai, and the other countries sampled during the ASIA-AQ study.

There are many other compounds that are not unique to burning but are strongly influenced by burning. The carbon monoxide shown in Figure 6 is an excellent example. Examining the relative behavior of benzene and toluene is also useful. These two aromatic compounds vary differently depending on the source with biomass burning and biofuel use favoring benzene while vehicular and industrial sources favor toluene. This is consistent with the increased benzene in the north on 16 and 18 March when burning was dominant (see Figure 13). By contrast, toluene was consistently highest in Bangkok on all four flight days (see Figure 14). Along with the compounds highlighted here, many additional compounds are undergoing analysis using statistical techniques such as Positive Matrix Factorization. Application of PMF to the DC-8 observations will provide useful information in further quantifying the relative influence of vehicular and industrial emissions versus biomass burning across northern Thailand during the ASIA-AQ study period.

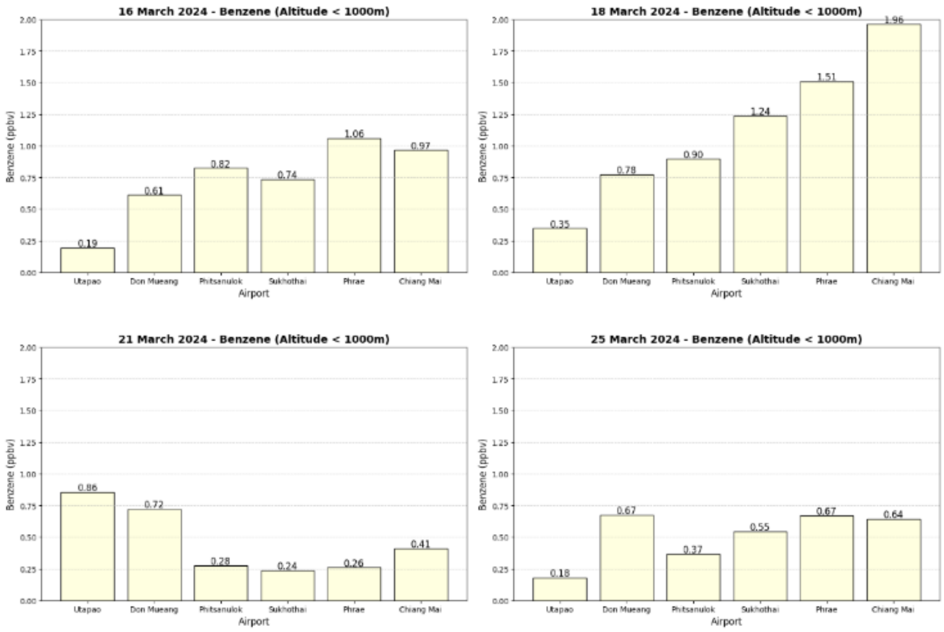


Figure 13. Average DC-8 observations of benzene in the lowest km during low approaches over six airports during the four ASIA-AQ flights.

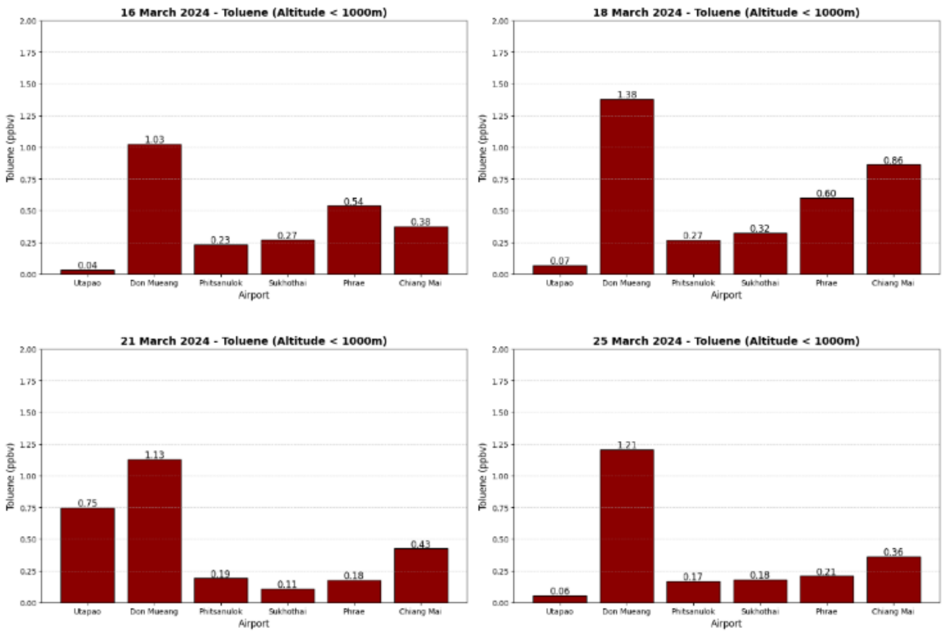


Figure 14. Average DC-8 observations of toluene in the lowest km during low approaches over six airports during the four ASIA-AQ flights.

The DC-8 airborne observations are complemented by ground measurements in Chiang Mai by Korea University. Particularly noteworthy are results from a filter analysis of $PM_{2.5}$ examining three key indicators of biomass burning influence (see Figure 15). The Fraction Modern (f_M) carbon determines the amount of organic material derived from plant matter versus fossil fuels. Values for f_M always exceed 0.7 indicating that biomass burning always makes a dominant contribution, but the highest f_M values exceeding 0.9 occur during peak $PM_{2.5}$ before the precipitation event on 20 March (top graph-blue). High levels of the potassium ion (K^+) are a second indicator of biomass burning that also correlates with $PM_{2.5}$ levels (middle graph - green) and maximize during the heavy burning period before March 20. Finally, the $\delta^{13}C$ isotope values decrease as $PM_{2.5}$ increases (bottom graph - red). Coal and fossil fuels have higher $\delta^{13}C$ values, while biomass burning produces lower $\delta^{13}C$ values. The isotopic results also corroborate that the majority of $PM_{2.5}$ during peak pollution originates from biomass burning rather than fossil fuel combustion.

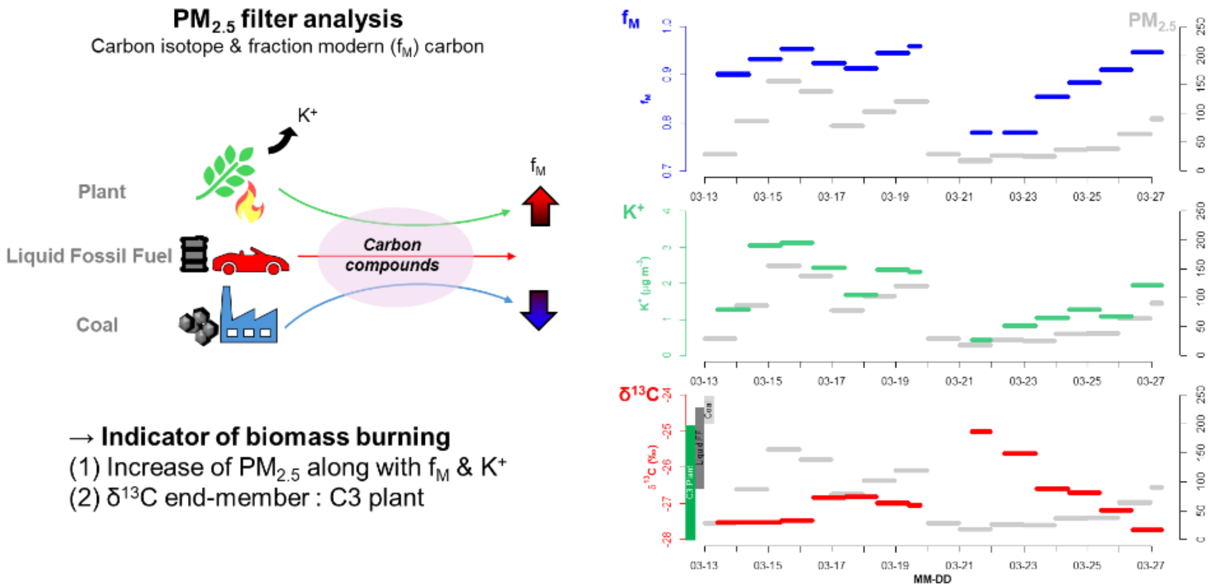


Figure 15. $PM_{2.5}$ filter analysis from the ground site in Chaing Mai during the ASIA-AQ flight period. (Figure provided by Junsu Gil, Korea University)

It has already been emphasized in the introduction that the strong influence of biomass burning (both forest and agricultural burning) comes from a broad regional source that include both local burning and burning in neighboring countries. By looking more closely at the distribution of aerosol composition with altitude, the combined impacts of local and transboundary transport of smoke can be discerned (see Figure 16).

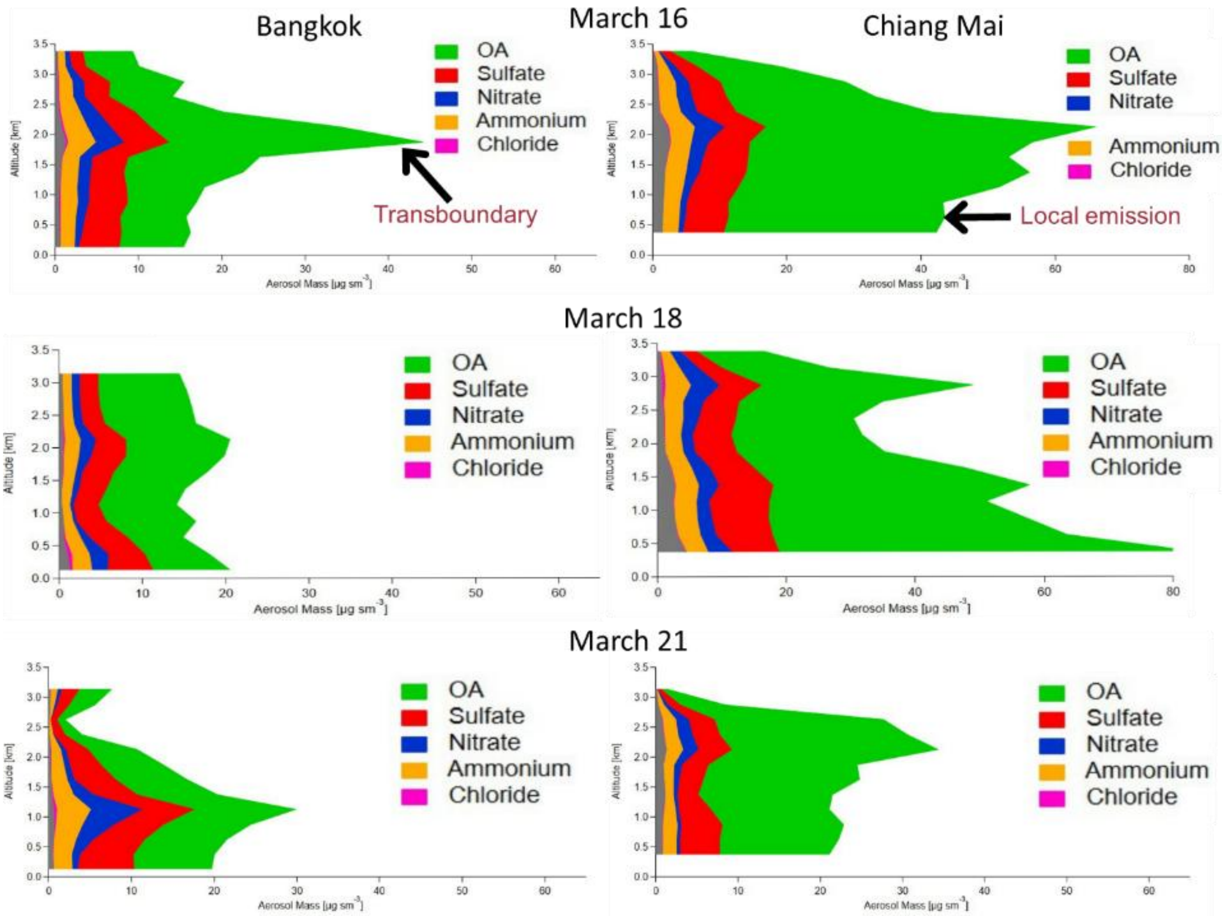


Figure 16. Comparison of DC-8 vertical profiles of aerosol composition over Bangkok (left) and Chiang Mai (right) for three of the ASIA-AQ flight days. (Figure provided by Sarunpron Khruengsai, NARIT)

On 16 March, Organic Aerosol (OA) dominates across all regions. In Chiang Mai, high OA concentrations at lower altitudes indicate local emissions, but a larger regional layer observed over both Chiang Mai and Bangkok at ~2 km suggests transport of aged aerosols from more distant sources. On 18 March, OA remains dominant. Chiang Mai exhibits even stronger strong local emissions at lower altitudes, while Bangkok sees increased sulfate and ammonium at low altitudes, pointing to industrial and vehicular pollution mixed with transported aerosols. By 21 March, local sources of OA in Chiang Mai have subsided as mentioned earlier due to precipitation, but transport from upwind sources remains unaffected. Bangkok shows increased sulfate and nitrate at low altitudes, reinforcing the accumulation of urban and industrial sources. Ammonium is uniformly distributed, showing that it is sufficiently available to support inorganic aerosol formation. These patterns underscore the importance of investigating biomass burning activity across Southeast Asia to fully quantify impacts of local and transported smoke on $PM_{2.5}$ in Thailand.

Question 2: What are the sources and factors controlling ozone production in Thailand?

Summary findings: Ozone pollution episodes occur regularly across Northern Thailand and were documented during ASIA-AQ. In Bangkok, these episodes can occur at any time, but farther to the north in Chiang Mai, ozone episodes peak along with particulate pollution from fires. Availability of nitrogen oxides (NOx) play a key role in all ozone episodes and NOx reductions would be expected to yield positive results for ozone almost immediately. VOC contributions to ozone production vary across Thailand with anthropogenic compounds being more important in Bangkok and compounds related to burning playing a larger role farther north. Strong ozone gradients pose a challenge that calls for more consistent and widespread monitoring.

Ozone is a respiratory hazard that is damaging to human health. Ozone also impacts the environment through damage to vegetation and reduced crop productivity. As a secondary pollutant, ozone is not emitted directly into the atmosphere. It is chemically produced by the catalytic cycling of nitrogen oxides (NOx). The efficiency of this catalytic cycle is sensitive to the breakdown of volatile organic compounds (VOCs), available sunlight, and humidity. With sufficient pollution in tropical settings such as Thailand, large amounts of ozone can be chemically produced in only a few hours. As noted in the introduction, the Thai air quality standard for ozone is frequently exceeded. This standard is based on an ozone amount of 70 ppb for the maximum daily eight-hour average (MDA8). Figure 17 shows MDA8 ozone from January to April of 2024. In northern Thailand, ozone exceeded the standard at one or more of five monitoring sites on 50% of all days. Those exceedances occur almost entirely in the latter portion of the period, closely following the historical trend for Chiang Mai (see Figure 3) and coincident with the increase in burning. By contrast, ozone in Bangkok (site 13T) exceeded the ozone quality standard on 26 days (20%) that were more evenly distributed across the time period. This is again consistent with the historical trend for Bangkok shown in Figure 3. Only two sites were measuring ozone in Bangkok during the ASIA-AQ period. The second site in Bangkok was site 20 located 22 km south of site 13T. Site 20T only exceeded the ozone air quality standard twice, indicating large gradients in ozone across the city. A third site (59T) operated through March 13, but unfortunately ceased reporting during the ASIA-AQ study period. This site behaved similarly to site 13T but exceeded the ozone standard fewer times.

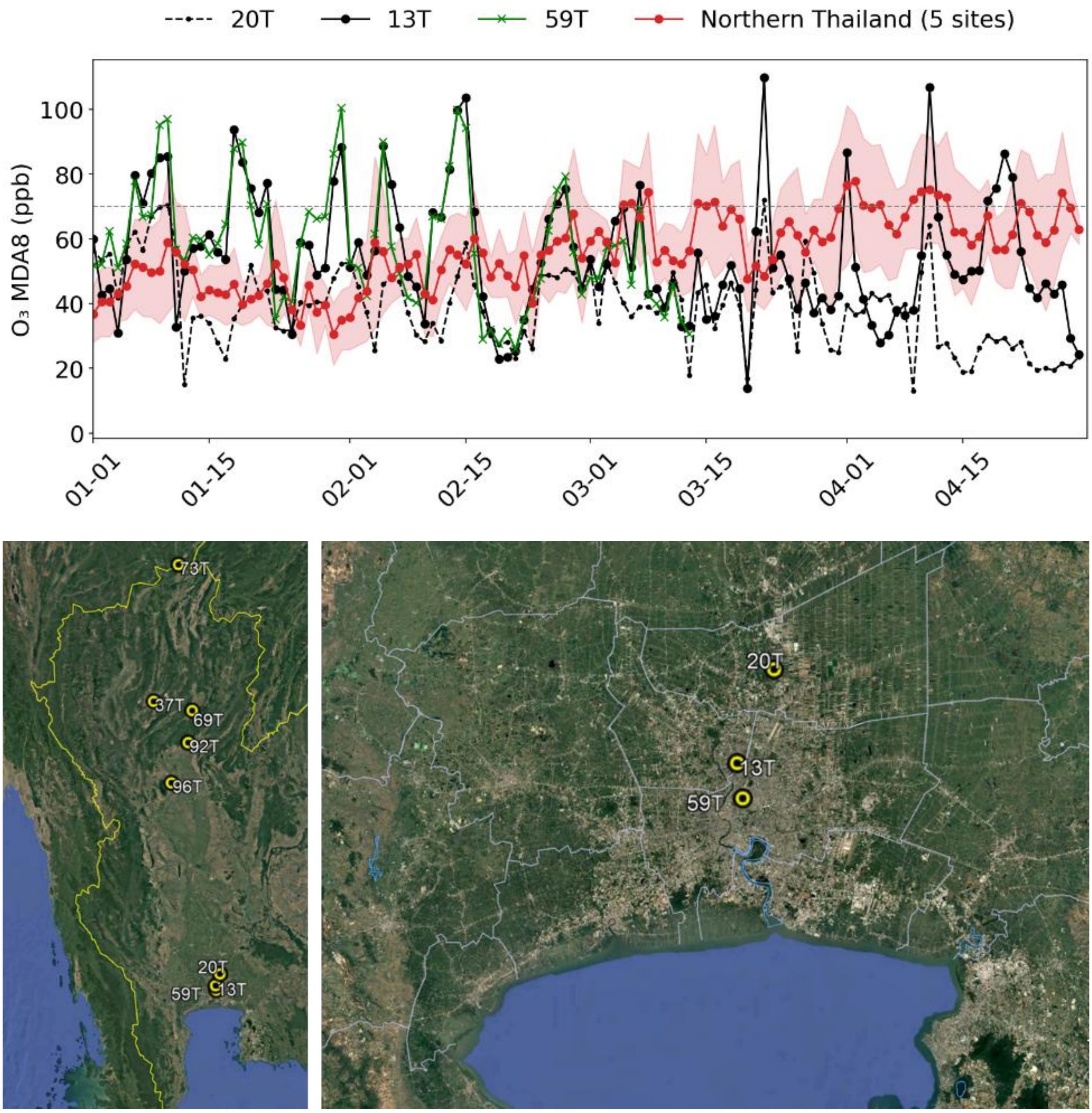


Figure 17. (Top) MDA8 ozone for three sites in Bangkok (13T, 20T, 59T) and five sites in northern Thailand (37T, 69T, 73T, 92T, 96T) for January-April 2024. The red data points indicate average values with light red shading for the standard deviation. The grey dashed line denotes the ozone standard of 70 ppb. Site locations are shown on the map on the bottom left with a zoomed-in view of Bangkok on the bottom right.

Focusing more specifically on the ASIA-AQ campaign period (Figure 18), regionally averaged ozone in northern Thailand met or exceeded the ozone standard for three days during the heaviest burning influence (15-18 March), and at least one site exceeded on eight out of eleven days. Ozone in Bangkok tended to be lower than northern Thailand, but the largest ozone episode occurred on 22 March in Bangkok. Reasons for the consistently higher ozone in northern Thailand with more extreme events in Bangkok are consistent with the historical behaviors shown in Figure 3.

ASIA-AQ research flights provide an opportunity to better understand these differences through the comprehensive measurements that were collected for ozone precursors (NOx and VOCs) and environmental factors (sunlight, humidity, temperature) affecting ozone production rates. Using the NASA Langley Photochemical Box Model, ozone production rates were calculated along the DC-8 flight path enabling an assessment of sensitivities to changes in precursors. For VOCs, an analysis was conducted by systematically removing common groupings of VOCs from the model for comparison with calculations including all VOCs. The VOC groupings included alkanes (ethane, propane, butane, etc.), alkenes (ethene, propene, butene, etc.), aromatics (benzene, toluene, xylenes, etc.), oxygenated VOCs (ethanol, methanol, acetone), and isoprene.

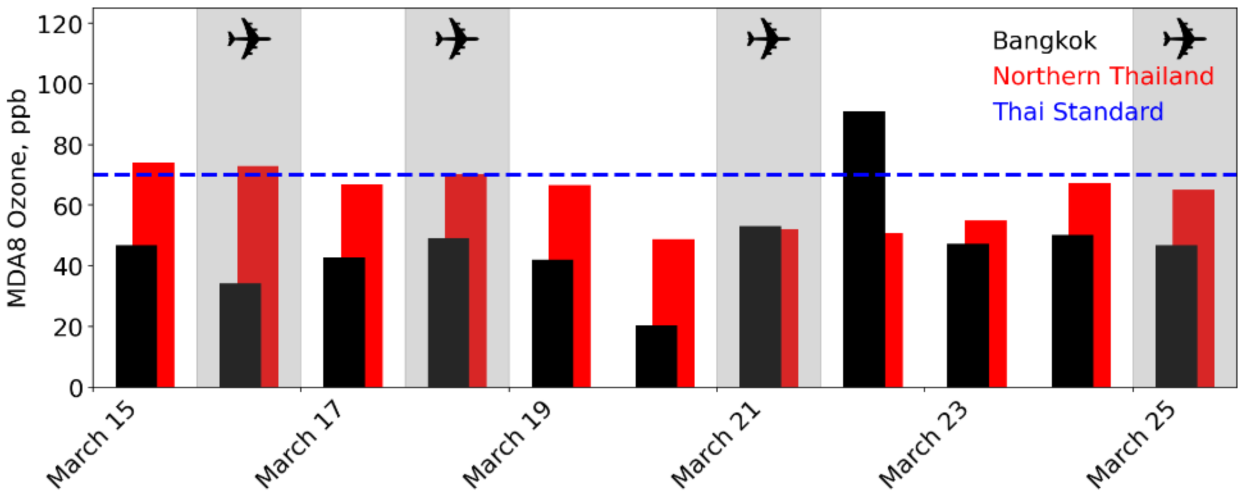


Figure 18 – Maximum daily eight-hour average ozone (MDA8) averaged across northern Thailand (sites 69T, 92T, 96T, 73T) and Bangkok (sites 13T and 20T) from 15 to 25 March 2024. The days when the NASA DC8 aircraft flew are designated with grey backgrounds. The Thai ozone standard of 70 ppb is given as a horizontal line.

Results of the sensitivity analysis for VOCs are shown in Figure 19. Bars indicate the average reduction in ozone production when each VOC grouping is removed from the model calculations. Symbols also show results for individual days. The influence of isoprene is consistently in the range of 20% across Bangkok and northern Thailand. This biogenic compound emitted by trees and vegetation is ubiquitous and not generally considered controllable due to its natural origin. When considering the other VOC groupings, it is not surprising that the relative contribution of different VOCs to ozone production differs between Bangkok and northern Thailand given strong influence from urban sources in Bangkok and burning sources farther north. In Bangkok, aromatics were the most important driver of ozone production. The aromatic contribution was also consistent across all four flight days. In northern Thailand, very similar impacts are seen for alkenes, oxygenated VOCs, and aromatics.

Recall that the aromatics in the north have a distinctly different source behavior with a larger benzene:toluene ratio compared to Bangkok due to the influence of burning emissions.

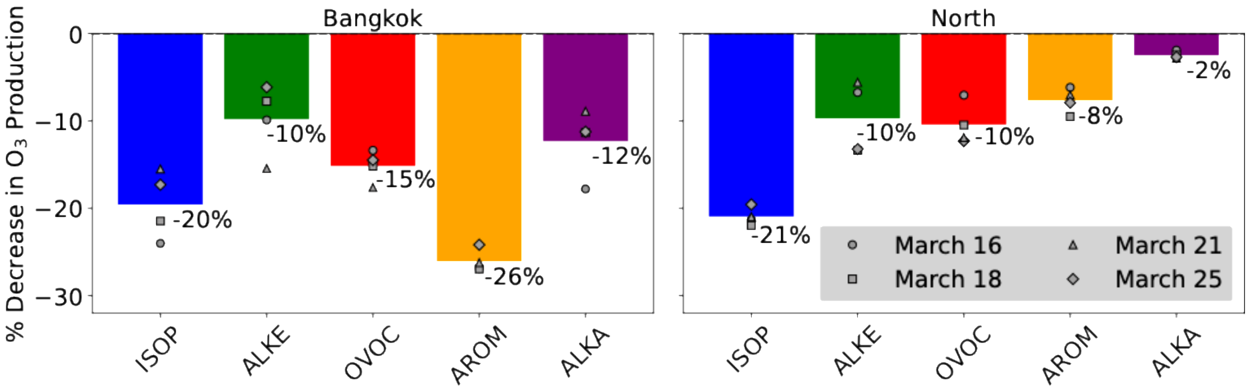


Figure 19. Sensitivity of ozone production when removing VOC groupings from model calculations for Bangkok and northern Thailand. The average decrease in ozone production across all days is annotated at the bottom of each bar. The decrease for individual flight days is designated by the symbols in the legend. ISOP = isoprene, ALKE = alkenes, OVOC = oxygenated VOCs, AROM = aromatics, ALKA = alkanes. (Figure provided by Nantaporn Noosai, Prince of Songkla University and Katherine Travis, NASA)

As with particulate pollution sources, a deeper understanding of the sources influencing ozone production will be made possible by future work based on Positive Matrix Factorization (PMF). To improve interpretation of PMF results for the full suite of VOC observations, direct sampling of sources was accomplished through coordination with Thai colleagues during the ASIA-AQ study. This included samples taken in PCD’s automotive emissions laboratory and outdoor locations enabling direct sampling of fuel stations, street cooking, incense burning, and roadside emissions. A sample of these source signatures are shown in Figure 20. Vehicle emissions show high levels of compounds including CO, ethene (diesel), and toluene (2- and 4-stroke), with 2-stroke and diesel engines emitting the most CO on average in these samples. Ambient samples collected from street food cooking and incense burning exhibit distinct VOC signatures, with ethene, propene, ethane, and benzene dominating. High levels of benzene from incense burning (up to 360 ppbv) and street food cooking (up to 1600 ppbv in one of the two samples) are of potential concern as benzene is a known carcinogen. Overall, while recognizing that other sources such as industry and solvents were not sampled, traffic emissions contribute heavily to urban VOC pollution, while cooking and incense burning add localized sources of air pollutants, particularly in dense urban environments.

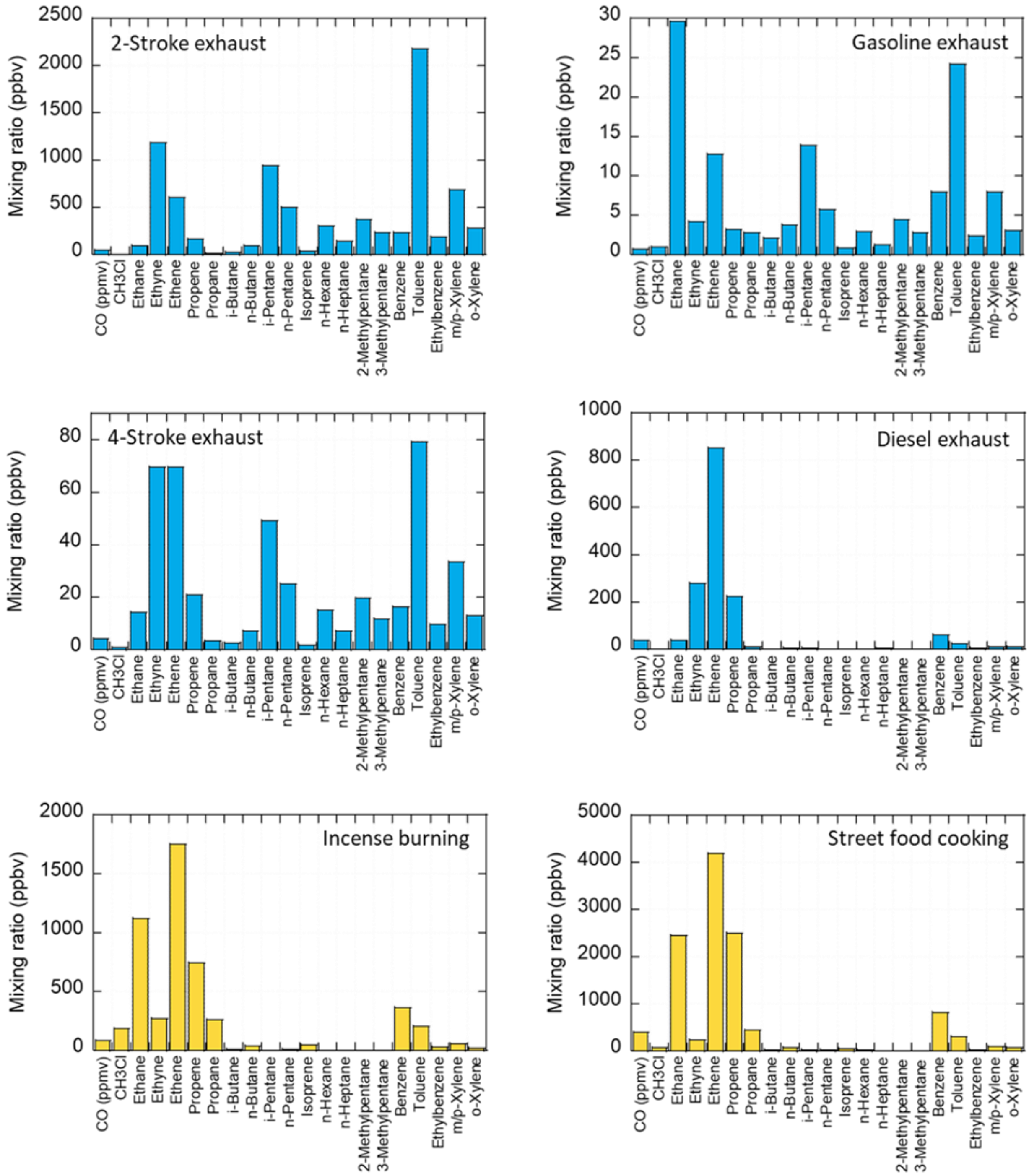


Figure 20. Preliminary VOC signatures obtained by direct sampling of sources in Thailand. (Figure provided by Isobel Simpson, University of California-Irvine, Ittipol Pawarmart, PCD, and Savitri Garivait, King Mongkut's University of Technology Thonburi)

Despite the complexity of the VOC analysis, NOx remains as the dominant driver of ozone production. This is demonstrated in Figure 21 showing the distribution of ozone production as a function of measured NO for Bangkok and northern Thailand. Typically, ozone production rates increase with increasing NO with peak production occurring at approximately 1 ppb (NO_x-limited regime). Beyond this point, ozone production becomes nonlinear as further increases in NOx begin to suppress oxidant availability and the rate of catalytic ozone production (VOC-limited regime).

Peak ozone production rates exceed 10 ppb/hr on average across Thailand and can reach as high as 20 ppb/hr in Bangkok (see shaded area in Figure 21). These rates are not always sustained, but they can explain the rapid increase of ozone observed from the morning through midday at monitoring sites on the ground. Examples of calculations with the removal of aromatics and alkenes show that VOC controls would have the effect of reducing ozone production, especially for aromatics in Bangkok. However, the impacts of VOC controls are limited to conditions of higher NO at or above the peak in ozone production. For Bangkok, about 20% of observations fall at or above peak ozone production, and for northern Thailand even less (~10%). This indicates that controlling NOx can be expected to be of nearly immediate value to the improvement of ozone pollution in Thailand.

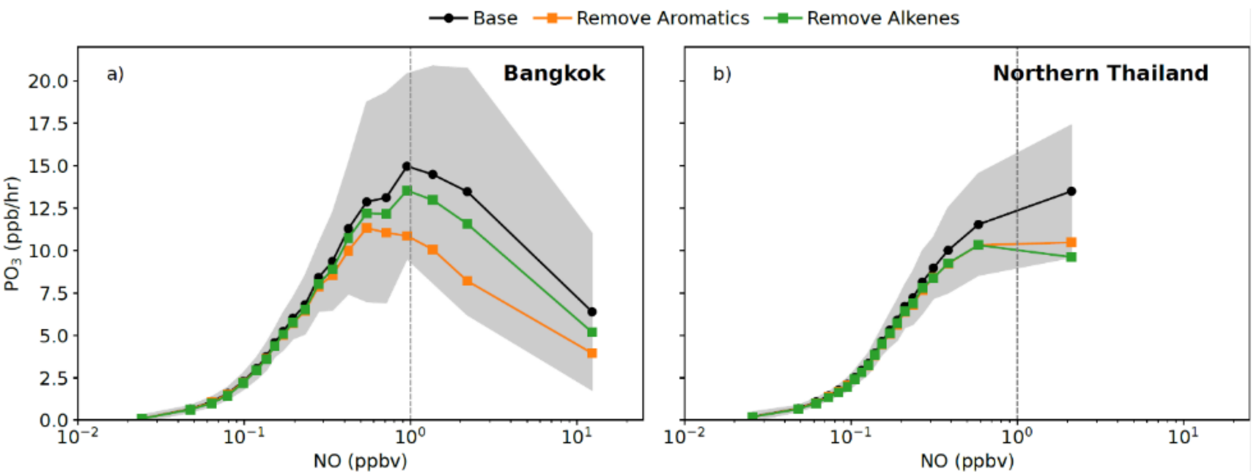


Figure 21. Distribution of ozone production vs. NO for Bangkok and northern Thailand averaged into twenty bins of equal data size. Grey shading indicates the standard deviation of PO_3 for the Base calculations. (Figure provided by Nantaporn Noosai, Prince of Songkla University and Katherine Travis, NASA)

In addressing ozone pollution, a particular concern is gathering sufficient evidence for changes in the ozone environment. As noted in Figure 17, large differences in ozone behavior are seen between monitoring sites. Further evidence for large ozone gradients in Bangkok was observed by the HSRL2 lidar onboard the NASA G-III aircraft. Figure 22 shows a lidar image of average ozone in the lowest 500 m on the afternoon of 25 March. On this day, ozone decreased by a factor of five from north to south over a distance of approximately 60 km. Such gradients cannot be characterized by current monitoring with only two to three sites in the city.

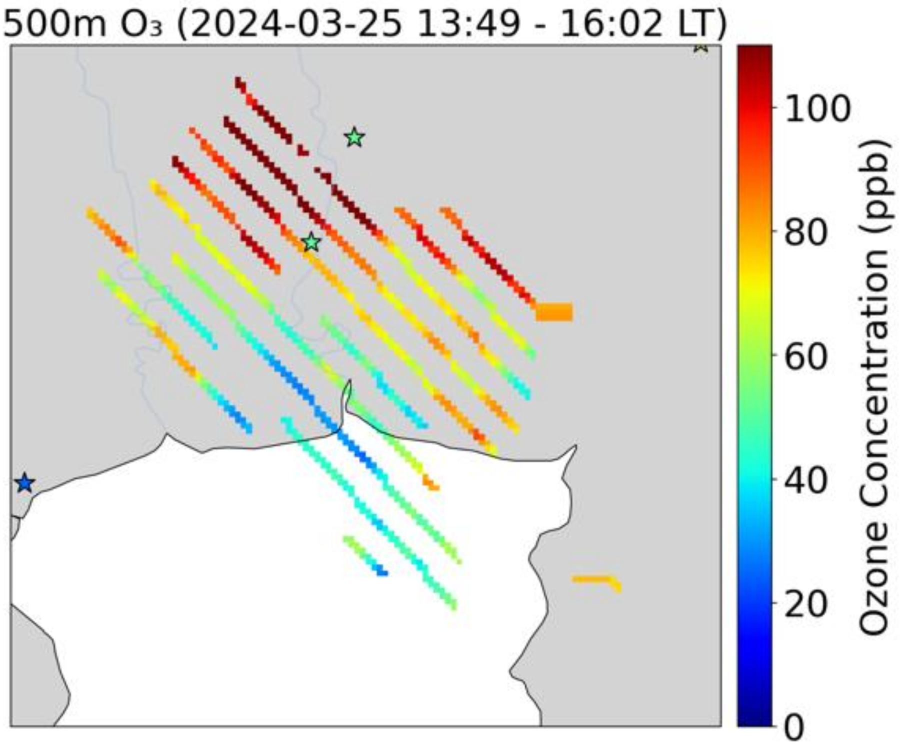


Figure 22. Lidar observations of average ozone below 500 m in Bangkok on the afternoon of 25 March 2024. Surface monitor locations and concentrations are shown by stars.

Figures 23 and 24 show how ozone monitoring changed between March 2021 and March 2024 during the ASIA-AQ study. In 2021, PCD operated 73 air quality sites, of which 67 had ozone observations. In 2024, there were 99 operating air quality sites, but only 49 had ozone observations. Furthermore, monitors were more widely distributed across northern Thailand with far less monitoring around Bangkok and Chiang Mai where dense populations and high ozone episodes are more likely. Similar to the lidar image in Figure 22, data for 2021 in Bangkok also shows a strong gradient from north to south. Restoring higher density monitoring in Bangkok and northwestern Thailand would be of great value in tracking progress in reducing ozone pollution and capturing precisely where problems persist.

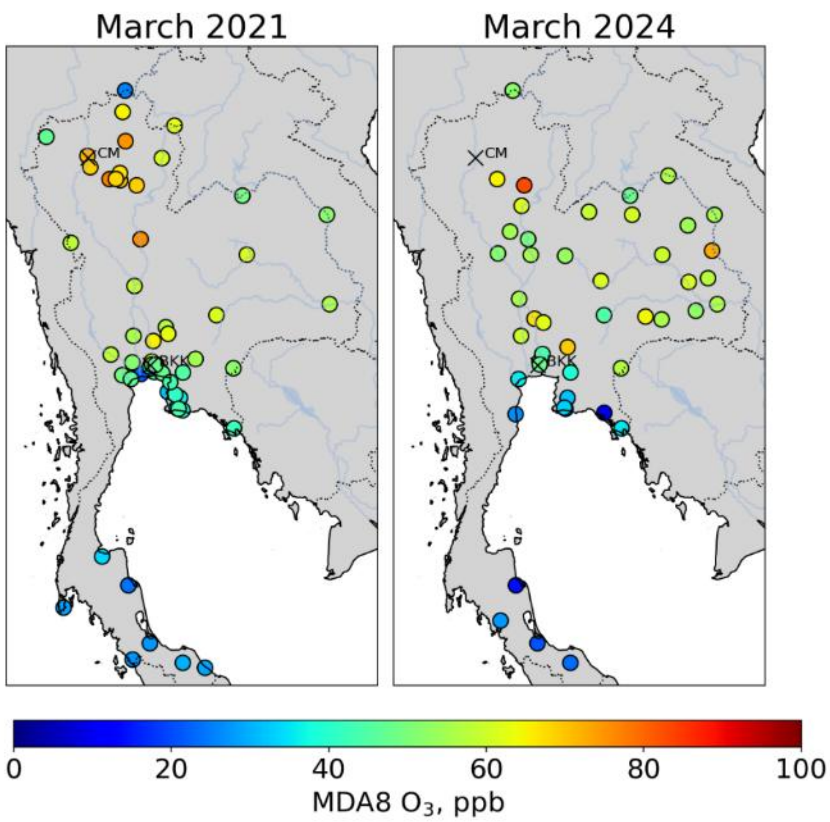


Figure *23*. Average MDA8 ozone for March 2021 and March 2024 at PCD locations across Thailand.

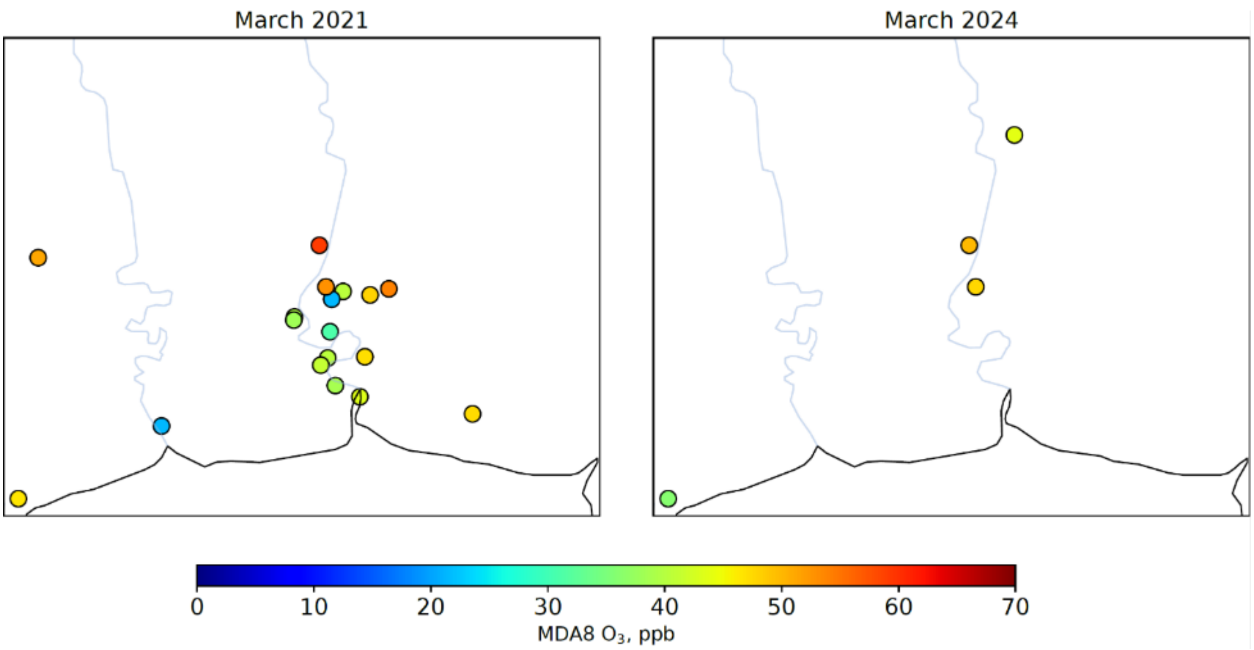


Figure 24. Average MDA8 ozone for March 2021 and March 2024 at PCD locations in Bangkok.

Question 3: What is the role of local and regional meteorology in driving air pollution patterns in Thailand?

Summary findings: Although not the cause of poor air quality, weather conditions are critical to the development of air quality episodes. Understanding the influence of regional weather across Southeast Asia as well as localized circulations such as coastal winds in Bangkok and mountain breezes in Chiang Mai help to improve the predictability of air quality episodes. The ASIA-AQ observation period provides valuable case studies for evaluating air quality models.

Air pollution in Thailand is shaped by complex atmospheric dynamics within a particular region or across multiple regions, which determine how pollutants are mixed and transported. These dynamics are influenced by weather and topographical conditions, in addition to anthropogenic, biomass burning (including forest and agricultural fires) and natural emissions. A thorough understanding of these factors is crucial for enhancing air quality management and mitigation strategies. In this chapter, we discuss key atmospheric processes and their potential linkages to observations during the two-week ASIA-AQ flight campaign in Thailand.

Relevant Atmospheric Processes

1. Synoptic weather patterns and pollution transport

Large-scale (synoptic) weather patterns significantly influence the distribution of air pollutants, transporting pollutants from upwind sources to downwind areas. ASIA-AQ occurred during the local warm and dry season (mid-February to April). Although no dominant monsoon is present during this time of year, certain regional winds exist and affect Thailand and its surrounding areas. The warm conditions, coupled with low-to-moderate humidity, also amplify fires and associated smoke emissions, in addition to typical anthropogenic emissions. Four distinct phases of meteorology were observed during the ASIA-AQ measurement period of 13-27 March 2024, as depicted in Figure 25:

1. Weak synoptic flow and moist (15 March to 19 March AM)
2. Strong northeast monsoon surge (19 March PM to 20 March)
3. Weather disturbance in the north (21 March 21 to 23 March AM)
4. Return to weak synoptic flow and dry (23 March 23 PM to 25 March)

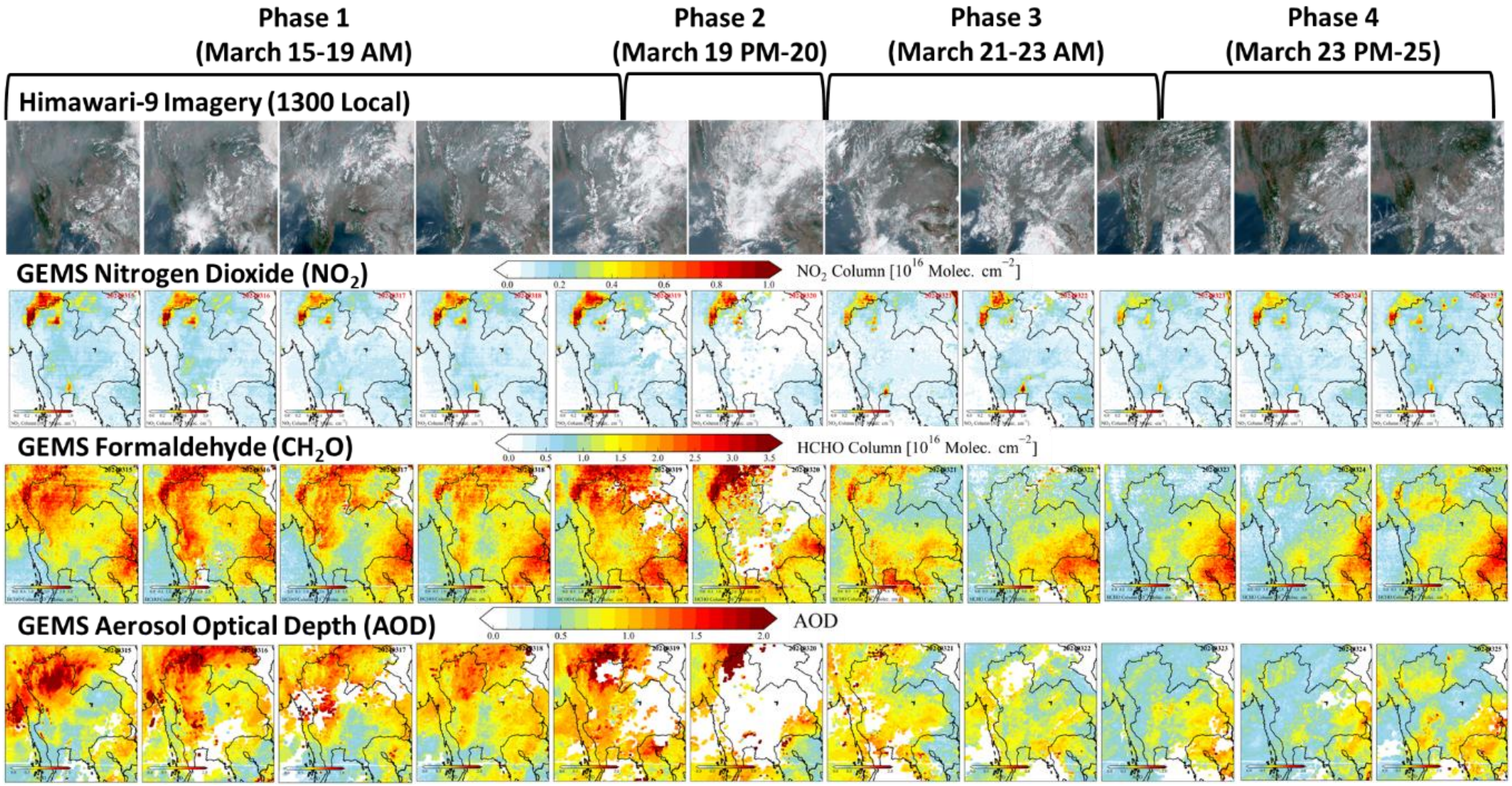


Figure 25. Timeline of satellite images during the ASIA-AQ observation period (15-25 March 2024). Images span from central Thailand (Bangkok area) to northern Thailand.

The first phase featured weak synoptic influence, creating relatively stagnant conditions. This pattern was accompanied by dryer than average conditions in northern Thailand, and moister conditions in central Thailand, which produced scattered convection in the Bangkok Metropolitan Area and conditions favorable for burning in the North. Widespread smoke across northern Thailand can be seen in the Himawari satellite imagery. Consistent with burning activity, the GEMS satellite also shows greater abundances for NO_2 and formaldehyde (CH_2O) and higher AOD over northern Thailand than the other phases. This phase was characterized by heavy $PM_{2.5}$ pollution from regional sources across upper Indochina carried by westerly winds, leading to high particulate levels over northern Thailand.

The second phase was characterized by a significant wind shift from the persistent southerly winds in central Thailand from 19 March to 20 March. This wind shift was accompanied by increased moisture, which led to widespread convection over much of Thailand and especially the Bangkok area. This increased coverage in thunderstorms can be seen as clouds in the satellite imagery. These resultant thunderstorms and rain in the Bangkok area produced cleaner conditions. The presence of widespread cloudiness is evident in the GEMS data, especially on 20 March, with clouds preventing observation across much of Thailand.

The third phase featured a change to a synoptic-dominant pattern in northern Thailand as an anomalous low pressure system swept across Southeast Asia. This weather disturbance in the north produced rain over the biomass burning areas in Myanmar. The rain, combined with stronger synoptic wind flow, helped reduce both pollution and fire emissions across much of Thailand. Again, the reduced burning activity is corroborated by the GEMS observations showing much lower amounts of NO_2, CH_2O, and AOD.

The final phase featured a return to weak synoptic influence and locally dominant weather. This weather pattern was similar to that of phase one, except for a significant lack of moisture. This lack of moisture results in the clear skies over most of Thailand that can be seen in the satellite imagery. Biomass burning and pollution emissions did not return to the levels seen in phase one as shown in the GEMS observations.

2. Planetary boundary layer and vertical mixing

Vertical mixing is a key factor in how pollutants are diluted and dispersed in the atmosphere, with the planetary boundary layer (PBL) playing a critical role in regulating pollutant concentrations near the surface. When the PBL is shallow and stable, pollutant emissions are trapped closer to the surface in a smaller volume resulting in higher pollution levels. In contrast, when the PBL deepens, pollutants are more effectively mixed and diluted. Vertical mixing is driven by two key processes: convective turbulence and wind-shear turbulence. Convective turbulence is controlled by surface heating and tends to dominate during the day. Wind-shear turbulence, generated by variations in wind speed with altitude, is often more important at nighttime. Both of these processes are influenced by the overarching synoptic weather conditions described above.

Intense aerosol pollution can affect the PBL through the scattering and absorption of solar radiation, influencing the surface energy balance and, in turn, the growth of the PBL, creating a feedback loop that further limits vertical mixing and traps pollutants near the surface. Temperature inversions can further complicate this process by acting as a lid that prevents pollutants from rising and mixing with the air above. Aerosols can also act as cloud condensation nuclei, influencing cloud formation and precipitation, further affecting PBL dynamics. Biomass burning presents an additional complication because the heat from the fire itself can provide enough energy for smoke to be injected above the PBL. The timing of burning emissions can also influence whether they remain trapped in the PBL or are ventilated into the lower troposphere. This has a major impact on transboundary transport as well as impacts on near-surface $PM_{2.5}$ exposure in regions influenced by burning emissions. The complexity of these outcomes is demonstrated in Figure 26, which shows a variety of cases encountered.

The ascents from Don Mueang airport on the afternoon of 16 and 25 March show similar conditions within the PBL. However, these two profiles show very different conditions above the PBL with a transported smoke plume on 16 March and clean conditions on 25 March. The profile from Chiang Mai airport on the afternoon of 18 March shows intense aerosol pollution fully contained within the PBL with the highest absorption compared to other cases. Conditions above the PBL are cleaner, but still quite polluted compared to Don Mueang on 25 March indicating residual aerosol pollution aloft from previous days. Two consecutive profiles from Sukothai airport on the morning and afternoon of 16 March both show an enhanced layer of aerosol pollution above the PBL indicating regional influence from fires and some indication that the plume is still slowly rising. Compared to the aerosol layer over Don Mueang on 16 March, the aerosol layer over Sukothai is more intense, likely due to closer proximity to burning further north. Finally, the profile over Phrae on the afternoon of 18 March shows strong aerosol pollution that is evenly distributed within the PBL near 1000 m and above the PBL up to 3000 m.

In each case, predicting the observed distribution is a challenge, requiring models to capture vertical mixing both within the PBL and mechanisms for pollution layers aloft above the PBL. Witnessing such a wide range of outcomes provides an excellent opportunity to assess the ability of air quality models to capture the impact of PBL dynamics on pollutant distributions. This unique dataset also provides an opportunity to analyze how absorption and scattering of solar radiation by aerosol particles in these pollution layers affects the thermodynamic structure of the atmosphere. Future studies will examine the potential impact of this aerosol radiative feedback mechanism on local and regional weather forecasts and the subsequent impact on pollution forecasts that rely on skillful weather inputs.

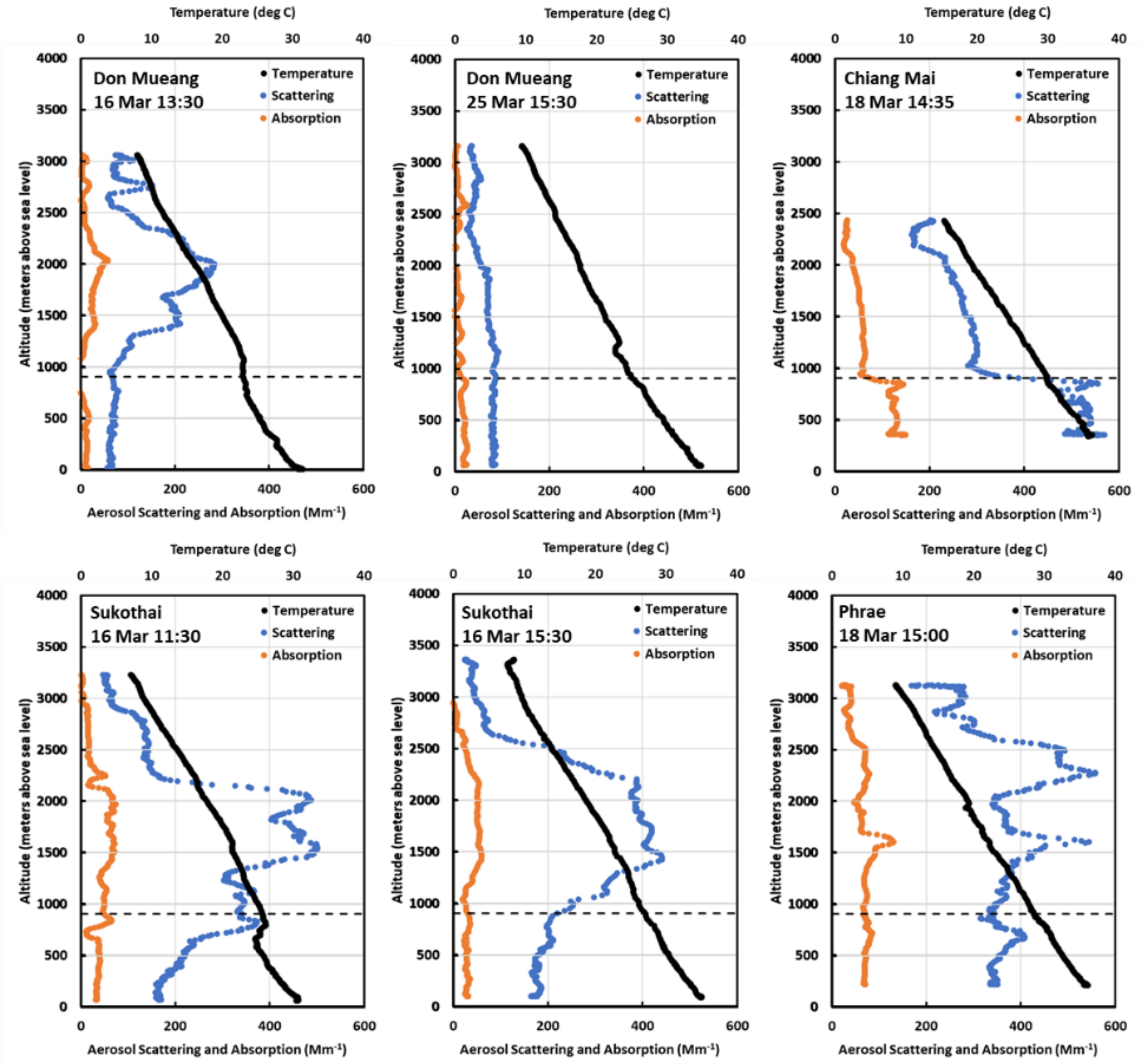


Figure 26. Selected NASA DC-8 profiles of temperature, aerosol scattering, and aerosol absorption at different locations and times across Thailand. PBL heights are indicated by a dashed line.

3. Influences of urban, coastal, and mountainous features

Bangkok and its vicinity form one of the largest urban agglomerations in Southeast Asia. The region includes numerous sources of anthropogenic pollutants and heat, with a highly urbanized landscape in the city center. Urban areas are predominantly covered by impermeable surfaces, buildings, and other man-made infrastructure, with intense energy-consuming activities that alter the surface energy balance due to reduced albedo, increased heat retention, and increased heat emissions, ultimately resulting in an urban heat island effect. Built structures also increase surface friction, slowing low-level winds and modifying wind patterns, thereby reducing pollutant dispersion and ventilation in the city. Furthermore, transport of polluted urban plumes can affect air quality in downwind areas. This transport is affected by Bangkok's proximity to the Gulf of Thailand due to the differential surface heating between land and sea.

In coastal settings, sea- and land-breeze circulations can develop during the daytime and nighttime, respectively. This occurs due to the temperature gradient between the land surface which tends to be hotter than adjacent waters during the day, inducing onshore flow. At night, this flow is expected to reverse when the land surface cools, and adjacent waters retain their warm temperature. However, this change in wind direction was not observed in Bangkok during ASIA-AQ, where onshore flow was prevalent at all times of day during much of the sampling period. The lack of a strong, diurnal land-sea breeze circulation likely resulted from persistent southerly synoptic winds overwhelming any impact from land-sea temperature contrast, which is minimal near Bangkok where sea surface temperatures are very warm.

The impact of coastal winds on Bangkok is demonstrated in Figure 27 which provides maps of NO_2 remotely sampled over Bangkok by the NASA G-III on four flight days. 24-hr wind roses are also provided for three monitoring sites spanning Bangkok from south to north (sites 5T, 13T, and 20T). On three of the four days (18, 23, and 25 March), transport of NO_2 sources to the north/northeast is observed. This is consistent with wind roses showing consistent southerly onshore winds during the entire 24-hr period. Higher wind speeds are also found closer to the coast, with winds further inland being slower and having more variable direction, though still southerly.

The exception is on 21 March when lighter northerly winds are observed pushing air towards the coast. This is corroborated by the strong pooling of NO_2 with a maximum on the coast. As noted in the discussion of synoptic weather patterns, this situation coincides with the large-scale surge in the northeast monsoon flow in Southeast Asia, which temporarily reduced the southerly wind flow near Bangkok. The condition on 21 March is exceptional as wind data for the expanded period of January-April 2024 exhibits onshore flow (135-225° wind direction) for just over 75% of the time (regardless of time of day) and has a southerly component (90-270° wind direction) over 80% of the time at site 5T closest to the coast.

The change in meteorology affecting Bangkok during the third phase is also visible in Figure 25. The strongest NO_2 signal for Bangkok in the GEMS data is observed on 21-22 March due to the buildup of NO_2 as the light winds push emissions closer to the coast and inhibit dispersion.

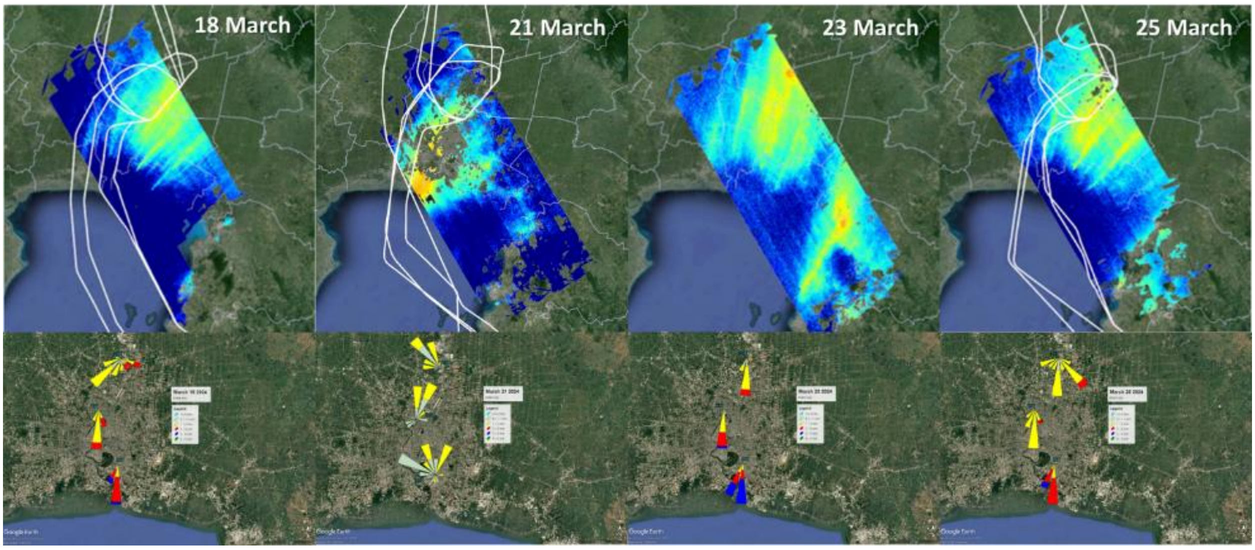


Figure 27. (Top) NASA G-III observations of tropospheric NO_2 column measurements over Bangkok four different flight days. (Bottom) 24-hr wind roses colored by wind speed for three monitoring sites in Bangkok from south to north (5T, 13T, 20T) across the city.

In northern Thailand, air pollution is modulated by the region's mountain-valley topography. The mountains act as natural barriers, restricting ventilation and trapping pollutants within valley cities. Differential heating on mountain slopes and valley floors (both in intensity and timing) drives local mountain-valley circulations, which diurnally regulate low-level inversion layers. It is suspected that nighttime mountain winds (i.e., cold-air drainage) may enhance the downslope transport of smoke from forest fires, carrying pollutants from higher elevations into valley areas, as illustrated in Figure 28. These localized effects caused by complex terrain are likely to be most impactful during periods of weak synoptic wind flow, such as during the first phase of sampling illustrated in Figure 25.

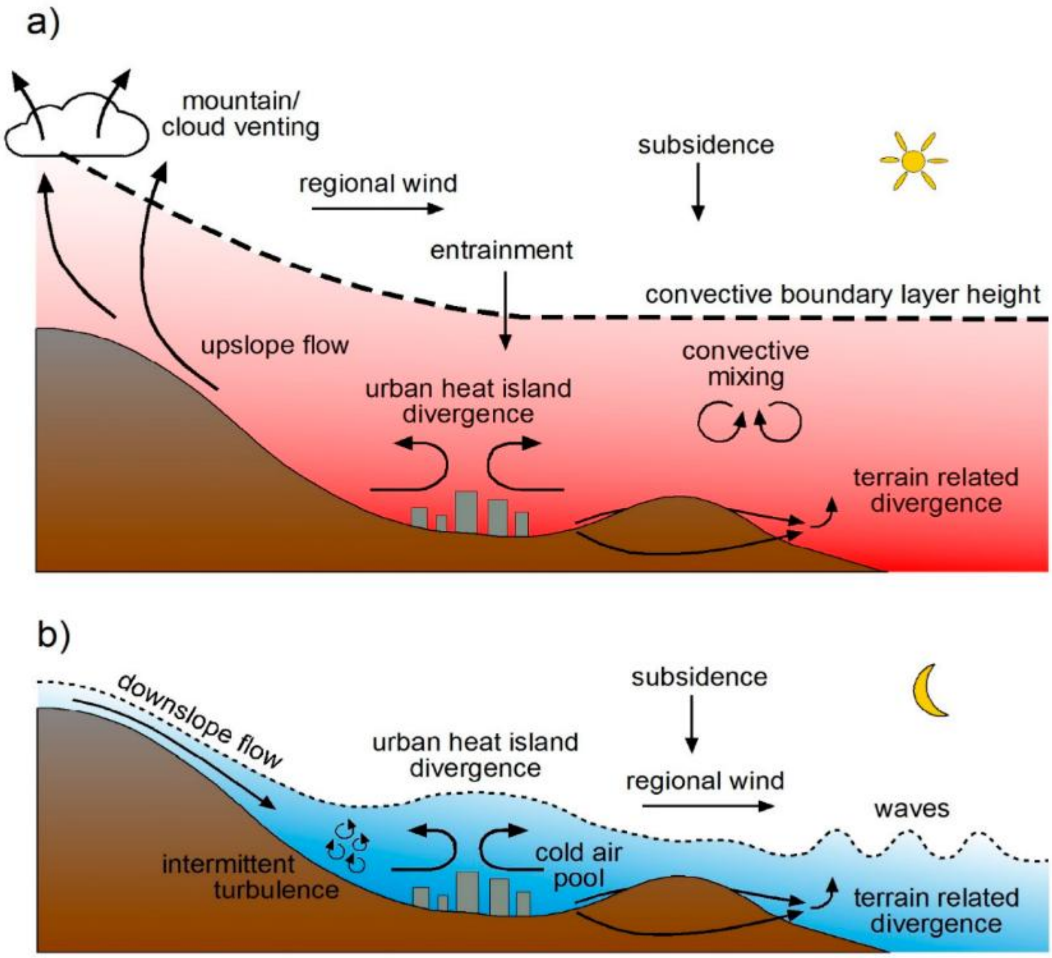


Figure 28. Schematic of air pollutant dispersion over complex terrain under unstable (a) and stable (b) boundary layer conditions. Mountains limit ventilation, trapping pollutants in valleys, while differential heating drives mountain-valley circulations that regulate inversion layers. At night, cold-air drainage enhances downslope smoke transport, worsening valley pollution. Source: De Wekker et al. (2018), *Atmosphere*, 9(10), 371, doi.org/10.3390/atmos9100371.

Even when the patterns regulating mountain-valley circulations are consistent, predicting their intensity is a critical aspect of determining air quality outcomes. Figure 29 shows statistics for ozone and winds over two consecutive 5-day periods (9-13 March and 14-18 March). Based on the hourly averages and standard deviations, the two periods are characterized by very different daily ozone cycles. Both days exhibit very similar increases in ozone each morning, demonstrating the potential for local emissions to produce ozone pollution each day. During 9-13 March, ozone decreases after 11 am, falling below the air quality standard for the day. For 14-18 March, ozone continues to increase into the mid-afternoon, and the 8-hour daily average for ozone exceeds the Thai air quality standard (70 ppb) on each day. The reason for this shift in ozone behavior appears related to the wind speed (see Figure 29), which increases throughout the morning and into the afternoon during 9-13 March. While still not a strong wind, this flow is enough to dilute and transport ozone pollution away from the measurement site. By contrast the weak and invariable winds on 14-18 March allow the daily buildup of ozone pollution to occur. Looking at wind direction, the patterns are very similar with only subtle differences. In each case, winds from the northeast each morning gradually turn to the southeast each day. This turning can be a little faster for 9-13 March, but the light winds on 14-18 March show larger variability. By early evening, the winds come from the west, consistent with expectations of downslope flow from the mountains, but this is not sustained as winds return overnight to the northeast. The consistency in these flows throughout the entire 9-18 March period do indicate important terrain effects that also persist when assessing longer-term conditions present from January to April 2024.

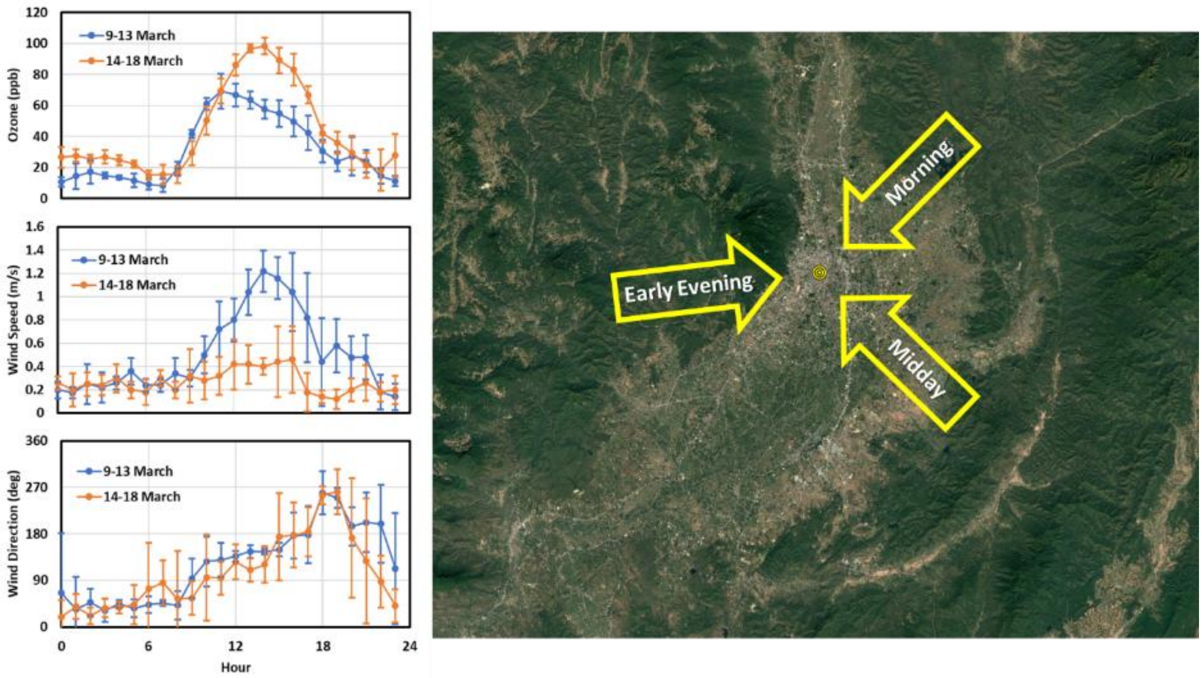


Figure 29. Comparison of daily ozone and wind behavior in Chiang Mai for two consecutive periods (9-13 March and 14-18 March). Plots show hourly average and standard deviations for each 5-day period. Map of Chiang Mai shows the measurement site location and predominant wind direction at different times of day.

ASIA-AQ Summary of Early Findings and Recommendations

The following statements represent ASIA-AQ findings for Thailand that can be stated with confidence. Deeper analysis is expected to provide additional valuable insight as scientific peer-reviewed publications are completed over the next few years. At that time a Final Science Synthesis Report will be provided.

1) Strategies to address burning remain the key to reducing peak pollution for $PM_{2.5}$.

The evidence for burning as the dominant influence during peak $PM_{2.5}$ episodes in northern Thailand is overwhelming. Evidence comes from many corroborating sources of information, including a repetitive annual cycle of high $PM_{2.5}$ coincident with satellite fire counts (Figures 1 and 2), greater organic aerosol in measurements when $PM_{2.5}$ is increased in northern Thailand (Figure 10), presence of increased acetonitrile (a key biomass burning tracer) corresponding with high $PM_{2.5}$ in northern Thailand (Figure 11) and much higher acetonitrile across Thailand compared to other ASIA-AQ countries (Figure 12), increased benzene along with higher benzene to toluene ratios in northern Thailand (Figures 13 and 14), and aerosol filter analysis from Chiang Mai showing high $PM_{2.5}$ associated with burning of plant matter indicated by large modern carbon fractions, high potassium ion concentrations, and low carbon-13 isotope values (Figure 15). Burning practices and their impacts are longstanding and difficult to change, but any success in reducing burning will have immediate benefits.

2) Analysis of burning needs to be extended to neighboring countries. This is critical to understanding what is under Thailand's control and what requires regional negotiation.

GISTDA produces high quality assessments of burning in Thailand. This includes monthly information on area burned and hot spots (Table 1) that provides great detail on what is burning (forest and specific crop types.) For neighboring countries, only hot spot data is available, but hot spots for Myanmar and Laos often outnumber those for Thailand (Figure 2). Evidence for heavy burning along the northern Thailand-Myanmar border can also be seen in the NO_2 distribution from the GEMS satellite (Figure 25). This demonstrates that a significant portion of the smoke from burning is not directly under the control of Thailand. Extending GISTDA's high quality burning assessments to include neighboring countries is an indispensable piece of information needed to quantify transboundary impacts and work across borders to assess the regional impacts that are affecting everyone.

3) Addressing NOx emissions remains key to reducing ozone, with the expectation that results would come quickly. Addressing VOCs will also help, especially in regions of high NOx emissions. These controls will not only improve ozone but also contribute to $PM_{2.5}$ reductions.

DC-8 in situ observations enable high-resolution modeling of ozone production and sensitivities to precursors. Though not surprising that the largest amounts of NOx were encountered in Bangkok, it is encouraging that only about 15% of NOx observations exceeded the peak of ozone production efficiency (Figure 21). In the north, only 5% were above the peak. Unlike other Asian megacities (e.g., Seoul) where there is a penalty for initial

NOx reductions, strategies to reduce NOx in Thailand can be expected to be of immediate value for reducing ozone. VOC sensitivity (Figure 19) also shows benefits from reducing aromatics (dominated by toluene) in Bangkok, while several categories (alkenes, aromatics, and OVOCs) all show similar sensitivity. While reductions in burning should help reduce both NOx and VOCs in northern Thailand, strategies for reducing NOx and aromatics in Bangkok have less overlap. A future update to ozone production sensitivity based on specific source signatures (Figure 20) will provide more insight. Finally, the overlap in precursors for ozone and $PM_{2.5}$ show that emission reductions of any type should provide some benefit for both pollutants.

4) Monitoring of ozone needs improvement. Without additional monitoring, it will be difficult to document improvements and adequately represent impacts.

Ozone monitoring density has shifted dramatically in Thailand over the past few years. This is most obvious in Bangkok, but Chiang Mai is also lacking reliable ozone monitoring (Figures 23 and 24). Compared to $PM_{2.5}$, there also appear to be stronger gradients in ozone across the Bangkok Metropolitan Area (Figure 22). Increased monitoring of ozone will be essential for both demonstrating quantifiable changes in ozone in response to emission reductions as well as improved forecasting of the strong ozone gradients that exist across Bangkok.

5) Increased integration of satellite observations will provide critical evidence on the drivers of poor air quality as well as improved conditions and policy impacts.

GISTDA already makes extensive use of satellite data for hot spots and burned area. For trace gases, examples of useful information have been shown for both the GEMS satellite (Figure 25) and the G-III (Figure 27). While validation is still underway for GEMS using ASIA-AQ observations, the patterns in NO_2, CH_2O, and AOD add to the weight of evidence that burning is affecting all three constituents. Their changes also follow meteorological shifts that help to see the evolution and distribution of air pollution at a regional level. Conditions over Bangkok for NO_2 also corroborate meteorological conditions that lead to high ozone episodes. In combination with modeling and surface observations, satellite remote sensing provides broad context valuable for extending information to unmonitored areas.

6) In addition to pollution episodes, attention to annual average conditions is needed.

ASIA-AQ sampling purposefully targeted the annual peak of pollution in Thailand. This was important to demonstrate the dominance of fire activity in northern Thailand. Emissions in Bangkok, however, are present year-round, and it is important to not just consider exposure to pollution events. Long-term exposure is potentially even more important. With good forecasting and alerts, people can take measures to limit their exposure during pollution episodes, but daily pollution cannot be easily avoided. This chronic exposure can have prolonged effects that lead to persistent health problems and shortened life expectancy. Shown in Figure 30 are annual data for $PM_{2.5}$ for monitors in Bangkok. From the months of November to April, sites consistently exceed the annual average goal of 15 $\mu g/m^3$ with monthly average values at sites peaking in January or February (not during primary burning season) with an overall average for Bangkok of 40 μg/m^3 for January-February and a 6-month average of 29 μg/m^3. This more than offsets the cleaner conditions for May-October (6-month average of 12 μg/m^3) for an annual average of 20.6 μg/m^3. The annual average across these same stations for 2023 and 2024 reveal similar, but slightly higher annual averages of 23.5 and 21.2 μg/m^3, respectively. This emphasizes that reducing urban and industrial emissions will be critical to meeting annual air quality goals.

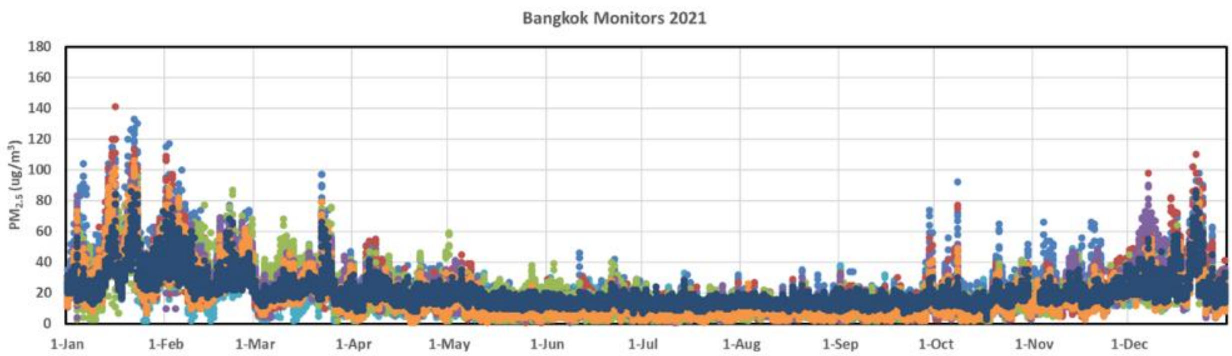


Figure 30. Hourly $PM_{2.5}$ for Bangkok air quality monitoring sites in 2021.

Appendix

A History of Environmental Law and Monitoring Programs in Thailand

The government of Thailand has long recognized the problem of air pollution in particular the frequent $PM_{2.5}$ episodes mainly in the Bangkok Metropolitan Region (BMR) and 17 northern provinces, and the country has already implemented a range of air quality and emission standards largely comparable with those of other major countries. The legal basis of environmental quality standards in the country is the Enhancement and Conservation of National Environmental Quality Act established in 1992. The law is enforced by the Pollution Control Department (PCD), the primary national agency of environmental regulation under the Ministry of Natural Resources and Environment. The national ambient air quality standards (NAAQS), which were based on the law and first issued in 1995, are reviewed and modified by the National Environment Board. The Thai NAAQS have been set for major air pollutants. Originally, the standards were established for carbon monoxide, nitrogen dioxide, sulfur dioxide, lead, PM_{10} (particulate matter of 10 micrometers or less in diameter) and TSP (total suspended particles). Later the regulation has been extended to $PM_{2.5}$ and it has been effectively promulgated since March 2010. The NAAQS for volatile organic compounds (VOCs) have also been made effective since 2007. The latest update to the $PM_{2.5}$ standard was in June 2023 as a daily average of 37.5 microgram/m^3. The monitoring of ambient air quality in Thailand has been conducted since 1983 by the PCD. At present, the ambient air quality monitoring network consists of 96 continuous fixed ambient air quality monitoring stations that are spread across 65 provinces. The BMR has in total 30 continuous automatic monitoring stations operated by PCD (as of 2024). There are nine mobile stations operated by PCD. These stations are used to monitor air quality close to sources and to respond to area-specific pollution complaints and research purposes. The stations record hourly data of SO_2, NO_2, CO, O_3, PM_{10}, and meteorology parameters. The hourly mass of $PM_{2.5}$ is recorded using the online method, e.g., using the Beta attenuation, but there is no compositional data produced by the PCD network. In addition to the PCD monitors, several international collaboration projects have reported $PM_{2.5}$ mass and composition for source apportionment studies.

Thailand has implemented emission standards for mobile and point sources, adopted Euro 5 standards for vehicles, promoted alternative fuels, and regulated emissions from modified cars and industry

Thailand also has a set of emission standards for mobile and point sources. Control of mobile source emissions is managed by the PCD. The regulatory body has adopted the Euro emission standards for automobiles since 1998. New light-duty vehicles in Thailand have been obligated to conform with the Euro 5 emissions standards since January 1, 2024. These regulations on mobile sources are complemented with public campaigns for the use of public transportation and of transportation based not on petroleum, but on alternative fuels, such as natural gas and electricity. Meanwhile, PCD also issued a standard in 2018 on the emissions of small passenger cars that have been modified to use natural gas, which have become a large contributor to air pollution. Regulation of emissions from point sources are managed by different national ministries depending on the source type, i.e., the Ministry of Industry oversees the emissions from industry and refineries, while the Ministry of Natural Resources and Environment regulates emissions from power plants.

Thailand combats air pollution with VOC regulations, biomass burning controls, and targets for zero crop residue burning by 2030, alongside seasonal bans and emergency measures for severe haze.

The government has recently introduced regulation for VOCs, for example, as a mandate for the installment of vapor collectors for oil distribution depots, oil road tankers, and service stations which also help to reduce the precursors of secondary organic aerosol (a component of $PM_{2.5}$) in the country. In addition, a major contributor to air pollution in Thailand is the biomass burning including forest fires and open burning of crop residues, both of them are associated with human activities. For air pollution from biomass burning, the Thai government has made the National Master Plan for Open Burning Control and the National Fire and Haze Control Plan of Action, which correspond to the regional framework, the ASEAN Agreement on Trans-boundary Haze Pollution that was signed in 2002. The master plans specify control measures for the burning of forest and agricultural residues. The plan has a target of burning no more than 48,000 ha/year of forest area by 2030 and zero burning for crop residues throughout the country. For example, in 2017, the Thai government imposed the policy to mitigate the haze problem by banning burning in Northern Thailand during the period from 20 February to 17 April that reduced the number of hotspots and PM_{10} concentrations measured in March in the Chiangrai province. Additionally, in cases of severe haze and smoke incidents, the provincial governor can issue a ban on open burning under the framework of the Public Disaster Prevention and Mitigation Act. As the most recent development, Bangkok experienced serious episodes of $PM_{2.5}$ air pollution in January 2019.

Addressing $PM_{2.5}$ pollution in the Bangkok Metropolitan Region requires a holistic approach integrating air quality regulation with energy, urban, and agricultural policies, as well as behavioral incentives and systemic economic transformations, to overcome challenges posed by economic growth and tropical climatic conditions that exacerbate pollution.

The $PM_{2.5}$ problem in BMR is a challenging issue because, on one hand, the country expects rapid economic growth in the next decades that will likely raise the air pollutant emissions, and on the other hand, its stringency and completeness of air quality regulatory system are already largely comparable with international standards. Indeed, the PM air pollution problem has not been fully resolved even in higher income countries with very tight regulation. Thailand may be disadvantaged relative to these high-income temperate countries because of its tropical climatic conditions with relatively large potential for secondary formation of PM. This means that different approaches, which could be outside the conventional realm of air quality regulation, are also needed to tackle the air pollution problem in BMR. In particular, policies for air pollution control should be more integrated with other types of national policies, such as energy, urban and agricultural policies. Effective pollution control would require a holistic approach combining a range of measures, including those affecting people's incentives on their behavior and those involving a transformation of an economic system.

In Thailand, concerns about air pollution remain a pressing issue, driven by the high levels of fine particle pollution associated with haze observed across the country. To address this, the Thai government is currently moving closer to the implementation of a Clean Air Act (CAA), but Thailand has a strong history of environmental law and monitoring programs that are detailed in the Appendix to this report. The Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) provides an opportunity for valuable feedback on current conditions in Thailand and detailed observations to identify the causes of unhealthy air quality conditions.

ASIA-AQ assembled a large team of experts to focus on air quality in Thailand under the leadership of the Geo-Informatics and Space Technology Development Agency (GISTDA) of Thailand in collaboration with the National Aeronautics and Space Administration (NASA) of the United States and the National Institute of Environmental Research (NIER) of South Korea. The study connected international researchers with local experts from GISTDA and the academic community in Thailand as well as Thailand's Pollution Control Department (PCD) and the National Astronomical Research Institute of Thailand (NARIT).

The overarching goal of the study was to improve understanding of the factors contributing to poor air quality in Thailand. To accomplish this, NASA's DC-8 and G-III aircraft collected detailed measurements during research flights in late March of 2024. A research team from Korea University also established a ground-based research site in Chiang Mai during the study period. Observations were guided by model forecasts of meteorology and air quality, and comparison with these models serves as an important evaluation of air pollutant emissions and understanding of air quality chemistry and transport.

The detailed report that follows provides a set of early high-level findings that are intended to be useful for policy makers to consider in the development of ongoing air quality mitigation strategies and the identification of specific emission sources that could be targeted for reduction.

The ASIA-AQ study collected observations across Asia. In addition to Thailand, flights were conducted over the Philippines, South Korea, and Taiwan. Flights in each location provided unprecedented comprehensive measurements of pollutants for both gaseous and fine particle pollution with extensive spatial and vertical sampling coverage. It is important to recognize that the brief ASIA-AQ measurement period is insufficient to address all of the air quality issues confronting Thailand. This introduction is provided to summarize both the value and limitations of the ASIA-AQ observations.

Collaborating Partners

This work was made possible through close collaboration with the Thailand Working Team, including:

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