# Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ)

*********A draft concept open for comment (last revised on 2 Aug 2021)*********

## Abstract

The Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) is an international cooperative field study designed to address local air quality challenges. Specifically, ASIA-AQ will contribute to improving the integration of satellite observations with existing air quality ground monitoring and modeling efforts across Asia. Satellite air quality observations are evolving with new capabilities from South Korea's Geostationary Environment Monitoring Spectrometer (GEMS). Traditional satellite measurements from low earth orbit (LEO) are only available once per day. GEMS measures hourly to provide a new view of air quality conditions from space that both complements and depends upon ground-based monitoring efforts of countries in its field of view. NASA is proposing to contribute two research aircraft to the study with the potential to conduct flights in early 2024 from 3-5 locations in Asia.

Short-term airborne measurements provide a unique, multidimensional view of pollution that is comprehensive in chemical detail and vertically resolved to provide information on the distribution of pollutants throughout the lower atmosphere. This perspective is valuable for informing how satellite observations connect to surface measurements and for assessing air quality models used to forecast and diagnose the conditions leading to poor air quality. Through these connections, ASIA-AQ can better characterize local emissions, aid in source identification and apportionment, enable assessment of processes leading to secondary production of ozone and fine particle pollution, and lead to better air quality modeling and interpretation of ground-based and satellite observations.

ASIA-AQ flights would be conducted in full partnership with local scientists and environmental agencies responsible for air quality monitoring and assessment. These partners would contribute to the design of the flight sampling strategies, participate in the execution of the study, and be involved in the analysis of observations collected. NASA is committed to open sharing of flight data during all phases of the study (planning, execution, and analysis) as well as capacity building opportunities for visiting scientists and students.

This white paper discusses the specific science goals and benefits to participating countries. Science and logistics plans tailored to each country and their specific air quality needs have been developed in collaboration with local scientists for the consideration of potential participating countries.

## 1. Rationale

The composition of the atmosphere is one of the most rapidly changing components of the Earth system. As such, it often provides the first clues to changes in human activity and ecosystem responses that can have both immediate and long-term impacts. Many of these impacts can be categorized into short-term issues related to Air Quality and long-term effects of Climate Change. Air Quality is largely driven by local factors, but it is not immune to large-scale impacts related to transboundary pollution transport between neighboring countries and the collective impact of human activity on changes in hemispheric and global background concentrations of key pollutants. Climate Change relates to global-scale trends in long-lived greenhouse gases, but the driving emissions are highly variable in time and space, requiring attention at local-to-regional scales. Both involve outcomes that depend on the intersection of anthropogenic and natural emissions.

Along with the availability of the first satellite observations for atmospheric chemical constituents came efforts to diagnose emissions. Over the last two decades, increasingly sophisticated top-down emission assessment methods based on satellite observations have been developed to compare with traditional bottom-up emissions assessments. Such bottom-up emissions are more detailed, but they rely on assumptions in order to scale up each emissions sector using statistics on activity levels and average emission factors for specific processes. Observation-based, top-down efforts have typically focused on individual species (e.g., CO, $NO_2$, $SO_2$, $NH_3$, $CH_4$, $CO_2$) and have provided insight on long-term emission trends. With the introduction of geostationary satellite observations, additional insight into diurnal and seasonal variability in emissions is expected. Deducing these finer-scale emissions patterns and the resulting atmospheric pollutant distributions will lead to a better understanding of local and regional air quality issues, improved modeling of the relationship between primary emissions and secondary pollutants (e.g., ozone and particulate matter), and more informed decision making to support pollution mitigation strategies.

The Geostationary Environment Monitoring Spectrometer (GEMS) satellite instrument is the first of its kind to provide geostationary observations of air quality for both trace gases and aerosols. It is situated over Korea, with a field of view that extends from Japan in the east to India in the west and from southern Mongolia in the north to the southern tip of Sumatra. In all, GEMS can observe all or part of twenty-two countries (https://nesc.nier.go.kr/product/view). The GEMS domain is diverse in emissions and air quality conditions that are related to geography, meteorology, economics, and policy. Understanding this diversity would benefit from sampling with research aircraft within the GEMS domain, particularly over and in the vicinity of highly populated megacities and metropolitan areas. This would enhance the interpretation and use of hourly geostationary satellite observations for estimating and tracking emissions and would improve our understanding of how emissions ultimately impact air quality conditions and climate change in greater detail.

Atmospheric composition has historically been a challenging problem for satellite observations. Detection of trace gases relies on their interaction with specific wavelengths of light passing through the atmosphere and returning to the satellite. Thus, satellites are sensitive to trace gas distributions throughout the entire atmospheric column. Surface air quality in particular requires careful consideration of vertical distributions for constituents throughout the depth of the atmosphere and the impact on satellite retrievals. Some species (e.g., ozone and $NO_2$) have large stratospheric contributions that must be considered, and the sensitivity of retrievals to near-surface trace gases can be reduced in environments with heavy particle pollution that can reduce the amount of light reaching back to space from the lowest levels of the atmosphere. For estimating particulate matter concentrations, additional information is needed on ambient conditions (humidity) and aerosol composition which affect how aerosols scatter and absorb light.

To aid in the validation and interpretation of GEMS observations, a network of ground-based remote sensing instruments (Pandora spectrometers) is being established across the GEMS domain. Pandora spectrometers can provide continuous information on the atmospheric column trace gas amounts of nitrogen dioxide ($NO_2$), formaldehyde ($CH_2O$), sulfur dioxide ($SO_2$), and ozone ($O_3$). When operated at the surface in a direct-sun observing mode, Pandora retrievals have much lower uncertainties than those from satellites as they are not subject to the complex assumptions required in satellite retrievals about the behavior of scattered light transmitted through the atmosphere and back to space. Instead, the Pandora instrument sees the direct solar transmission of light through the atmosphere and provides an excellent point of validation for the satellite observation. The Pandora Asia Network (PAN) is funded by the Korean International Cooperation Agency (KOICA) and implemented by Korea's National Institute of Environmental Research (NIER). Plans include twenty instruments in thirteen countries by 2022, with an emphasis on large cities and metropolitan areas. The Pandora instruments will provide valuable information on trace gas column densities for direct comparison with GEMS. To be most effective, these instruments will need to be located to take optimal advantage of local ground monitoring of air quality and other sources of contextual information (e.g., lidars, ceilometers, soundings, AERONET sunphotometers, etc.) that may be available in some locations. In particular, co-location of AERONET with Pandora instruments provides aerosol information that is often critical in interpreting the remote sensing of trace gases. For example, heavy aerosol loadings of absorbing particles over some of these locations reduces the solar flux significantly in the UV. Additionally, specific properties of aerosols over urban areas need to be accounted for (e.g., spectral AOD, size distributions, spectral single scattering albedo) to enable more accurate retrievals of trace gases from GEMS in the presence of these aerosol layers.

The establishment of PAN is also related to the formation of the Pan Asia Partnership for Geospatial Air Pollution Information (PAPGAPI), which is organized under the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP). PAPGAPI could play an important role in building the international collaborations needed for ASIA-AQ to be successful. PAPGAPI aims to:

1) Fill the data and information gap in the nationwide monitoring of air quality;
2) Integrate satellite-derived data with reliable ground monitoring information for better understanding of air pollution, and improve model simulations of air quality, including its forecasting and warning service;
3) Enhance national and regional capacity to undertake the comprehensive analysis of data derived from space and ground networks; and
4) Promote policy dialogue and enhance the capacity for monitoring and management of air pollution.

Alongside PAPGAPI and PAN, there are several additional international efforts relevant to building air quality collaborations across Asian countries. The International Global Atmospheric Chemistry Project (IGAC) sponsors the Monsoon Asia and Oceania Networking Group (MANGO) that brings together atmospheric chemists from relevant countries across the GEMS domain. IGAC also sponsors several activities relevant to the science needed to support PAPGAPI goals. These include Atmospheric Composition and the Asian Monsoon (ACAM), Global Emissions InitiAtive (GEIA), Analysis of eMIssions usinG Observations (AMIGO), and Modeling, Analysis and Prediction of Air Quality (MAP-AQ). Finally, the World Meteorological Organization (WMO) Global Air Quality Forecasting and Information System (GAFIS) will bring additional attention to PAPGAPI priorities.

Aircraft observations provide invaluable context to the satellite and ground-based perspectives that are used more routinely to inform air quality models for both forecasting and source attribution. Satellites and ground monitors focus on only a small subset of relevant atmospheric constituents. For a more complete understanding, detailed atmospheric composition measurements throughout the lower atmosphere are needed to understand how emissions, chemistry, and meteorology combine to affect ozone and particulate pollution. These are often termed “secondary pollutants” since ozone and a large fraction of particle pollution are formed in the atmosphere rather than directly emitted. Important information from aircraft includes measuring detailed chemical composition for source fingerprinting, vertical profiling of composition for satellite validation and model assessment, observing chemical and dynamical processes affecting secondary pollution (i.e., fine particles and ozone), relating specific volatile organic compound (VOC) mixtures to satellite formaldehyde ($CH_2O$), providing fine scale pollution mapping with remote sensors, etc. Such information is critical for understanding the local factors influencing air quality for a specific location, quantifying emission sources, and assessing potential mitigation strategies for decision makers.

While there are many common elements in the factors driving air quality across the globe, the specific combination of emissions and meteorological conditions affecting chemistry and air quality for a given location can differ substantially. GEMS provides a view of many large population centers across Asia that can contribute to the consideration of both the individual and collective issues Asia faces in regard to air quality. Figure 1 identifies several large megacities that stand out in current satellite observations of nitrogen dioxide ($NO_2$), a key indicator of emissions from combustion. Specific candidate locations for potential airborne sampling are also identified by yellow circles in the figure.

ASIA-AQ builds upon strategies that were developed in earlier studies. The Deriving Information on Surface conditions from COlumn and VERtically-resolved observations related to Air Quality (DISCOVER-AQ) series of campaigns in North America and the Korea-United States Air Quality (KORUS-AQ) field study in South Korea were conducted in anticipation of geostationary satellite observations. ASIA-AQ will be able to fully harness the combination of multi-perspective observations (satellite, ground, and aircraft) and models to improve understanding of the factors controlling air quality. This calls for an international collaborative effort that includes air quality scientists, government officials, and monitoring agencies working together.

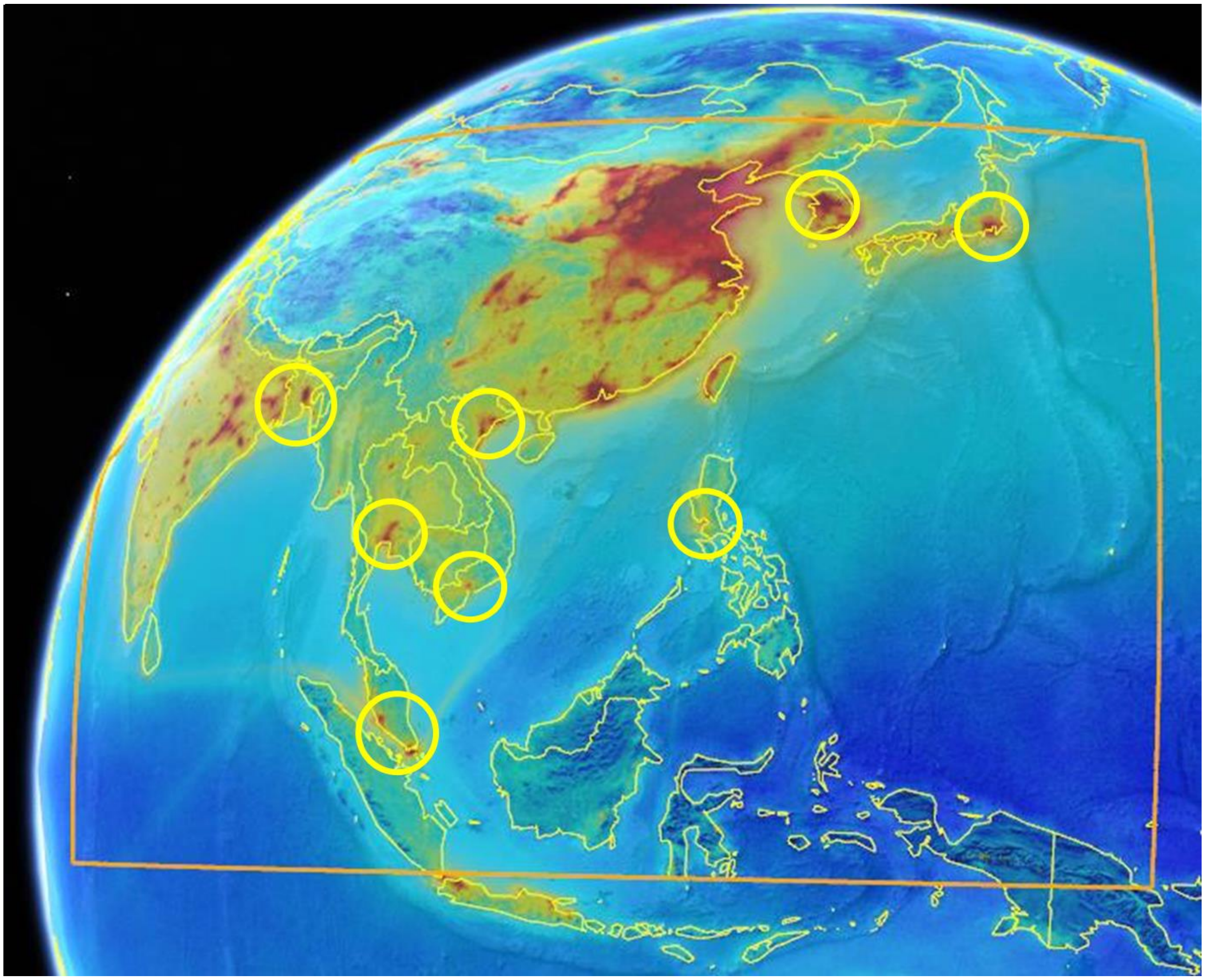

Figure 1. Observing domain for GEMS (orange box) and candidate locations for airborne sampling (yellow circles) during ASIA-AQ. The overlaid colormap shows annual average nitrogen dioxide ($NO_2$) concentrations observed by the TROPOMI satellite with red colors indicating the most polluted locations. Candidate cities include: Seoul, South Korea; Tokyo, Japan, Manila, Philippines; Hanoi and Ho Chi Minh City, Vietnam; Bangkok, Thailand; Kuala Lumpur, Malaysia; Singapore; Dhaka, Bangladesh and Kolkata, India.

## 2. Deployment Concept

To be successful, ASIA-AQ would need to include at least three deployment locations and could potentially accommodate up to five locations. Since some locations would support sampling of city pairs, up to seven cities could be sampled during the study. If five locations are secured, the expectation would be that four 8-hour research flights could be dedicated to each location. Flight patterns would be negotiated in advance given the busy and complex airspace for populated areas. Flights would also be repetitive, attempting to sample the same locations at multiple times per day to complement the hourly geostationary satellite observations and build statistics for studying the factors governing air quality on each flight day.

Figure 2 outlines how assets will be combined to support a multi-perspective view of air quality in each location that is visited. Sampling would involve two aircraft. The NASA DC-8 would serve as the in situ aircraft, measuring detailed chemical composition of the lower atmosphere. The NASA GV (or suitable substitute) would serve as the remote sensing aircraft flying at high altitude (28 kft or higher), mapping the given city with both a passive remote sensor for trace gases (proxy for GEMS), lidar for ozone and particulate pollution, and polarimetry for aerosol properties. These airborne measurements would be directly integrated with existing satellite observations of air quality, local air quality monitoring networks, other available ground assets, and models to provide a level of detail otherwise unavailable to advance understanding of local air quality and improve future integration of ongoing satellite and ground monitoring information.

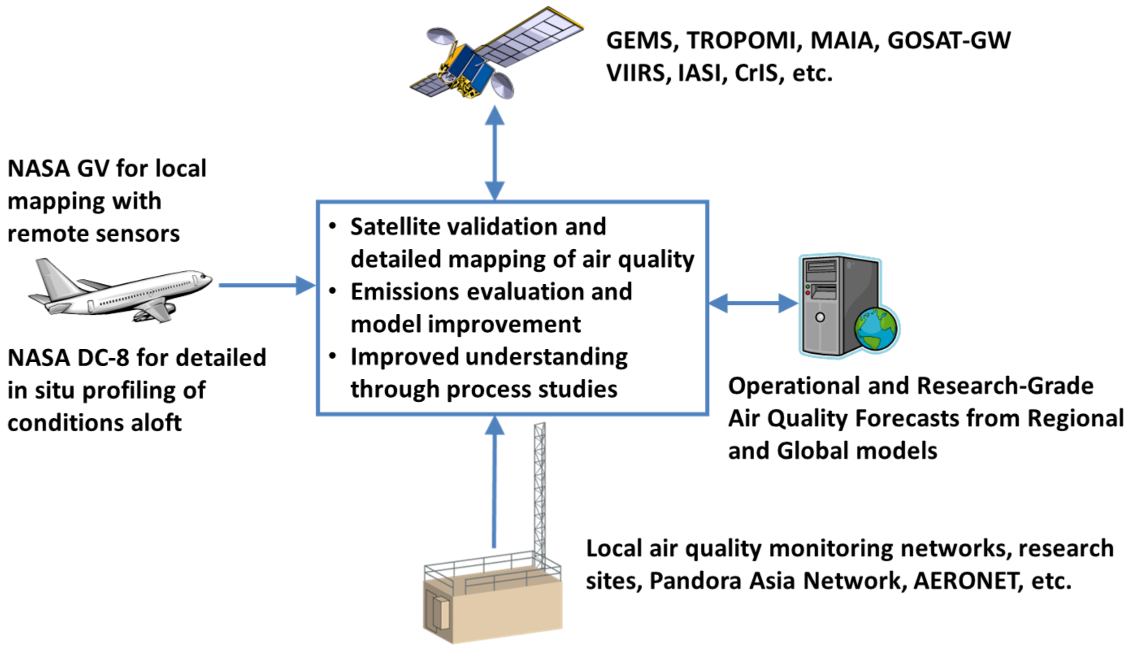

Figure 2. Schematic representation of the observing strategy for ASIA-AQ. Multi-perspective observations from the ground, air, and space will be leveraged along with multi-scale modeling focused on air quality.

The importance of sampling the vertical distribution of constituents affecting air quality is demonstrated with an example from the KORUS-AQ field study in Figure 3. The left panel of Figure 3 shows diurnal statistics for in situ measurements of $NO_2$ observed at the Olympic Park site in Seoul and for co-located measurements of the $NO_2$ column abundance by a Pandora spectrometer. While both instruments are observing the same constituent, the two perspectives capture very different behaviors. Surface $NO_2$ is seen to maximize in the morning and decrease into the afternoon before increasing again as evening approaches. By contrast, column $NO_2$ increases throughout the morning and levels off in the afternoon. A third perspective shown in the right panel of Figure 3 is based on descents of the NASA DC-8 over Olympic Park that provide context for understanding the differences in behavior for surface and column $NO_2$. Morning observations (blue profile) show $NO_2$ to be contained below 0.5 km as emissions have accumulated in the shallow boundary layer. As the day proceeds and surface heating leads to deeper vertical mixing, $NO_2$ is diluted near the surface and redistributed to higher altitudes. By late afternoon, $NO_2$ is often mixed up to 2 km, but the $NO_2$ gradient always decreases with altitude since emissions are occurring at the surface. Each of these perspectives has value. The surface measurements are critical for understanding exposure, but the column measurements provide a better assessment of emissions that have led to the increase in column abundances.

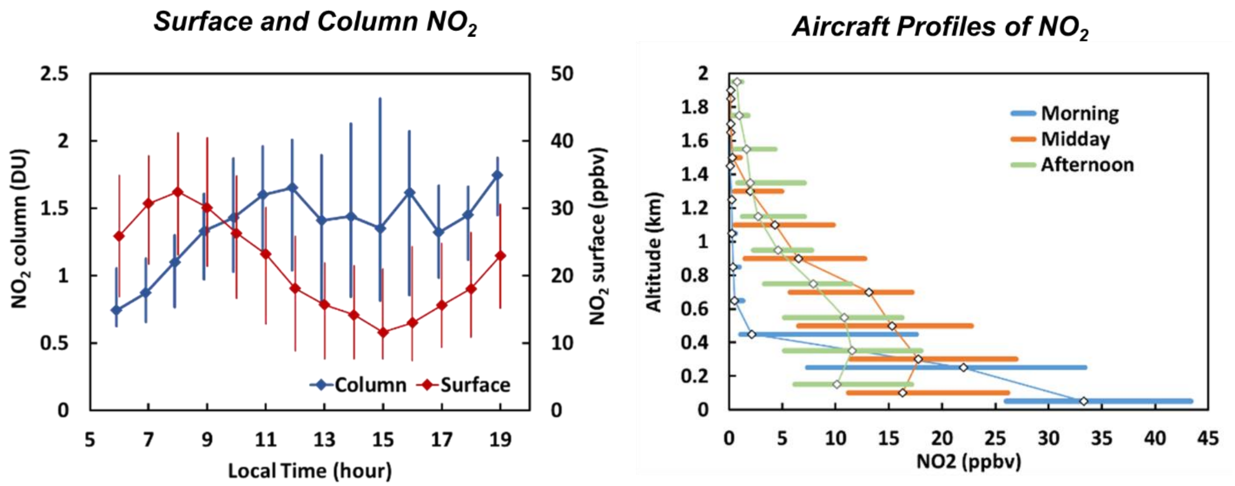

Figure 3. Multi-perspective observations of $NO_2$ at Olympic Park in Seoul during the KORUS-AQ field study (May-June 2016). The left panel shows diurnal statistics for in situ $NO_2$ measurements (red) at the surface and column $NO_2$ (blue) observed by a Pandora spectrometer. The right panel shows statistics for over fifty airborne profiles collected by the NASA DC-8 as it descended over Olympic Park during different times of day. Symbols on all plots indicate median values with lines spanning the interquartile range of observed values. (taken from Crawford et al., 2021)

The vertical distribution (along with the detailed composition measurements from the DC-8) further informs understanding of the rates of secondary formation of ozone and fine particle pollution. For instance, ozone formation is often more efficient in the upper boundary layer in regions when $NO_x$ emissions are strong enough to suppress production at the surface. It is also important to note that while the diurnal pattern for surface $NO_2$ is quite common (morning maximum, afternoon minimum), the pattern for column $NO_2$ has been observed to vary much more from one urban area to another depending on the amount of vertical mixing, the strength and pattern of emissions, and chemical removal processes. Airborne observations are essential to account for these factors in the interpretation of differences between surface and column $NO_2$.

When considering the vertical distribution of $CH_2O$, the picture is even more complex (Figure 4). $CH_2O$ is dominated by secondary photochemical production via the oxidation of VOCs. Thus, there is no systematic depletion of surface values due to vertical mixing. Instead, the amount of $CH_2O$ increases aloft as vertical mixing delivers VOCs to higher levels and oxidation processes occur over an increasing depth. Thus, airborne observations of speciated VOCs become particularly important as source mixtures differ from location to location. These differences include the balance between anthropogenic and natural sources as well as specific VOC sources and the lifetime of dominant compounds, all of which affect observed $CH_2O$.

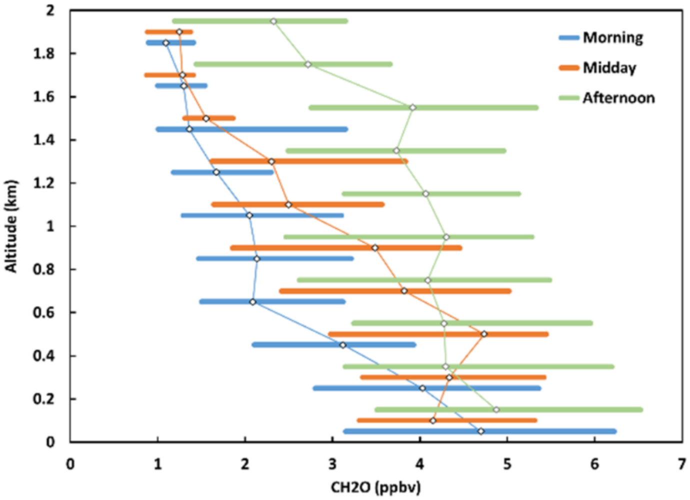

Figure 4. $CH_2O$ statistics for over fifty airborne profiles collected by the NASA DC-8 as it descended over Olympic Park during different times of day during KORUS-AQ. Symbols indicate median values with lines spanning the interquartile range of observed values. (taken from Crawford et al., 2021)

While it has been common to use satellite column $NO_2$ and $CH_2O$ measurements to diagnose the NOx-VOC sensitivity of ozone formation, the difference in profile behavior for these two compounds shows more complex behavior. Based on similar observations from the DISCOVER-AQ campaigns, Schroeder et al. (2017) demonstrated the value of airborne observations for assessing the limitations of this strategy.

## 3. Science Goals

ASIA-AQ will benefit our understanding of air quality and the factors controlling its daily variability by investigating the ways that air quality can be observed and quantified. Specific science goals will focus on the following topics:

**1. Satellite Validation and Interpretation**
**2. Emissions Quantification and Verification**
**3. Model Evaluation**
**4. Aerosol Chemistry**
**5. Ozone Chemistry**

More detailed discussion of each topic and associated science goals are provided below to explain the specific relevance of ASIA-AQ to the air quality interests of participating countries. Examples draw heavily from the 2016 KORUS-AQ study which serves as a model for ASIA-AQ.

**3a. Satellite Validation and Interpretation:** The GEMS satellite provides an unprecedented view of air quality across Asia, but these observations are of limited value without careful validation and combination with multi-perspective observations. Long-term validation is possible at ground sites, and the creation of the Pandora Asia Network plays a critical role in providing an ongoing connection between ground-based monitoring of local air quality and information from GEMS. As shown in Figure 3, vertically resolved information from aircraft even for a short window of time can provide valuable context for understanding the relationship between column amounts viewed from space and surface concentrations. Understanding how vertical distributions change with time of day is particularly important since satellite retrievals require a priori profiles that change with each passing hour. Expanding aircraft observations to locations in multiple countries enables an assessment of GEMS retrievals for a wide range of satellite-solar viewing geometries under a variety of cloud and aerosol conditions. Sampling when aerosol loadings are high will be of particular benefit given evidence that satellite sensitivity can be reduced near the surface under such conditions, leading to underestimates of column trace gas abundances (Kanaya et al., 2014; Liu et al. 2019; Ojeda et al., 2021).

In addition to GEMS, another new satellite called the Multi-Angle Imager for Aerosols (MAIA) will provide targeted observations of aerosol abundance and properties for several Asian cities (Seoul, Dhaka, Bangkok, and Hanoi) that will expand satellite validation opportunities should these locations participate in ASIA-AQ. The prospect for expanding MAIA observations to other participating locations through their designation as a secondary target area during the campaign will be explored in consultation with the MAIA team. Similar to GEMS validation support provided by the Pandora Asia Network, ground-based observations in support of MAIA include the Surface Particulate Matter Network (SPARTAN) which operates sites in Seoul, Dhaka, Hanoi, Singapore, and Manila. These sites provide continuous observations of $PM_{2.5}$ mass, composition, and optical properties co-located with an Aerosol Robotic Network (AERONET) sunphotometer.

ASIA-AQ will also provide validation opportunities for other satellites conducting global observations from low earth orbit (e.g., TROPOMI, IASI, CrIS, OMPS, VIIRS). The ASIA-AQ domain represents a region that is undersampled and would provide important data for improving the general level of confidence in satellite observations for the region.

Along with validation, ASIA-AQ will contribute to improved interpretation of satellite observations for the sampled locations. From space, only a limited range of compounds can be observed, and the development of proxies can provide value. Examples of such proxies include using satellite retrievals of formaldehyde ($CH_2O$) to diagnose surface ozone distributions (Schroeder et al. 2016) or organic aerosol abundance (Liao et al., 2019) which result from complex chemical interactions. While both of these proxies show some promise, they need much broader evaluation before they can be reliably used. As noted earlier, the use of the ratio of formaldehyde to nitrogen dioxide ($CH_2O$:$NO_2$) has been popularized as a method for diagnosing the sensitivity of ozone production. Observations continue to be needed to determine the viability of this proxy (Schroeder et al., 2017), which has been based primarily on early afternoon observations from low earth orbit rather than the diurnal time-resolved information now available from GEMS.

In summary, satellite observations can contribute to a better understanding of air quality and the impact of emissions, transport, and chemistry on the secondary production of both ozone and fine particulate matter pollution. Short-term field campaigns provide the additional information needed to evaluate the impact of satellite observations for a range of uses including data assimilation, top-down inversions to assess emissions, and satellite-model comparisons. Numerous studies of this type were enabled by KORUS-AQ (e.g., Tang et al., 2018; Goldberg et al., 2019; Jung et al., 2019; Miyazaki et al., 2019; Saide et al., 2020; Souri et al., 2020) and would be expanded upon by ASIA-AQ to improve the applicability of satellite observations for air quality across Asia.

**3b. Emissions Quantification and Verification:** The impact of emissions depends on myriad sources with different locations, magnitudes, timing, and composition. Bottom-up methods are often considered the best way to account for all of these sources and their attributes together. Such bottom-up assessments also rely on intensive gathering of economic data and statistics on emissions activities such that they often lag current conditions by several years as emissions continually change. Opportunities to conduct observation-based assessments are thus valuable to both assess bottom-up inventories and inform their updates. Such assessments are difficult to achieve purely from the ground since surface measurements are unduly influenced by the ventilation of emissions into the lower atmosphere (see Figure 3) and can be biased by proximity to specific sources. Satellite observations provide the broad coverage to enable top-down emissions that are useful to assess the magnitude of emissions and their timing. This works well for $NO_2$, CO, $SO_2$, and $NH_3$ but is more complicated for VOCs which rely on the proxy measurement of $CH_2O$ as a common oxidation product. Although less mature, satellite retrieval of glyoxal (CHOCHO) and its potential for aiding in the differentiation of anthropogenic and biogenic emissions when ratioed with $CH_2O$ has been explored. Aerosol emissions are also complicated given the variable role of primary emissions versus secondary production, thus top-down aerosol emissions from satellites tend to be limited to strong primary sources such as wildfires and windblown dust events.

When available, airborne observations can make a unique and valuable contribution to observation-based emissions assessments. Comparison of in situ observations with air quality models based on existing emissions inventories provides a quick means of assessment. Figure 5 shows model-measurement comparisons for the Seoul Metropolitan Area from the KORUS-AQ Rapid Science Synthesis Report. The underestimation of both NOx and aromatic VOCs in model simulations compared to observations revealed important discrepancies in emissions of precursors relevant to both ozone and secondary organic and inorganic aerosol. These initial simulations demonstrated that the available emissions inventories were insufficient for a realistic model investigation of local air quality. During the process of updating emissions inventories, top-down analysis of satellite observations corroborated the NOx underestimation (Goldberg et al., 2019). To address the aromatic VOCs, updated speciation profiles for total VOC emissions included a larger fraction attributed to aromatic compounds. These updates were critical to enabling model investigation of current air quality conditions and simulations of how air quality could be expected to respond to changes in emissions.

In addition to comparison with models, in situ airborne observations provide the opportunity to measure detailed chemical composition that is useful to fingerprint sources and understand their relative contributions through source apportionment analyses. Continuing to use KORUS-AQ as an example, broad sampling of the composition of VOCs and other compounds over the Seoul Metropolitan Area enabled the use of Positive Matrix Factorization (PMF) analysis to identify factors that discriminated the influence of sources associated with traffic, solvents, biogenic emissions, and long-range transport (Simpson et al., 2020). The direct sampling of large point sources was also effective in demonstrating that inventory values for power plant NOx emissions were in good agreement with observations while VOC emissions from the largest petrochemical facility upwind of the Seoul Metropolitan Area were underestimated by a factor of four (Fried et al., 2020).

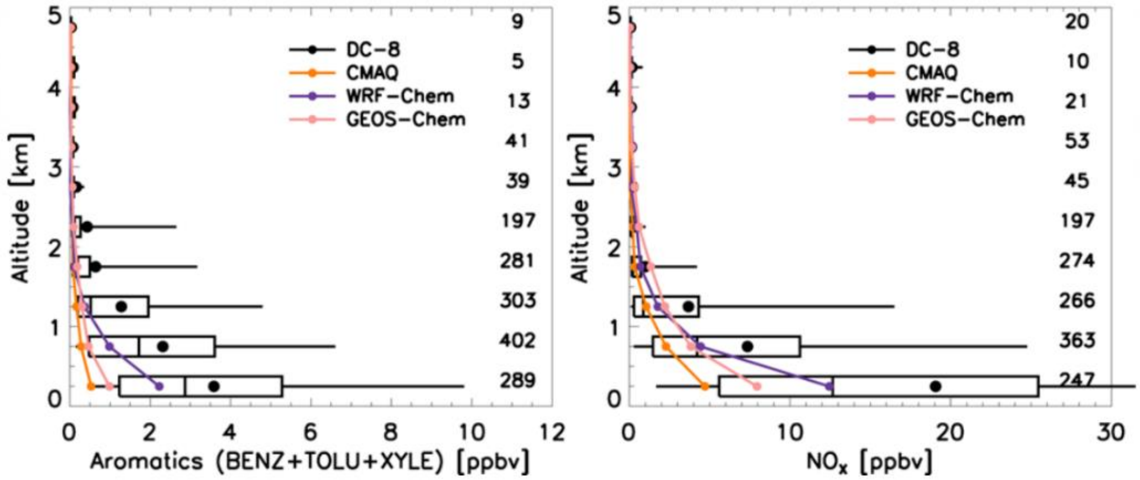

Figure 5. Comparison of in situ observations from the DC-8 aircraft with model simulations for aromatic VOCs (left) and NOx (right) in the lower atmosphere over the Seoul Metropolitan Area during KORUS-AQ (figure taken from the KORUS-AQ Rapid Science Synthesis Report; https://espo.nasa.gov/sites/default/files/documents/KORUS-AQ-ENG.pdf).

Airborne remote sensing during KORUS-AQ provided further insight into emissions by cataloging $SO_2$ emissions from industrial sources and power generation using high resolution mapping (Chong et al., 2020; see Figure 6). Top-down assessment of VOC emissions during KORUS-AQ was accomplished by combining in situ aircraft observations from the DC-8, remote sensing of $CH_2O$ from GeoTASO overflights, and model simulations (Kwon et al., 2021).

ASIA-AQ data will provide a similar framework for combining airborne in situ and remote sensing observations with models and satellite observations to assess emissions derived from bottom-up and top-down methods. These important checks on emissions are the first step in ensuring that air quality models are well equipped to investigate air quality in each studied location.

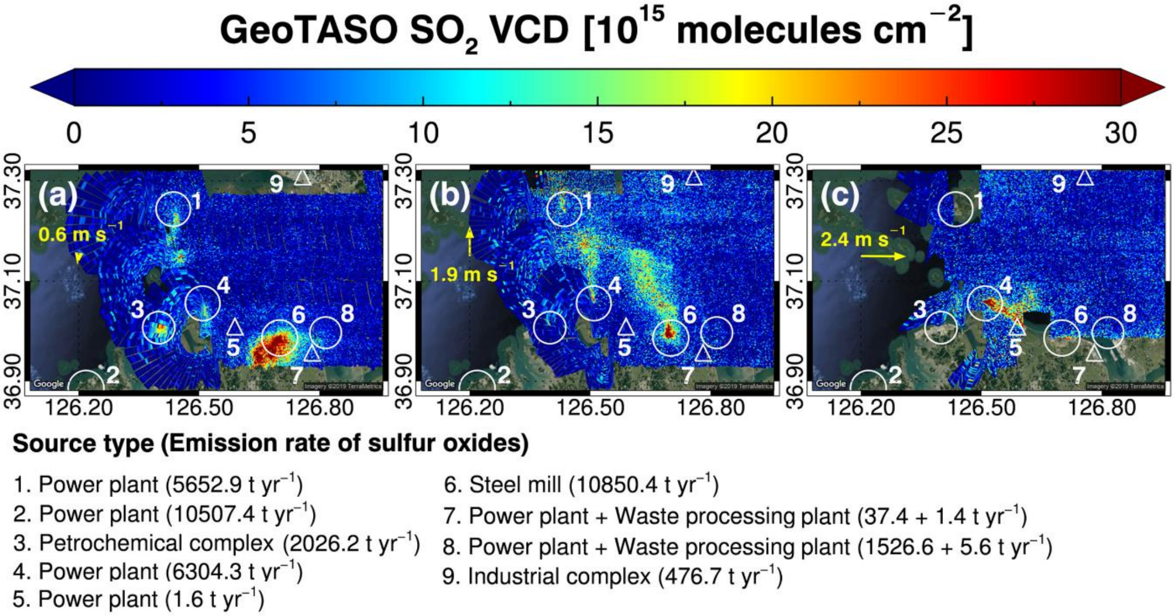

Figure 6. GeoTASO SO$_2$ VCD (vertical column density)observations over the northern Chungnam area to the southwest of Seoul on (a) 11 May am, (b) 17 May am, and (c) 17 May pm. Individual sources in the Stack Tele-Monitoring System (TMS) are numbered and listed.
(adapted from Chong et al., 2020)

**3c. Model Evaluation:** Airborne field studies provide short but intensive periods of observation that provide excellent opportunities for model evaluation. This goes well beyond the evaluation of emissions noted above and is evidenced by the differences between individual models shown in Figure 5. These differences can come from model resolution, chemical mechanism, boundary layer schemes, other parameterized processes, etc. used by individual models. For this reason, it is often most useful to employ an ensemble of models to understand the range of answers they provide and their ability to represent local air quality. KORUS-AQ observations were used to evaluate an ensemble of six regional and two global models using recently updated KORUSv5 emissions inventories resulting from the study (Park et al., 2021). Ensemble comparisons can be useful in exposing problems for a specific model as well as problems common to all models. Models struggle to simulate the formation of secondary organic and inorganic aerosol observed during KORUS-AQ, and this reduces confidence in predictions of the relative contributions of local and transboundary pollution sources. This is most important during pollution episodes when models often underpredict peak concentrations. Aerosol schemes in models are also highly parameterized, so testing them with observations in new locations and under different conditions as in ASIA-AQ will help determine if they are more broadly applicable or more attuned to the environments for which they were developed.

**3d. Aerosol Chemistry:** Each ASIA-AQ location is expected to differ in the balance between primary and secondary aerosol as well as the sources and conditions governing the formation of secondary organic and inorganic aerosol. Comprehensive measurements of atmospheric composition will be needed to fully explore the link between aerosols, their sources, and the meteorological conditions leading to episodes of fine particle pollution. Such measurements include gas-phase precursors, aerosol physical and chemical properties, and important meteorological parameters related to aerosol formation processes. Fully characterizing aerosol optical properties is also fundamental to improving the interpretation of satellite observations related to aerosol and understanding aerosol feedbacks on meteorology and chemistry through radiative effects. Quite often, measurement payloads fall short in one way or another in enabling the full constraint of aerosol physical and chemical behavior. Addition of $NH_3$ measurements to the DC-8 payload during ASIA-AQ represents an important priority for filling a previous gap in constraining inorganic aerosol chemistry. Improved speciation of organic aerosol components will further enhance opportunities for understanding the links between emissions, chemistry, and aerosol composition. New capabilities from AERONET retrievals will provide enhanced ability to infer absorbing organic carbon (BrC) and more accurate aerosol properties in the UV wavelengths that are important in aerosol-gas photochemical interactions.

**3e. Ozone Chemistry:** In regions of strong particulate pollution, ozone often receives limited attention, but the chemistry of ozone is closely intertwined with aerosol outcomes. While the fundamentals of ozone chemistry are well understood, the specific outcomes related to local sources and meteorological conditions need to be assessed to fully understand how emission, chemistry, and transport unfold to affect air quality conditions in each location. Again, the need for comprehensive in situ measurements comes into play. It is especially important to measure the family of reactive nitrogen compounds as completely as possible. For instance, a sensitive and artifact-free HONO measurement would be a valuable addition to the DC-8 payload that has not been routinely available. Speciated VOCs have already been mentioned and have broad value for evaluating emissions, aerosols, and ozone chemistry. In the case of VOCs, any opportunity to expand the number of identified compounds is helpful, with additional value in measuring intermediates of VOC oxidation and speciated termination products (e.g., organic nitrates, organic peroxides, organic acids, etc.). The need for as much detail as possible is important to provide the best assessment of ozone production rates and their nonlinear response to variations in NOx and VOCs which is sensitive to the intensity of photochemistry and radical oxidant production rates.

## 4. ASIA-AQ Observations and Modeling

**4a. Aircraft Observations:** As noted in Section 2, ASIA-AQ would employ two aircraft, one for in situ observations and the other for mapping with remote sensors. The remote sensing aircraft would have a fairly simple payload that includes a passive UV-VIS spectrometer (e.g., GeoTASO or GCAS) for mapping of trace gas columns ($NO_2$, $CH_2O$, $SO_2$) at high spatial resolution and a high spectral resolution lidar (e.g., HSRL-2) for profiles of aerosols and ozone. This payload is scheduled to fly on the NASA GV during the TRACER-AQ study over Houston in the summer of 2021. If possible, ASIA-AQ would add an aerosol polarimeter to the GV (or similar platform) payload for the 2024 study. For in situ measurements, the NASA DC-8 is the desired research aircraft due to the need for a complex payload and space for collaborating scientists and observers. Table 1 outlines measurement priorities for the payload. Priorities are expressed as follows: 1 = required, 2 = desired, 3 = useful. For Priorities 1 and 2, instruments may be dedicated to a specific need. For Priority 3 observations, these needs are typically met by instruments that also provide higher priority measurements. Detection limit and resolution specifications must be met or exceeded for a measurement to be useful. The suite of measurements identified as Priority 1 are important science goals related to satellite validation and emissions assessment. Priority 1 measurements also enable a high-level assessment of chemical evolution and its representation in models. Priority 2 measurements allow for a more detailed examination of aerosol and ozone chemistry by adding information on radical chemistry, reservoir species for reactive compounds, and source-specific tracers. Priority 3 encompasses value-added observations, including measurements that could be easily accomplished by groups already performing higher priority measurements and measurements that would provide a more complete assessment of the radiative environment.

**4b. Ground-based observations**: Close integration with ground measurements is fundamental to this study. The nucleus of any ground effort should necessarily leverage the existing air pollution monitoring networks administered by each participating country and any research sites. Highly accurate ground based remote sensing networks (e.g., Pandora, AERONET, MPLNET etc.) play a critical role linking surface, airborne, satellite and modeling results during and beyond the field campaigns through diurnal, seasonal and annual cycles at local and regional scales. The DRAGON networks implemented in DISCOVER-AQ, KORUS-AQ and FIREX-AQ (Holben et al., 2018) will serve as a model for extended 4-dimensional remote sensing characterization supporting research and validation.

**4c. Modeling:** Following the example of KORUS-AQ, it will be most beneficial if there is involvement from both NASA-sponsored modeling teams as well as local air quality modeling teams. These teams will employ an ensemble of models from local to global scales that will be used during all phases of the study. During the execution of flights, the models will be used to forecast air quality conditions for flight planning. This also creates an environment where the modeling groups can establish rapport and assess how each model’s strengths and weaknesses complement the ensemble. During post-mission analyses, modeling groups would continue to work together to generate multi-model assessments (e.g., Park et al., 2021) and perform independent studies as well.

**Table 1. NASA DC-8 Payload Measurement Priorities. NA=not applicable**

| Gas Phase In Situ | Priority | Detection Limit | Resolution |
|---|---|---|---|
| $O_3$ | 1 | 1 ppbv | 1 s |
| $H_2O$ | 1 | 10 ppmv | 1 s |
| CO | 1 | 5 ppbv | 1 s |
| $CH_4$ | 1 | 10 ppbv | 1 s |
| $CO_2$ | 1 | 0.1 ppm | 1 s |
| Speciated NMHCs | 1 | <10% | 1 min |
| NO | 1 | 10 pptv | 1 s |
| $NO_2$ | 1 | 20 pptv | 1 s |
| $CH_2O$ | 1 | 50 pptv | 1 s |
| $SO_2$ | 1 | 10 pptv | 1 s |
| $NH_3$ | 1 | 30 pptv | 1 min |
| $H_2O_2$ | 2 | 50 pptv | 10 s |
| ROOH | 2 | 50 pptv | 10 s |
| CHOCHO | 2 | 20 pptv | 10 s |
| $HNO_3$ | 2 | 50 pptv | 10 s |
| HONO | 2 | 10 pptv | 1 s |
| PANs | 2 | 50 pptv | 10 s |
| $RONO_2$ | 2 | 50 pptv | 10 s |
| $CH_3CN$, HCN | 2 | 10 pptv | 1 min |
| OH, $HO_2$, $RO_2$ | 2 | 0.01/0.1/0.1 pptv | 30 s |
| OH reactivity | 2 | 1 $s^{-1}$ | 10 s |
| NOy | 3 | 50 pptv | 1 s |
| Halocarbons | 3 | variable | 1 min |
| $N_2O$ | 3 | 1 ppbv | 10 s |
| Organic Acids | 3 | 10 pptv | 10 s |
| Aerosol In Situ | Priority | Detection Limit | Resolution |
| Size Distribution/Number | 1 | NA | 10 s |
| Volatility | 1 | NA | 1 s |
| Scattering | 1 | 1 Mm-1 | 1 s |
| Absorption | 1 | 0.2 Mm-1 | 10 s |
| Hygroscopicity | 1 | NA | 10 s |
| Ionic composition | 1 | 50 ng $m^{-3}$ | 5 min |
| Organic composition | 1 | 100 ng $m^{-3}$ | 1 min |
| Black carbon | 1 | 50 ng $m^{-3}$ | 1 s |
| Size-resolved composition | 2 | 100 ng $m^{-3}$ | 1 min |
| Single particle composition | 2 | <4 µm dia. | 5 min |
| CCN | 2 | <4 µm dia. | 1 s |
| Cloud particle size distribution | 2 | 0.05-1000 µm | 1 s |
| Particulate PAHs / speciated OA | 3 | **TBD** | **TBD** |
| Radionuclides ($^{222}$Rn,/$^{7}$Be, $^{210}$Pb) | 3 | 1/100/1 fCi $m^{-3}$ | 5 min |
| Remote Sensing, Radiation, and Met | Priority | Detection Limit | Resolution |
| UV spectral actinic flux (4π sr) | 1 | 80° SZA equivalent | 5 s |
| High Resolution Met (T, P, winds) | 1 | 0.3K, 0.3 mb, 1 $ms^{-1}$ | 1 s |
| Hyperspectral solar flux | 3 | 4% | 1 s |
| Broadband flux | 3 | 5% | 1 s |

## 5. Expected Benefits

**An in situ airborne payload offers a common measurement suite applied across diverse locations to evaluate similarities and differences in the combination of emissions and other local factors that govern air quality outcomes for each location.** For instance, DISCOVER-AQ visited four locations and documented a variety of conditions related to emissions (e.g., traffic-dominated emissions in Maryland, petrochemical emissions in Houston, influences of oil and gas in Colorado and feedlots in California's Central Valley) as well as location (e.g., land-sea dynamics in Maryland and Houston, orographic effects in Colorado, and winter stagnation in California's central valley).

**Airborne measurements offer a perspective that is less prone to bias.** For instance, a ground-based supersite may be affected by its location and proximity to specific sources, while measurements aloft should be more regionally representative. Additionally, the influence of vertical mixing on surface measurements can be better understood in the context of airborne profiling of the lower atmosphere. This will contribute to improved interpretation of GEMS observations for each sampled location.

**Observations will contribute to ongoing dialogue between Asian countries.** The GEMS satellite offers a geographically and temporally integrated view of Asia that will improve understanding of air quality ranging from localized to regional influences. More detailed airborne and ground-based measurements at local scales will contribute to identifying both common and unique issues facing Asian megacities. The high-resolution graphical representations of pollutant distributions from the GV remote-sensing observations will be of critical value for communicating with decision makers and the public. In addition to fostering more dialogue between Asian countries, the high visibility of an airborne campaign also raises public awareness of air quality and the information available from local forecasts.

**Capacity building through science engagement.** To be successful, full engagement with local scientists and representatives of air quality agencies is essential. This includes a commitment to full data sharing of aircraft observations during all stages of data production (i.e., from initial field data to final quality-controlled data). Incorporation of existing ground measurements, the Pandora Asia Network, and advice from local air quality and meteorological forecasting experts will be essential. Collaboration will need to include pre-mission design of flight strategies, daily meetings to assess observations and forecasts during the execution of flights, and post-mission interaction in the interpretation of observations. Frequent online meetings and communication is expected. Opportunities for flight participation also need to be prioritized. This could be accomplished by sponsoring DC-8 investigators to include a scientist from one of the participating countries in their effort. This could be in the form of a graduate student, post-doc, or visiting scientist.

**Sparking local, multi-sectoral community engagement on air quality.** There is an immense opportunity for ASIA-AQ to be a catalyst for local, multi-sectoral communities to engage on air quality issues together. An airborne field campaign to sample local air quality, in collaboration with local scientists, will naturally be of great interest to local stakeholders working on air quality issues. The event itself can act as a convening force to facilitate local conversations on air quality actions. A workshop or series of workshops that facilitate conversations amongst local air quality actors, such as scientists, medical doctors, educators, media, local government (air quality agency staff and/or public health officials), NGO staff, etc., can help local communities identify common, low-hanging objectives toward improving local air quality. Such neutrally-facilitated workshops can also build goodwill and foster a shared sense of understanding and trust across institutions and countries that is truly inclusive.

**Lessons for other satellite air quality observations.** Supporting GEMS validation and science is important to inform TEMPO, Sentinel-4, and GOSAT-GW as they ramp up operations. Several candidate cities are also targeted by MAIA. Ongoing observations of trace gases and aerosols from LEO platforms will also benefit.

## 6. Important Challenges

**Diplomatic clearances.** US-Korea environmental commitments under their joint trade agreement played an important part in the planning of KORUS-AQ. Documenting and referring to such agreements between the US and other countries will provide valuable support for requests to conduct research flights.

**Air traffic coordination.** Airspace control measures over each city will be too complex to navigate without being highly coordinated. This was the case for flights over Seoul during KORUS-AQ which were guided by military airspace controllers. It is essential to develop a flight route that is repetitive and can be executed within airspace considerations. This includes identifying one or more airfields that are not too busy in order to enable profiling to the surface using missed approaches by the DC-8 in the absence of heavy air traffic. A predictable and repetitive flight path aids in both the science interpretation and the air traffic coordination.

**Logistics.** A minimum of three bases will be needed to execute flights: one in east Asia, one in southeast Asia, and one in south Asia (see discussion of candidate sites). This requires the identification of multiple airfields, complex shipping, and procedures to rapidly establish operations at each new site. This will require a more rigid schedule than typical for campaigns that have a single base of operations. Some lessons from the ATom campaign may help in this regard. Operational requirements for each instrument team will need to be considered to maintain the flight pace along with changing bases of operation. In some cases, a pair of cities may be able to be sampled with a single flight (see discussion of candidate sites below in Section 7).

**Local ground observations.** The ground presence with respect to monitoring and infrastructure is expected to vary across locations. At least one ground site along with a Pandora spectrometer should be the minimum requirement to conduct flights over a chosen city. Local monitoring, to include small sensor networks, should be acknowledged and welcomed to partner, with a priority on the evaluation of information coming from such data sources.

## 7. Candidate Deployment Sites and Seasons:

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**The specific plans for each candidate deployment site are a work in progress. Details will continue to be developed with scientific contacts in each country to summarize current understanding, existing air quality infrastructure, important collaborators and government points of contact, potential flight plans, etc. that are needed to advocate for approvals to conduct research flights, share data, and develop collaborative research plans that will develop into joint documents for each site.**

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A deployment period of January-March 2024 is proposed. This timing emphasizes fine particle pollution which tends to maximize during winter months when precipitation is at a minimum. Figure 7 shows a time series of $PM_{2.5}$ data for candidate cities with US Embassy monitors. The proposed deployment period is highlighted with yellow shading. Exact deployment dates are expected to result from further development of specific site analyses. Given the latitude of many of the proposed cities, photochemistry will be strong throughout the year, supporting investigation of both secondary ozone and fine particle pollution.

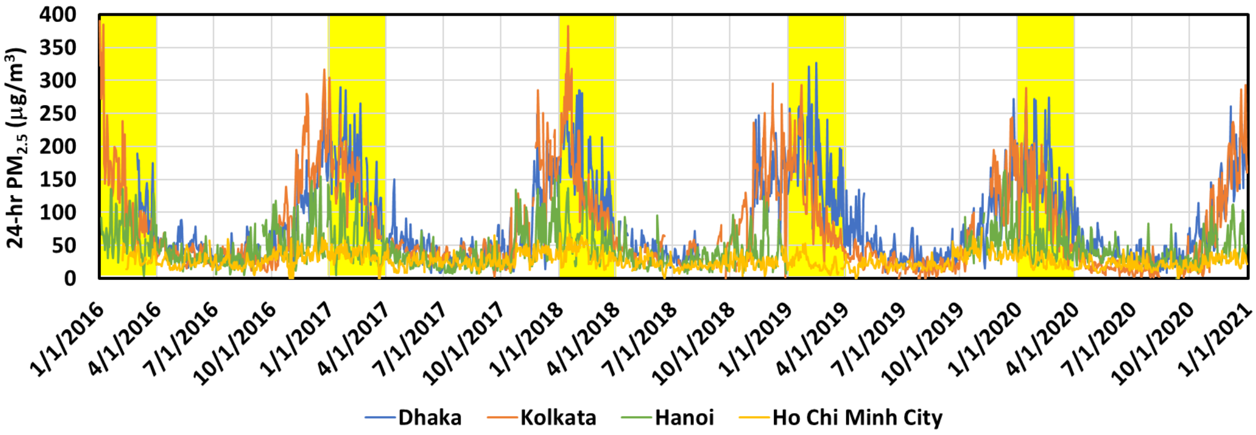

Figure 7. Time series of daily $PM_{2.5}$ for ASIA-AQ cities with US Embassy monitors for 2016-2021. The proposed deployment window of January-March is highlighted in yellow to emphasize the seasonal peak in $PM_{2.5}$ that is the target of ASIA-AQ.

A preliminary discussion of each candidate city is provided below with contacts and very coarse statements on the purpose of the observations and current state of air quality monitoring. Current monitoring descriptions are based solely on what can be obtained publicly. In some cases, historical data is provided to demonstrate viability for the deployment period. Maps for each country showing average $NO_2$ distributions from TROPOMI and Special Use Airspace are provided to demonstrate the challenge facing airborne sampling over areas of strong emissions activity associated with large cities and busy airspace. These sections will continue to be developed in much more detail in collaboration with the listed contacts and any others who they may identify to participate and provide science advocacy for their location.

### 7a. Seoul, South Korea

**Primary contacts:** NIER and KORUS-AQ science leads (Jhoon Kim, Rokjin Park, Gangwoong Lee)

**Purpose:** Collect observations during the season of peak aerosol pollution. With only a week on station, this may be the trickiest location in terms of whether a PM episode occurs during the measurement period. Nevertheless, observations of PM composition, secondary aerosol formation processes, and emissions will provide a valuable contrast with the KORUS-AQ observations from 2016.

**Monitoring:** The AirKorea network provides valuable information on PM, $O_3$, and precursors with dense coverage. There are also numerous Pandora sites and AERONET sites, an extensive ceilometer network, and other research sites maintained and operated by university scientists.

**Historical data:** The time series of AirKorea observations in Figure 8 provides some perspective on what might be expected for four science flights conducted over a 10-day period. Depending on the year, peak concentrations of $PM_{2.5}$ can occur at any time, offering no clear priority for when a 10-day deployment to Seoul might be most advantageous. It is useful, however, to determine what range of conditions might be encountered in any given 10-day window to facilitate better understanding. In order to understand emissions and their relationship to $PM_{2.5}$, the gradient (or range) of values observed is potentially more important than the peak value. Table 2 provides statistics for a running 10-day window on the time series in Figure 8.

**Table 2. 10-day expected $PM_{2.5}$ conditions for Seoul**

| Probability | Max $PM_{2.5}$ | $PM_{2.5}$ range |
|---|---|---|
| 10% | >75 $\mu g/m^3$ | >60 $\mu g/m^3$ |
| 50% | >48 $\mu g/m^3$ | >35 $\mu g/m^3$ |
| 90% | >35 $\mu g/m^3$ | >20 $\mu g/m^3$ |

**Flight Challenges:** Previous experience in KORUS-AQ demonstrates the ability to fly over the Seoul Metropolitan Area (SMA). Flights would again exploit the stereoroute descent over Olympic Park ending in a missed approach over Seoul air base. In contrast to KORUS-AQ, there would be value in a more restrictive flight plan that solely exercises the stereoroute and a flight leg over the northern part of the Yellow Sea. This would allow more frequent sampling over Seoul than the three times per day during KORUS-AQ, and it would keep attention a more continuous contrast between the SMA and upwind conditions. Given the shorter daylight hours, extending some flights into the early evening would be useful to sample the collapse of the boundary layer from afternoon into evening and the impacts to chemistry and aerosol composition. To demonstrate the complexity of the Seoul stereoroute and to provide a basis for understanding what might be possible for other deployment locations, figure 9 shows the route both with and without the Special Use Airspace overlaid. The need to define acceptable flight paths over urban areas that can be actively controlled and allow repetitive navigation of complex airspace is the most important challenge facing each ASIA-AQ candidate location.

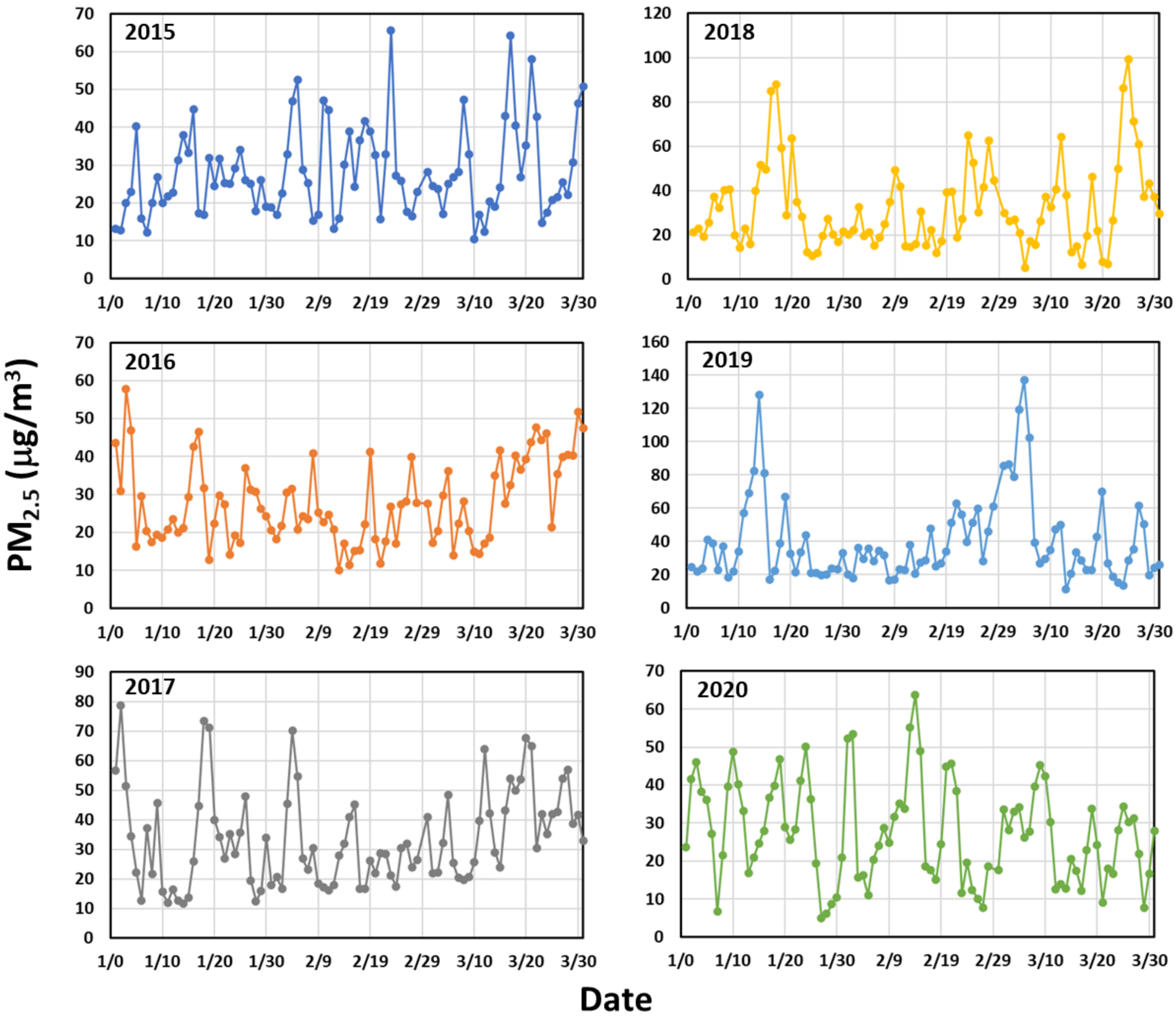

Figure 8. Time series of daily $PM_{2.5}$ averaged over AirKorea monitors in Seoul for January-March of 2015-2020.

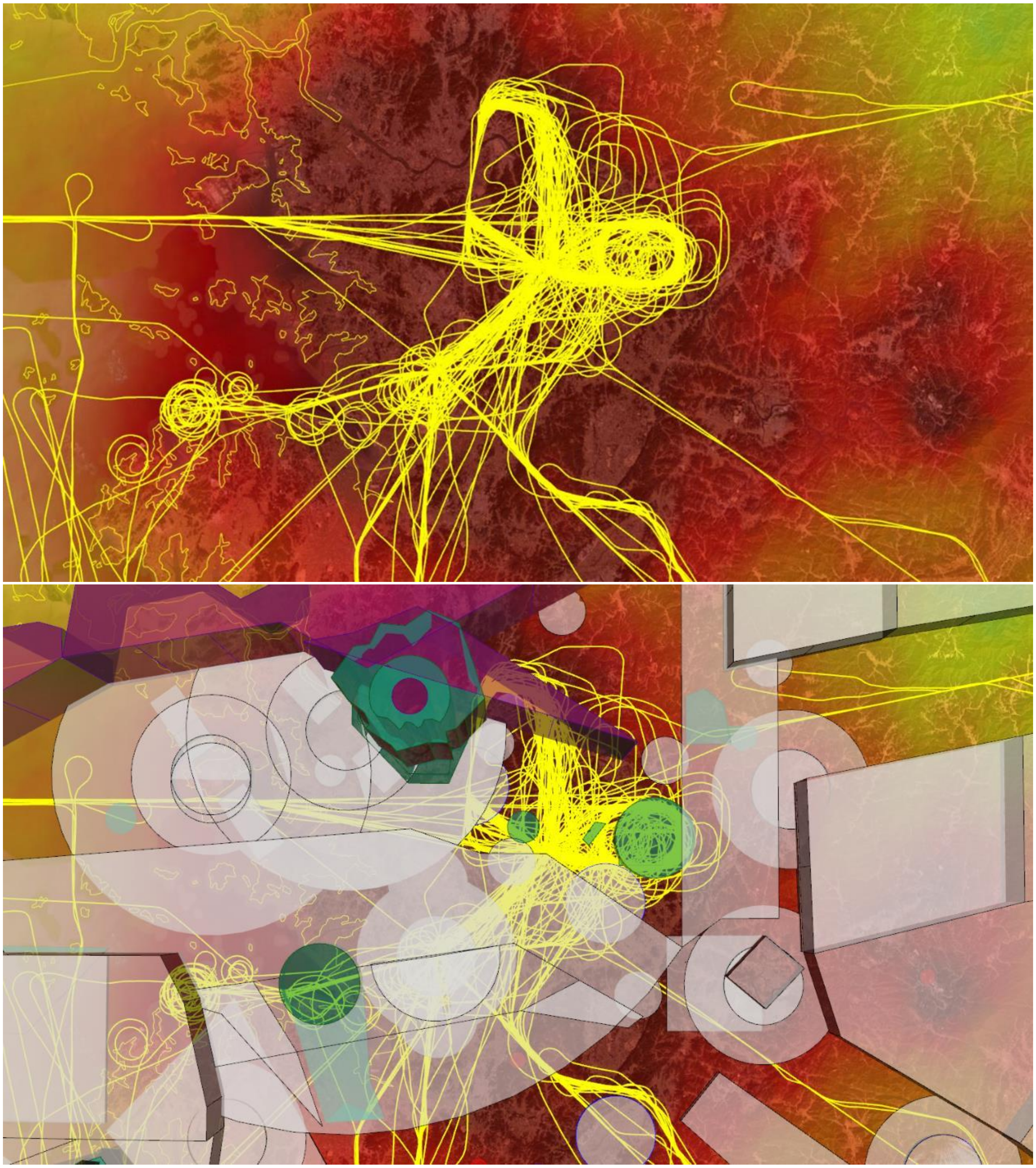

Figure 9. (top) DC-8 flight lines (yellow) over the Seoul Metropolitan Area during KORUS-AQ (bottom) same image as top overlaid by Special Use Airspace. Circles indicate airports, rectangles are Military Operation Areas, cyan areas are Restricted Airspace, and purple areas indicate Prohibited airspace.

### 7b. Dhaka, Bangladesh and Kolkata, India

**Primary contacts:** Abdus Salam (University of Dhaka); Sachin Ghude (Indian Institute of Tropical Meteorology, Pune)

**Purpose:** Assess emissions and secondary pollutants during the peak PM season. Explore the possibility of sampling these two cities as a pair. The two locations are within ~250 km, allowing for comparison of local/regional/transboundary conditions and identification of shared and unique challenges.

**Monitoring:** In addition to the US Embassy monitor, there is a SPARTAN and AERONET site in Dhaka. There are ~8-10 monitoring sites in Kolkata administered by the Central Pollution Control Board (CPCB).

**Historical data:** The time series of the US Embassy monitor in Dhaka is shown in Figure 10 to provide some perspective on what might be expected for four science flights conducted over a 10-day period. While concentrations peak in January, heavy aerosol pollution is present throughout January-March. The expected range of $PM_{2.5}$ values in Table 3 show that sampling of large gradients in $PM_{2.5}$ is essentially assured. Statistics for Kolkata (not shown) are essentially similar to Dhaka (see similarity in Figure 7).

**Table 3. 10-day expected $PM_{2.5}$ conditions for Dhaka**

| Probability | Max $PM_{2.5}$ | $PM_{2.5}$ range |
|---|---|---|
| 10% | >285 μg/m$^3$ | >185 μg/m$^3$ |
| 50% | >232 μg/m$^3$ | >122 μg/m$^3$ |
| 90% | >157 μg/m$^3$ | >76 μg/m$^3$ |

**Flight Challenges:** Airspace blankets both cities, demonstrating the need for direct negotiation of flight paths for both aircraft. If both cities were to able to be negotiated, a repetitive sampling path for the DC-8 going back and forth between the two cities could be accomplished. Discussion would be needed to see whether mapping by the GV could include both cities or would be best dedicated to only one city.

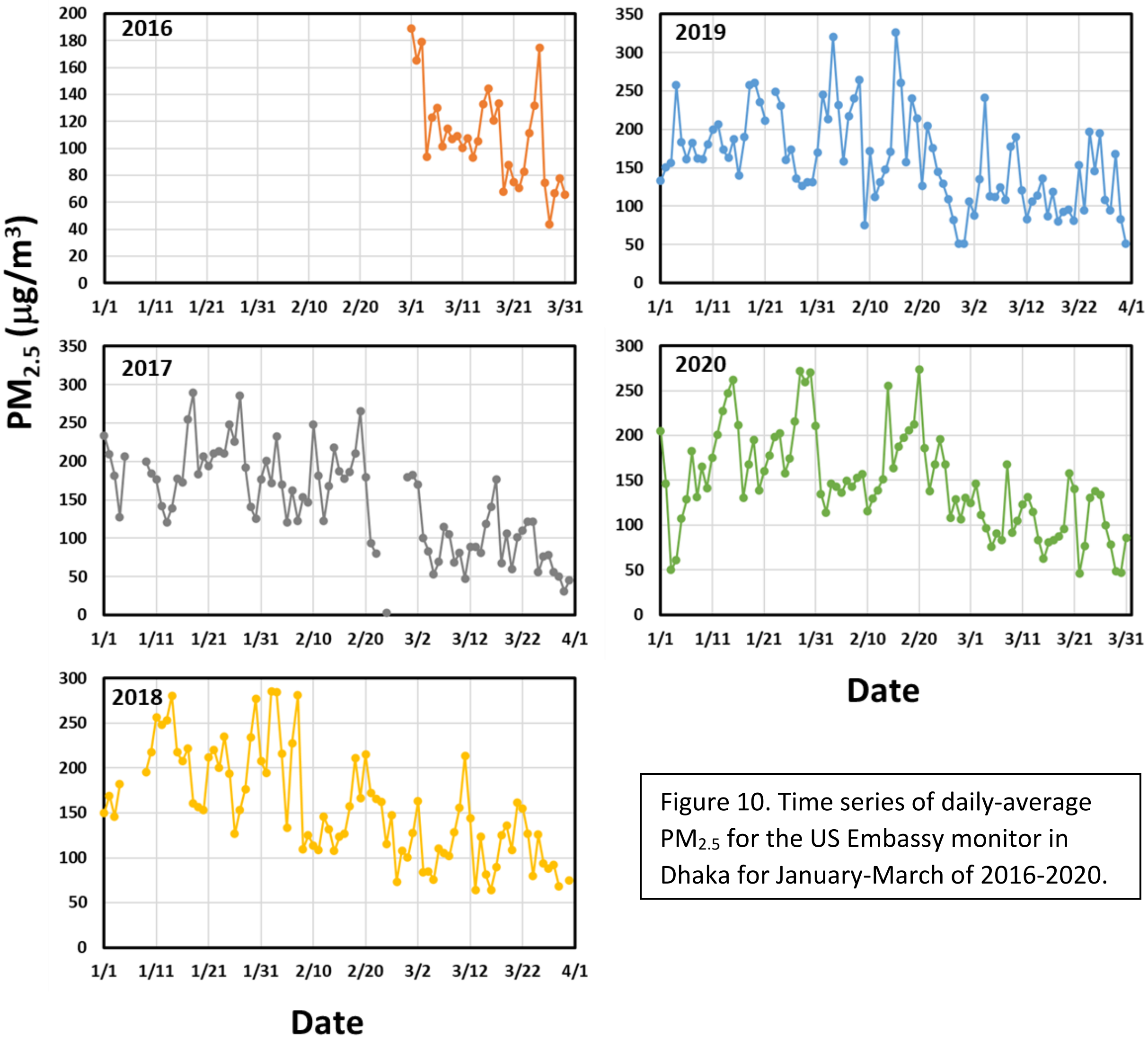

Figure 10. Time series of daily-average PM$_{2.5}$ for the US Embassy monitor in Dhaka for January-March of 2016-2020.

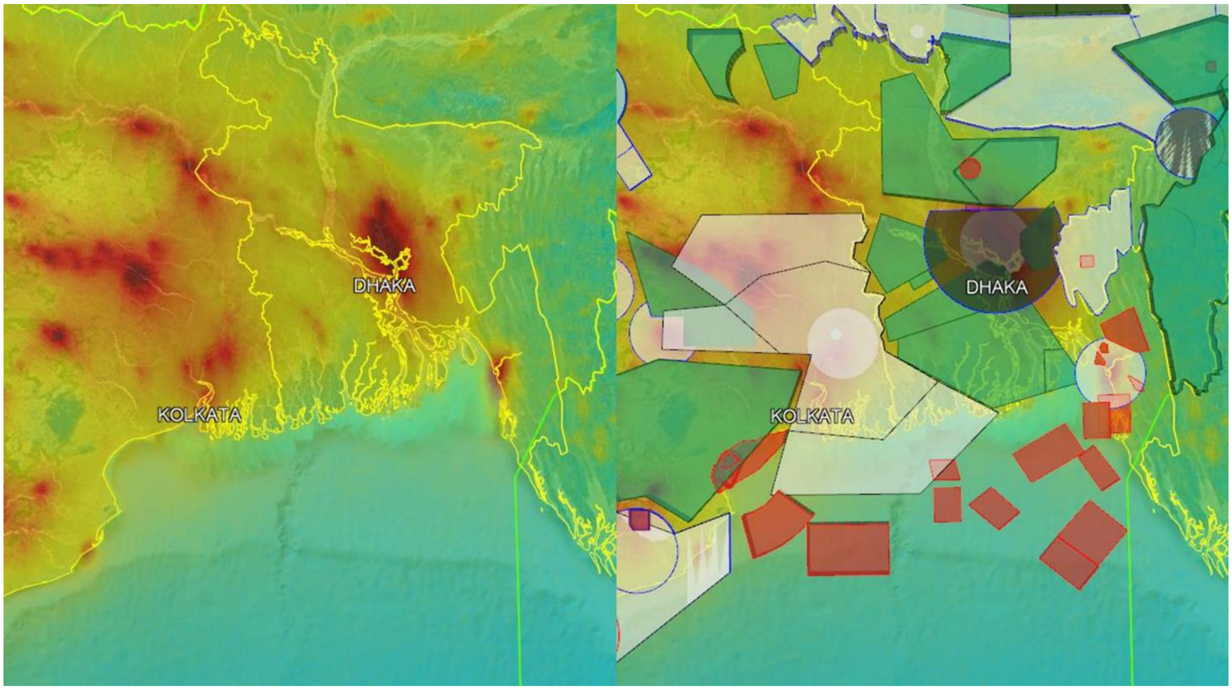

Figure 11. (left) Average distribution of $NO_2$ from TROPOMI over Dhaka and Kolkata. (right) same image as left overlaid by Special Use Airspace. Sampling of one or either city will require negotiation and active control by either military of civilian air traffic authorities. Airspace data obtained from https://3dairspace.org.uk/

### 7c. Ho Chi Minh City and Hanoi, Vietnam

**Primary contacts:** To Thi Hien (Vietnam National University Ho Chi Minh City); Ly Bich Thuy (Hanoi University of Science and Technology)

**Purpose:** Assess emissions and secondary pollutants during the peak PM season. The two locations are not close enough to sample as a pair, so it may be necessary to choose between the two. Hanoi has the larger satellite $NO_2$ signature (figure 13). It is expected that emissions from extensive agricultural burning will also play a large role in local air quality, with a large fraction of emissions from transboundary sources.

**Monitoring:** Information available online shows air quality monitoring by the Center for Environmental Monitoring (http://enviinfo.cem.gov.vn/) to be concentrated in Hanoi, with multi-pollutant monitoring at around a few dozen sites. Hanoi also hosts a SPARTAN and AERONET site. Ho Chi Minh City appears to have much less ground presence.

**Historical data:** The time series of the US Embassy monitor in Hanoi is shown in Figure 10 to provide some perspective on what might be expected for four science flights conducted over a 10-day period. Concentrations are highly variable, potentially due to daily variations in agricultural burning across Southeast Asia. The expected range of $PM_{2.5}$ values in Table 4 show that sampling of large gradients in $PM_{2.5}$ is essentially assured. Data are not shown for the less polluted Ho Chi Minh City (see figures 7 and 13).

**Table 4. 10-day expected $PM_{2.5}$ conditions for Hanoi**

| Probability | Max $PM_{2.5}$ | $PM_{2.5}$ range |
|---|---|---|
| 10% | >145 μg/m$^3$ | >127 μg/m$^3$ |
| 50% | >108 μg/m$^3$ | >75 μg/m$^3$ |
| 90% | >61 μg/m$^3$ | >42 μg/m$^3$ |

**Flight Challenges:** Airspace information shown in figure 13 may be incomplete, and the need for direct negotiation of flight paths for both aircraft is expected. The two cities are too far apart to effectively sample during the same flights, so priorities will need to be discussed if only one city is possible. Based on TROPOMI NO2 (figure 13), Hanoi appears to be of higher priority.

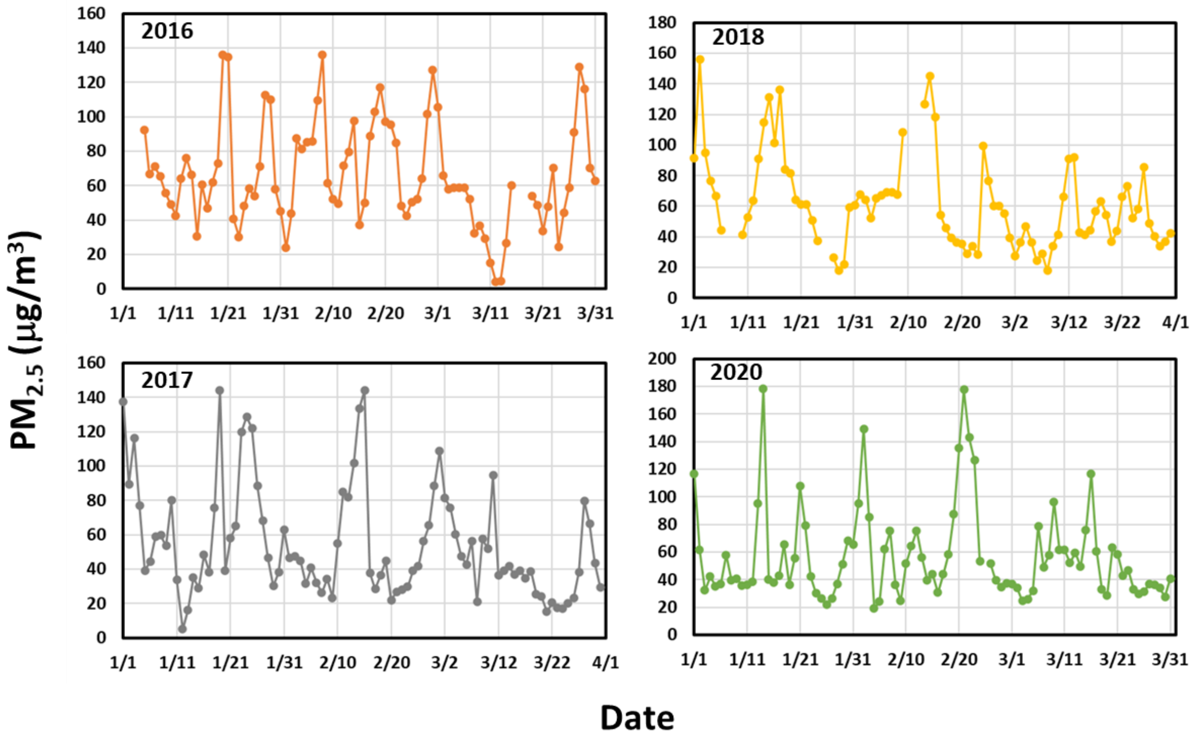

Figure 12. Time series of daily-average $PM_{2.5}$ for the US Embassy monitor in Hanoi for January-March of 2016-2018 and 2020.

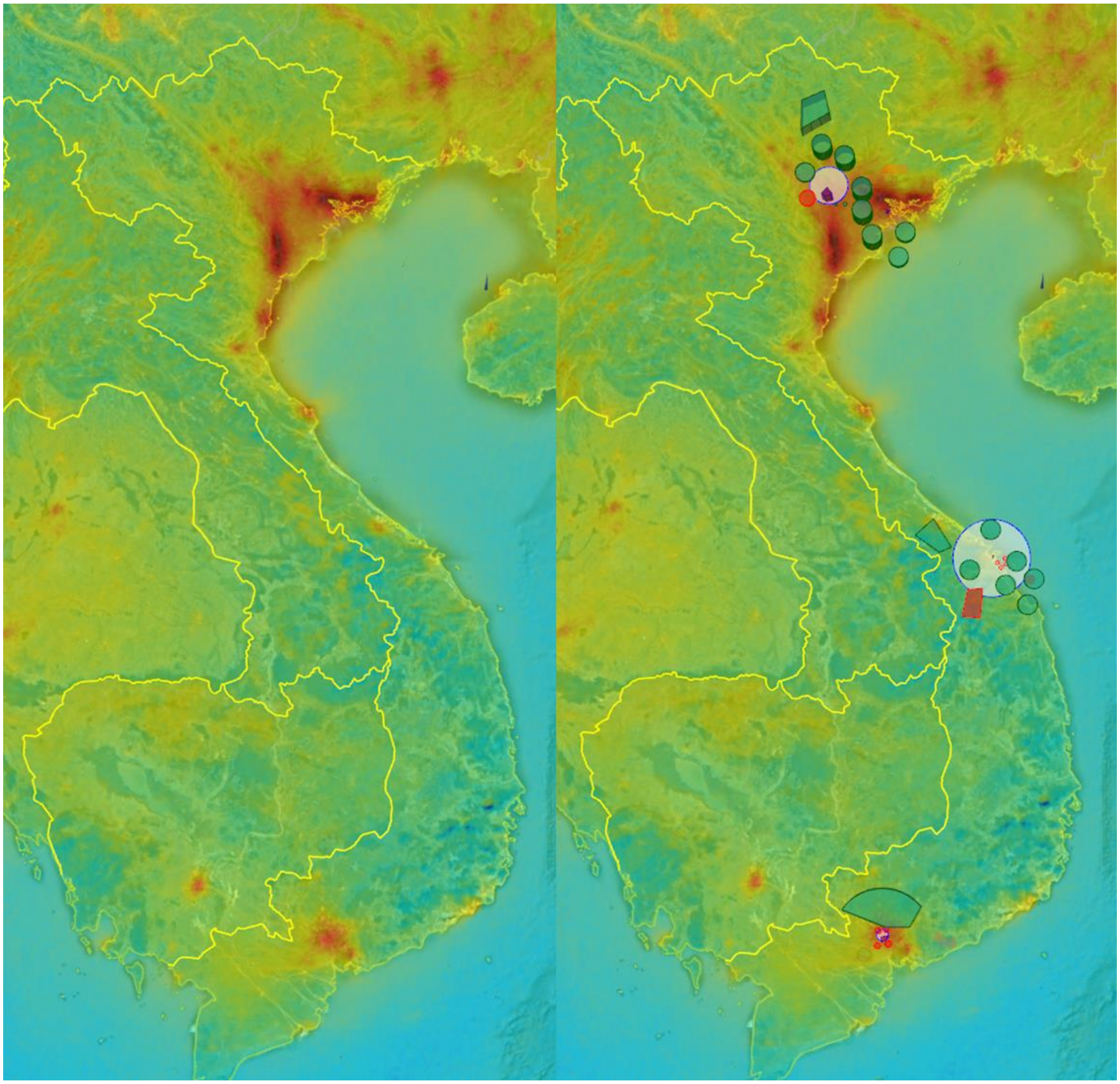

Figure 13. (left) Average distribution of $NO_2$ from TROPOMI over Vietnam showing strong emissions over Hanoi in the north and over a smaller region associated with Ho Chi Minh City in the south. (right) same image as left overlaid by Special Use Airspace (note: airspace information may be incomplete). Sampling of one or either city will require negotiation and active control by either military of civilian air traffic authorities. Airspace data obtained from [https://3dairspace.org.uk/](https://3dairspace.org.uk/)

## 7d. Bangkok, Thailand

**Primary contacts:** Narisara Thongboonchoo (King Mongkut's University); Ronald Macatangay and Vanisa Surapipith (NARIT); Kim Oanh (AIT)

**Purpose:** Assess emissions and secondary pollutants during the peak PM season. The agricultural burning season will also play an important role. Sampling the countryside to the north between Chiang Mai and Bangkok as well as the city will provide an important contrast between urban and biomass burning emissions and their mixtures. Sampling in Thailand will provide the best opportunity for direct sampling of smoke emissions.

**Monitoring:** The Thai Pollution Control Department (http://aqmthai.com/web/main.php) maintains an extensive monitoring program with 89 sites (24 in Bangkok) that includes many sites with PM, $O_3$, and precursor measurements. There also appears to be an extensive small sensor network for PM across the country administered by the Chiang Mai University CCDC. Pandora spectrometers are planned for Bangkok, NARIT, and southern Thailand as part of the Pandora Asia Network. AERONET sites have monitored for years in Thailand and includes an ongoing four site DRAGON in Chiang Mai with one MPLNET.

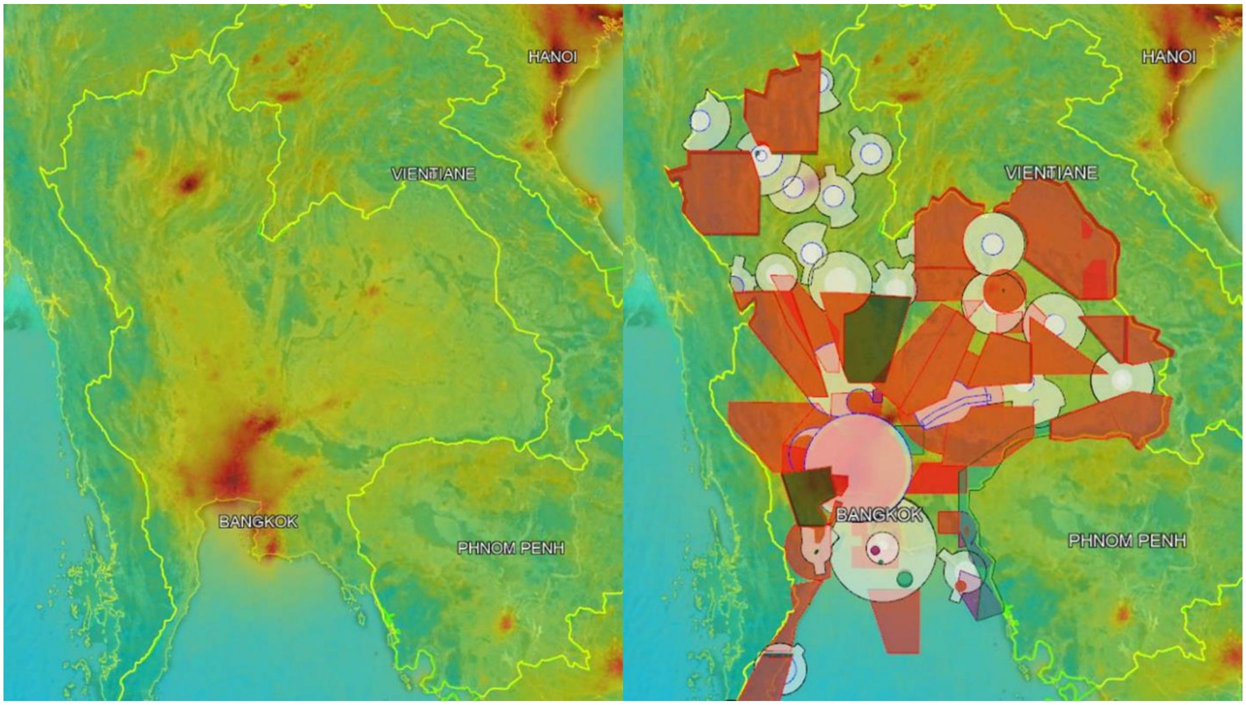

Figure 14. (left) Average distribution of $NO_2$ from TROPOMI over northern Thailand; (right) same image as left overlaid by Special Use Airspace. Sampling will require negotiation and active control by either military of civilian air traffic authorities. Airspace data obtained from https://3dairspace.org.uk/

### 7e. Kuala Lumpur, Malaysia and Singapore

**Primary contacts:** Mohd Talib Latif (UKM); Liya Yu (National University of Singapore)

**Purpose:** Situated much further south, these two cities offer an opportunity to sample isolated urban emissions. Sampling will avoid the smoke season associated with burning in Indonesia that peaks in July-October. Both cities are affected by the densest shipping lane in the world (see coastal $NO_2$ in Figure 15).

**Monitoring:** The Malaysian Department of Environment maintains a network of 68 monitoring stations and publishes and Air Pollutant Index (API), but specific data is not publicly available (http://apims.doe.gov.my/public_v2/home.html). Similarly, Singapore's National Environmental Agency provides online data for six monitoring sites (https://www.haze.gov.sg/resources/pollutant-concentrations).

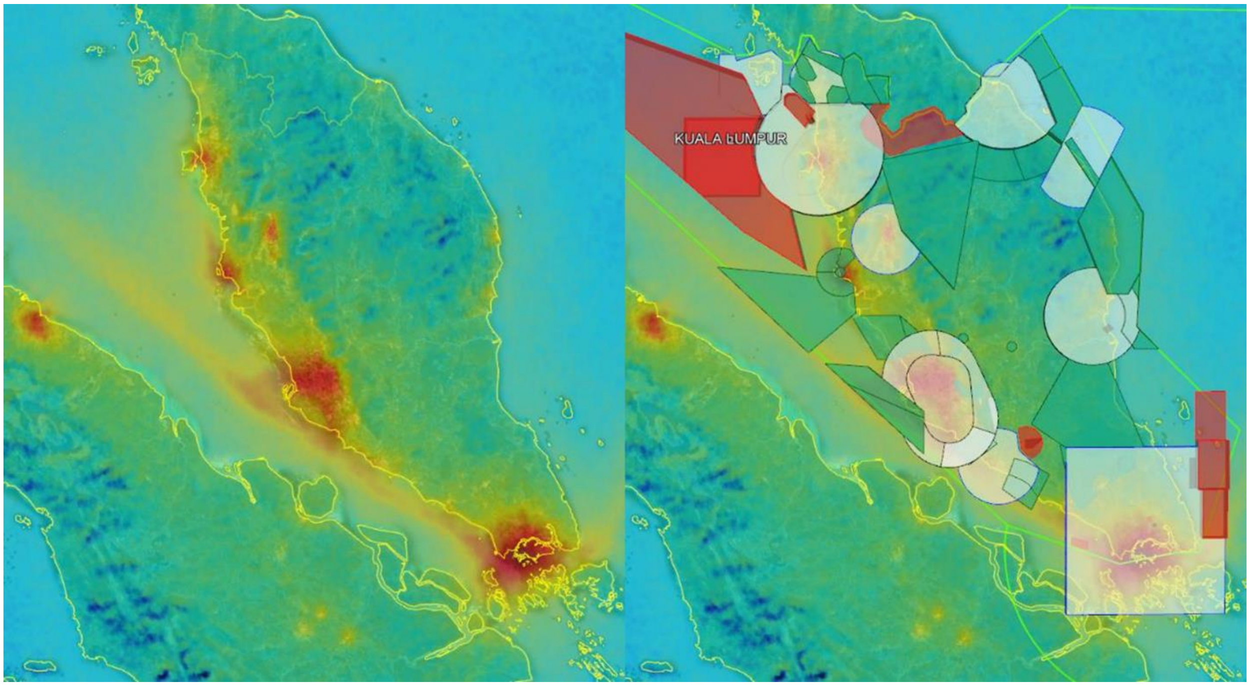

Figure 15. (left) Average distribution of $NO_2$ from TROPOMI over Malaysia and Singapore. (right) same image as left overlaid by Special Use Airspace. Sampling of both countries will require negotiation and active control by either military of civilian air traffic authorities. Airspace data obtained from https://3dairspace.org.uk/

### 7f. Manila, Philippines

**Primary contact:** James Simpas and Maria Obiminda Cambaliza (Manila University)

**Purpose:** Examine local conditions in Manila during the time of peak influence of Asian continental outflow on the South China Sea and the Philippines.

**Monitoring:** The Philippine Environment Management Bureau (http://air.emb.gov.ph/) maintains a network of monitors for PM and $O_3$. An AERONET site has monitored in Manila for more than 10 years.

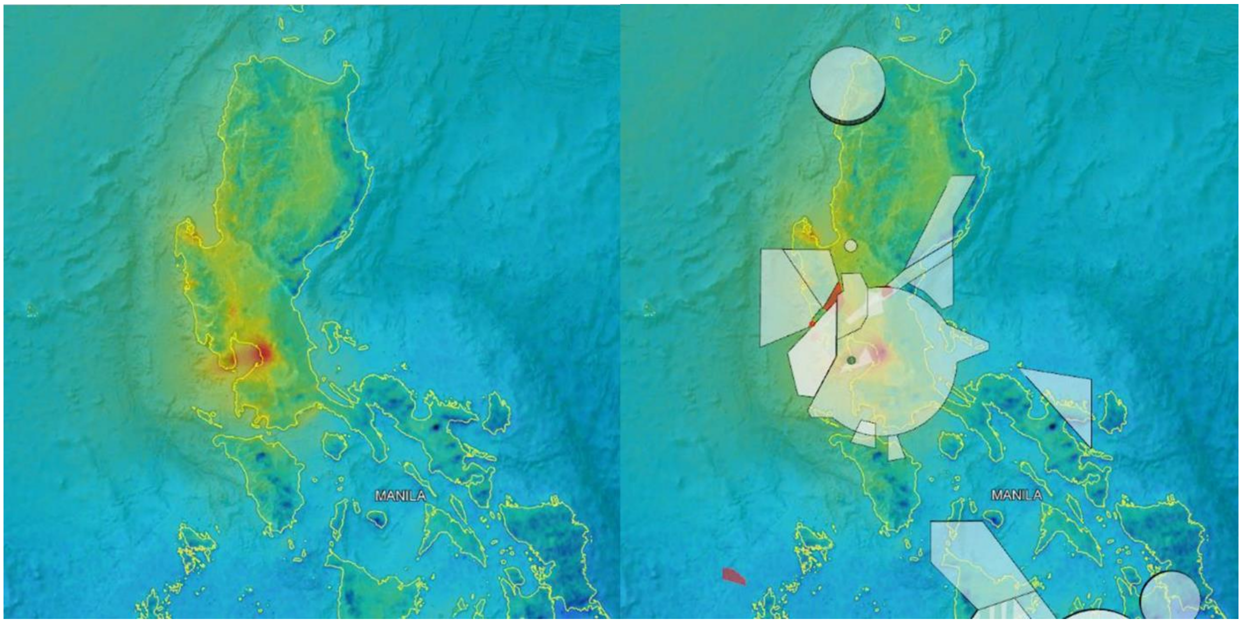

Figure 16. (left) Average distribution of $NO_2$ from TROPOMI over northern Philippines; (right) same image as left overlaid by Special Use Airspace. Sampling will require negotiation and active control by either military of civilian air traffic authorities. Airspace data obtained from https://3dairspace.org.uk/

### 7g. Tokyo, Japan

**Primary contacts:** NIES and GOSAT-GW science leads (Hiroshi Tanimoto, Yugo Kanaya, et al.)

**Purpose:** Obtain vertical structures of $NO_2$, HCHO, $O_3$, and other species to support satellite validation and interpretation under a variety of cloud and aerosol conditions. Assess emissions of NOx and other pollutants and help fine-scale mapping of pollutant distributions. Collect observations during the season of peak influence of Asian continental outflow to the western Pacific.

**Monitoring:** The Japan's Ministry of Environment air quality monitoring network provides valuable information on PM, $O_3$, and precursors with dense coverage (more than 1000 stations). There are also several MAX-DOAS sites, 18 AERONET sites, and multiple NIES sites. Eight Pandora sites will be set up soon.

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