NASA Contributions to KORUS-AQ: An International Cooperative Air Quality Field Study in Korea

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Introduction

Air Quality is an environmental concern of fundamental importance across the globe. The need to monitor and understand air quality requires continual effort as populations grow, energy use increases, and industrial activity evolves. Air quality goals have also evolved as improved understanding of health effects has demonstrated the added benefit of setting lower targets for exposure of humans and ecosystems to ozone, fine particles, and other toxic pollutants in the air. Long-term efforts have relied primarily on ground-based observations to diagnose regions of poor air quality and modeling to develop mitigation strategies. In recent years, satellites in low Earth orbit (LEO) have demonstrated the ability to observe the critical constituents affecting air quality. However, the impact of LEO observations has been limited by their infrequent nature and coarse resolution with respect to source distributions and timing (approximately once per day at horizontal scales of tens of km), insufficient to observe the details of air quality events that can develop over timescales of a single day. The promise of geostationary (GEO) observations as a vantage point for studying air quality can overcome these problems by providing observations many times throughout the day and at higher spatial resolution by taking advantage of longer viewing times. The drawback of GEO is the limited viewing domain, preventing global observations with a single satellite. This has led to an international effort to launch a constellation of satellite instruments focused on air quality over Asia, North America, and Europe. These instruments will provide hourly observations of those regions throughout the day at horizontal resolutions of better than 10 km. The funded GEO atmospheric chemistry instruments expected to launch in 2018-2019 include GEMS by the Republic of Korea, TEMPO by the US, and Sentinel-4 by Europe (Figure 1). Also, with its planned launch in 2016 the Sentinel-5 Precursor (S5P) mission will begin providing the next generation of once-daily global measurements from LEO at horizontal resolution similar to the GEO missions.

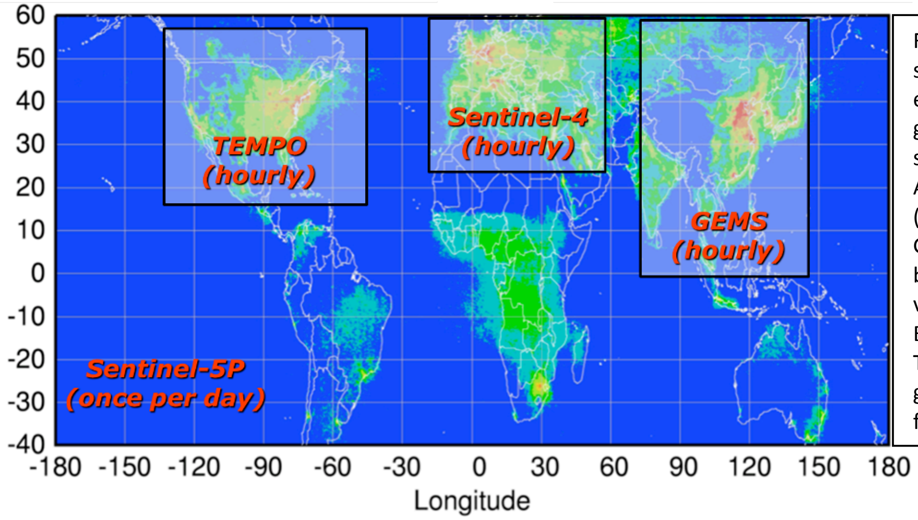

Figure 1. Global air quality satellite constellation showing expected fields of view for hourly geostationary observations from satellites positioned over North America (NASA-TEMPO), Europe (ESA-Sentinel-4), and Asia (KARI-GEMS). These observations will be supplemented by daily global views from TROPOMI onboard ESA's LEO satellite, Sentinel-5P. The background image is the global distribution of NO_2 as seen from space

These satellites will not be working in isolation. They will be part of a larger observing system, connecting with ground-based in-situ monitoring and remote sensing to more broadly capture and understand the local, regional, and hemispheric influences of emissions, chemistry, and transport. Preparation is critical to ensure that the international air quality community is ready to capitalize on the information available from these satellites to improve air quality forecasts, models, and strategies for mitigating poor air quality. Recent efforts are already beginning to show that carefully designed intensive field studies allow correspondence between remotely-sensed columns and in-situ concentrations to be built. Examples include DISCOVER-AQ campaigns in the US, DRAGON campaigns in Korea and the US, and ClearfLo and CINDI in Europe. These efforts are providing the information needed to define an optimum set of ground-based measurements to complement and exploit future satellite observations from GEO.

KORUS-AQ offers the opportunity to further advance NASA goals and those of its international partners related to air quality through a targeted field study focused on the South Korean peninsula and surrounding waters. The study, tentatively planned for the April-June 2016 timeframe would integrate observations from aircraft, ground sites, and satellites with air quality models to understand the factors controlling air quality across urban, rural, and coastal interfaces. The details outlined in this document address the rationale for such a study, its relevance to NASA, the detailed scientific questions to be addressed, and the assets and sampling strategies required to answer them. A companion document under development by Korean colleagues provides details on observational and theoretical activities that would be concurrent and collaborative with the NASA plans described in this white paper. Further effort by both the US and Korean Steering Committees will be necessary to ensure that these two efforts are harmonized to provide the best scientific value for the investments by both countries. KORUS-AQ serves as a model for international collaboration as Korean and U.S. scientists would cooperate on all aspects of air quality research. This would build relationships and strengthen future collaboration critical to the success of the constellation of geostationary air quality satellites to be launched by NASA, KARI, and ESA later this decade.

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Scientific Rationale

The advantages of conducting an air quality field study in Korea are related to the distribution of emissions within the country and its position along the Asian Pacific Rim. The Korean science community also offers good opportunities for collaborative research with strengths in air quality monitoring, ground-based measurements, geostationary satellite observations, and modeling. The following discussion expands on these unique advantages, outlining the benefits that in situ and remote sensing observations coordinated between airborne and ground-based perspectives would bring to scientific understanding and the design of future air quality observing systems.

Korea's urban/rural sectors are distinct, providing an attractive setting for understanding the relative importance of human and natural emissions.

Roughly half of Korea's population (~50 million) is located in the Seoul Capital Area (Sudogwon), which comprises only 12% of the country's area (see Figure 2). Some sources rank this metropolitan area as second largest in the world. While there are a number of other urban areas, there remains a strong segregation between urban and rural zones. From an air quality perspective, these zones each have unique emissions and considerations regarding exposure impacts for humans, agriculture, and ecosystems. Urban areas are expected to dominate overall emissions of nitrogen oxides (NO_x) which are mainly associated with burning of fossil fuels. In rural zones, forests and agriculture constitute a dominant source of hydrocarbons. The combination of emissions from these two regimes is expected to be more potent than either alone. Thus, assessing mixing across the urban/rural interfaces existing in Korea offers the potential to more completely explore the range of conditions affecting ozone production as anthropogenic NO_x and biogenic hydrocarbons interact.

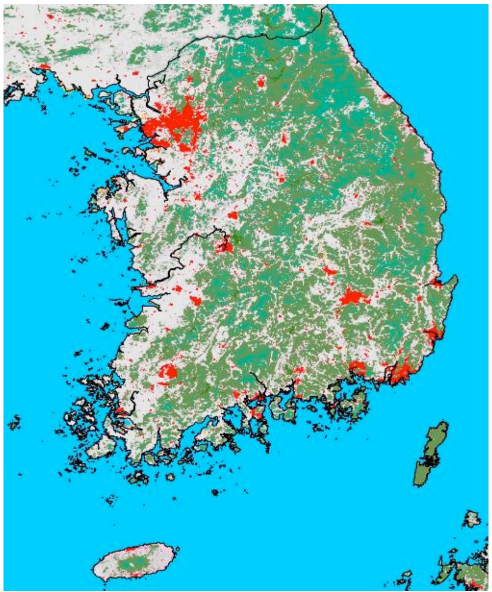

Figure 2. MODIS land cover map of South Korea. Red colors denote urban and built-up areas, greens are forests, and gray indicates croplands (courtesy Christine Wiedinmyer).

The relative importance of NO_x and hydrocarbons for controlling ambient ozone is often represented via ozone isopleth diagrams (see Figure 3). Such diagrams, however, depend on accurately modeling the specific photochemical environment. For instance, the mix of hydrocarbons and their reactivity are expected to change as emissions move from urban to rural settings, thus influencing the relative response of ozone to changes in NO_x and hydrocarbons. In terms of strategies for mitigating high ozone, it is also critical to identify the contributions of anthropogenic versus natural emissions and the resulting range of combinations for NO_x and VOC reactivity across the Korean peninsula.

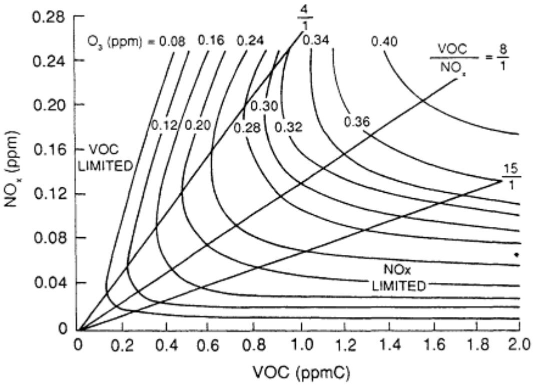

Figure 3. Typical ozone isopleth diagram showing the nonlinear response of ozone production to mixtures of NO_x and hydrocarbons. (Taken from National Research Council, 2008)

The interaction between urban and rural emissions is also important for aerosol formation and evolution. As air moves from the urban sector into rural areas, the oxidation of highly reactive biogenic VOCs in the presence of anthropogenic NO_x is expected to shift the partitioning of reactive nitrogen reservoirs and enhance the formation of secondary organic aerosol. Being able to observe rural areas under a range of urban influence offers insight into the relative importance of urban and rural aerosol formation, the influence of urban outflow on the amount of secondary organic aerosol, and the influence of rural emissions on the evolution of aerosol composition, hygroscopicity, and optical properties.

Korea is embedded in a region of rapid change with strong gradients in air quality in time and space.

Over the last several decades, East Asia has been a region of dramatic economic growth and increased energy consumption. Along with this prosperity, pollutant emissions have likewise increased. This increase in emissions has been demonstrated through traditional accounting methods based on activity data as well as through observations from satellites (see Figure 4). The more recent trends observed by satellite have been corroborated by updates of the REAS inventory [Kurokawa et al., 2013].

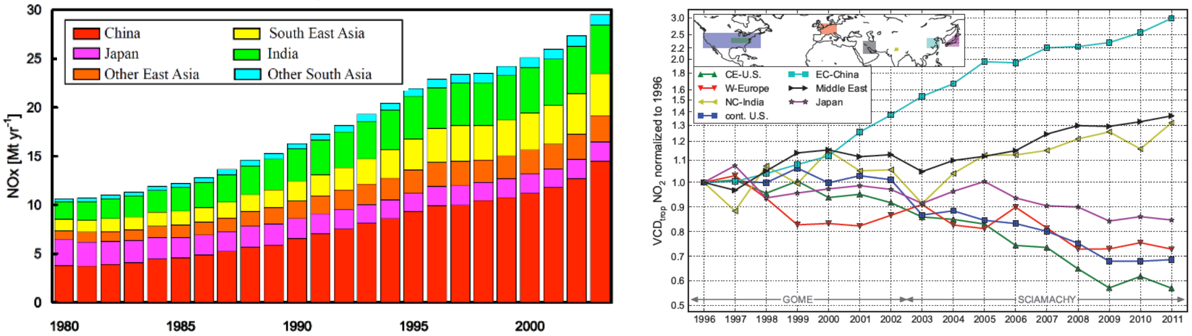

Figure 4. Left: Asian NO_2 emissions from 1980-2003 based on activity data (taken from Ohara et al., 2007) Right: Mean annual tropospheric NO_2 column densities detected by the GOME and SCIAMACHY satellites over key regions in the northern hemisphere. Abundances are normalized to 1996 to assess relative changes over the period 1996-2011. (taken from Hillbol et al., 2013)

As shown above, the most dramatic growth has been upwind of Korea on mainland China. Korea's location downwind results in strong gradients in air quality that are driven by meteorology as well as the patchwork of emissions. To a large degree, anthropogenic emissions follow population and the large number of megacities in East Asia creates discrete regions of enhanced emissions. This is most easily seen in satellite observations of NO_2, which is too short-lived to undergo significant transport by winds (see Figure 5).

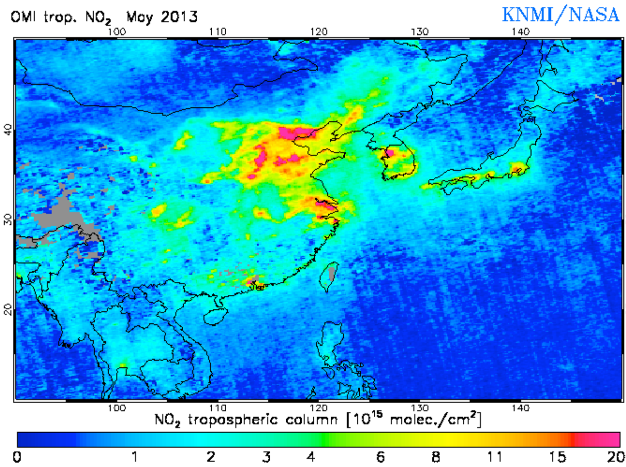

Figure 5. Patterns in the distribution of tropospheric NO_2 correspond closely to large population centers. (taken from http://www.temis.nl/airpollution/no2.html)

The Korean peninsula is also impacted seasonally by the long range transport of wind-blown dust and smoke from fires. These discrete emissions may subsequently either remain distinct or become intermingled as they are transported in the atmosphere. While satellite observations of NO_2 are ideal for locating regions of anthropogenic emissions and their rate of growth, understanding the downwind impacts of emissions requires in situ sampling to assess the complex mixtures of reactive nitrogen, volatile organic species, particulate matter, and photochemically produced ozone.

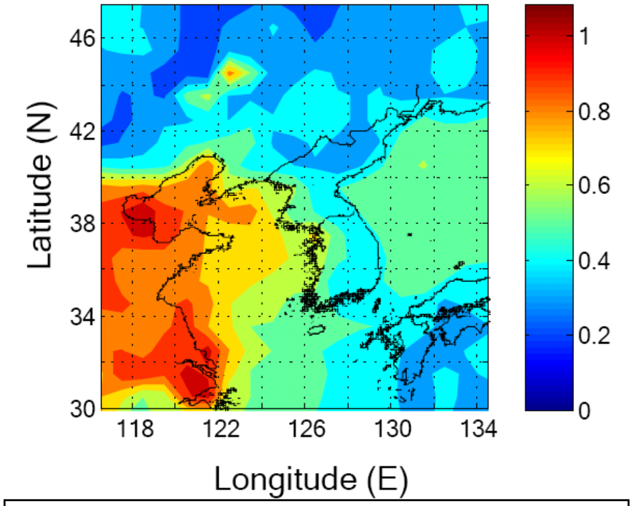

Figure 6. MODIS AOD in spring (2001-2008) (Kim et al., 2010).

An example of this transport can be seen in the average MODIS aerosol optical depth (AOD) during spring over the period 2001-2008 (see Figure 6). This climatological average shows a strong gradient in the West Sea between China and South Korea. This average gradient indicates transport of particulate pollution, smoke, and dust from China, which for particular events can lead to extreme pollution events in South Korea. In fact, several very large dust outbreaks, mingled with urban/industrial emissions, were sampled over the West Sea during the TRACE-P and ACE-Asia campaigns in 2001. The figure also shows a noticeable discontinuity in retrieved AOD along the east coast of Korea that is likely an artifact of the separate algorithms for MODIS retrievals over land and water. While this effect is not as obvious over the west coast, land/water effects on retrievals are important to understand for both AOD and trace gas retrievals.

The Korean peninsula and surrounding waters provide an advantageous experimental setting for distinguishing local and trans-boundary pollution.

The West (Yellow) Sea presents an important buffer by providing some distance between upwind and local sources, notwithstanding the busy shipping lanes. Thus, under the right meteorological conditions, sampling just off the western coast of Korea offers an opportunity to obtain an unambiguous sample of inflow of pollution, smoke, dust, and sea salt in varied mixtures for comparison with observations over the peninsula. Even over small distances from upwind sources, significant chemical evolution is expected for reactive nitrogen species and other short-lived constituents. Emissions are also likely to be vertically stratified due to differences in the locations of sources. For instance, springtime dust sources (particularly from the Taklimakan desert) originate from higher elevations than urban emissions [Sun et al., 2001], and depending on its transport, dust may be encountered in an isolated layer or mixed with urban pollution. During ACE-Asia [Arimoto et al., 2006] it was generally found that aerosol properties were altitude dependent as mixing between dust and pollution varied, with dust influences reaching higher altitudes than pollution influences. Springtime can also bring biomass burning emissions from wildfires in Siberia and agricultural burning across East and Southeast Asia. The altitude range over which the emissions are transported depends on frontal lifting. This synoptic-scale process leads to broad influence from upwind sources across the Korean peninsula that is episodic, allowing for the opportunity to sample conditions under strong and weak influences from transboundary pollution. Frontal lifting and transport also complicate satellite viewing due to extensive cloud cover. The altitude of transport is also of great interest. Near-surface transport of emissions allows for contact with the sea surface, raising the potential importance of air-sea interactions. Pollution, smoke, or dust transported at higher altitudes may leave the surface unaffected or may be mixed downward to the surface under the right conditions. The opportunity to sample air under different transport patterns is emphasized by the figures below. Climatological winds (left panels) averaged for the month of May over the period 2008-2013 emphasize the dominant influence of westerly flow across East Asia and the expected influence of upwind emissions across the Korean peninsula. An example of specific air mass trajectories (Yum et al., 2007; right panels) emphasizes the diversity of actual transport patterns from day to day and the opportunity to make observations of the various upwind influences.

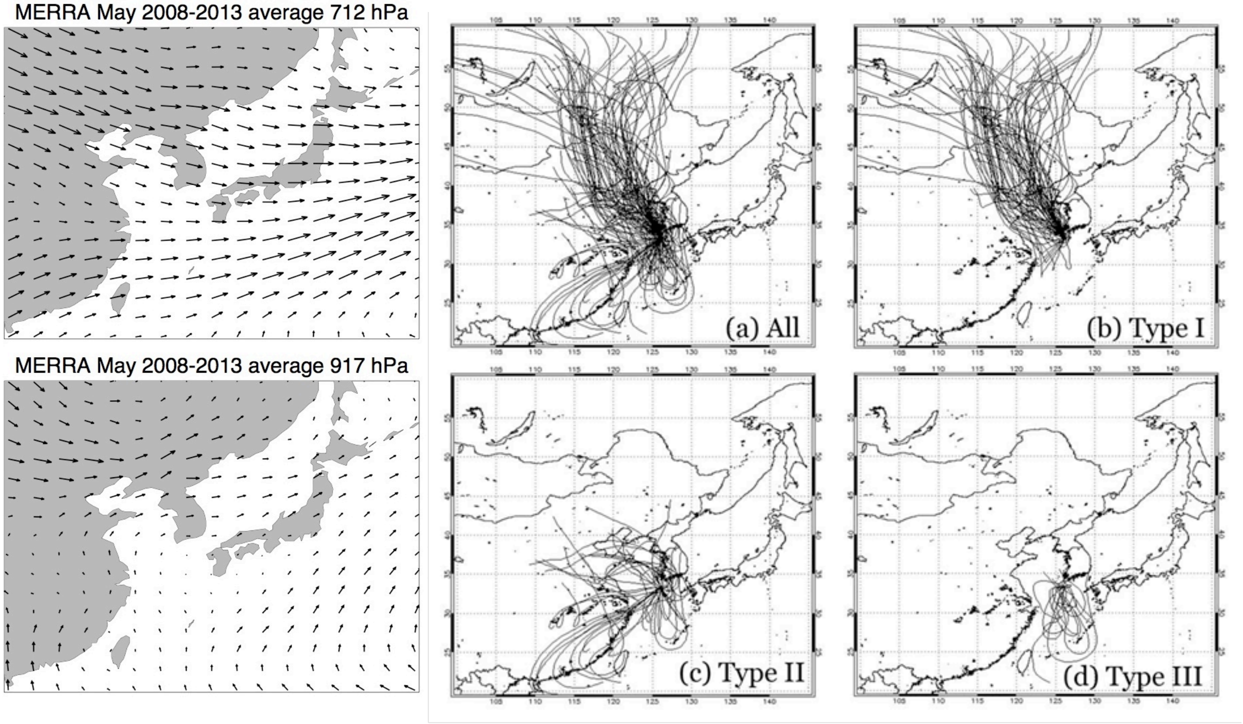

Figure 7. Left panels: Climatological winds from the MERRA reanalysis (courtesy of Louisa Emmons) Right panels: 3-day back trajectories from Gosan during 11 March - 8 April 2005 [Yum et al., 2007]. Trajectores are separated into three types: Type I – continental China, Type II – coastal China and Korea, and Type III - marine

Korea provides a collaborative environment with strengths in air quality monitoring and ground-based measurements, geostationary satellite observations, and modeling.

Progress in understanding atmospheric composition and chemistry requires an observation strategy taking advantage of satellites, research aircraft, and ground measurements coupled to modeling at local, regional, and global scales. Each of these perspectives has strengths and limitations as outlined by the schematic in Figure 8. For satellites, improved interpretation relies on complementary observations from aircraft and ground sites. For models, observations from all perspectives are useful for model evaluation and assimilation to enable representation of the current atmospheric state and prediction of possible future changes. In turn, satellites and models can be used to direct research aircraft to areas of interest or optimize the placement of ground measurements. This section describes existing capabilities that Korean partners propose to bring to this activity. Concurrent with this document, the Korean science community is actively proposing for support to participate in the field intensive and subsequent analysis of observations in collaboration with U.S. partners.

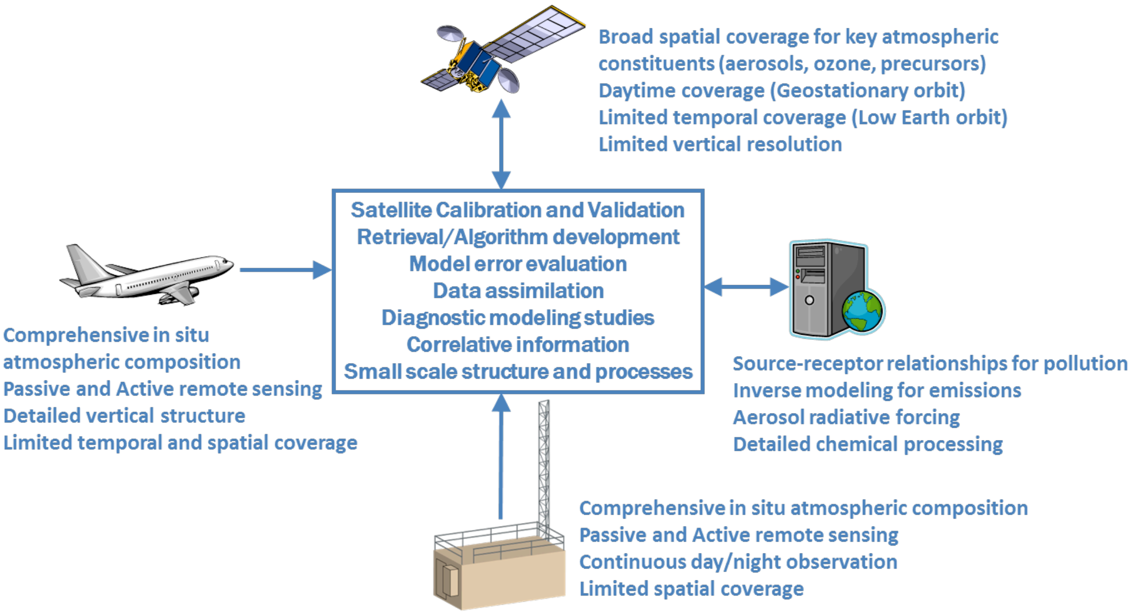

Figure 8. Observing system framework applied to atmospheric composition observations and modeling.

Korea is already operating the world's first GEO instrument for measuring ocean color and atmospheric aerosol. Within a domain around the Korean peninsula, the GOCI instrument provides hourly aerosol optical depth measurements using information from multiple wavelength bands. The data from GOCI present a unique opportunity for end-to-end demonstration and refinement of the cal/val campaign techniques that will be required for full use of the data from the forthcoming GEO atmospheric chemistry missions. Korea also offers the potential for strong gradients in both aerosol optical depth and ozone precursors (especially NO_2) for which remote sensing algorithms can be tested and improved in advance of the launches of GEMS, TEMPO, and Sentinel-4. For example, the over-ocean GOCI aerosol retrievals in the Kyonggi Bay off of Seoul are derived in the presence of significant water turbidity, so significant in fact that the MODIS operational aerosol algorithm does not routinely provide retrievals there. Only an airborne campaign that can evaluate the over-ocean aerosol retrievals and the aerosol evolution across the land-sea boundary can contribute meaningfully to the evaluation of aerosol retrievals relevant to air quality assessments in Seoul.

Korea also maintains an extensive ground-based air quality monitoring network of over 300 sites (http://www.airkorea.or.kr/airkorea/eng/index.jsp) (see Figure 9). Each of these sites provides continuous monitoring of PM_{10}, O_3, NO_2, SO_2, CO, and Met (T, RH, winds). Just under half of the sites are located in the Seoul Capital Area. While just over eighty percent of the sites are characterized as urban, there are also thirty-eight roadside sites, nineteen rural sites, and three background sites in the network. Additional information on VOCs is available at 31 sites.

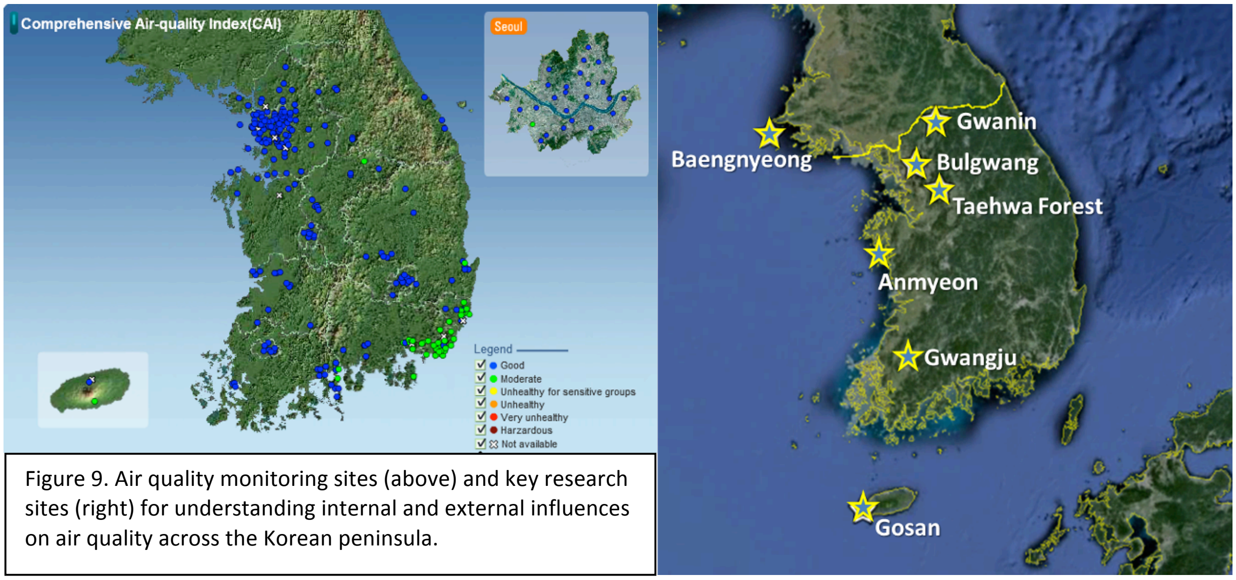

Figure 9. Air quality monitoring sites (above) and key research sites (right) for understanding internal and external influences on air quality across the Korean peninsula.

Major research sites are also shown in Figure 9 (right panel). These sites are situated to allow characterization of local sources in Seoul (Bulgwang), photochemical evolution downwind of Seoul (Taehwa and Gwanin), and upwind conditions along the peninsula ranging from continental outflow to marine background air masses (Baengnyeong, Anmyeon, Gwangju, and Gosan). Of these sites, the three northernmost are in areas where overflight is prohibited, but still provide important context regarding emissions internal and external to Seoul. Information on conditions aloft along the western coast is provided by aerosol lidars and aeronet sunphotometers at the four westernmost sites. Anmyeon also hosts a TCCON FTS.

Modeling activities in Korea include both research and operational efforts. Models in use by the Korean community include fine-resolution regional CTMs (CMAQ and WRF-Chem) and a global CTM (GEOS-Chem). Routine air quality forecasting for ozone and PM by NIER is anticipated to be fully operational by the start of 2015. The addition of observations from GEMS is expected to help improve the forecasts. However to maximize the impact on the forecasts, further efforts are needed to improve the retrievals. Airborne observations for validation and testing of this forecasting system could provide valuable constraints on emissions as well as chemical and dynamical processes.

In all of the abovementioned areas, opportunities exist for NASA-sponsored collaboration alongside Korean partners. However, it is in the area of airborne observations that NASA has the greatest potential for impact. Korea has a fledgling airborne science program that includes two small research aircraft. The Hanseo University King Air has already been used for atmospheric composition measurements and is outfitted with an isokinetic inlet installed in the roof of the aircraft for conducting aerosol measurements. By the end of 2015, the Korea Meteorological Administration (KMA) will acquire an instrumented research aircraft (King Air 350 HW, 13-passenger plane). Deploying a NASA research platform such as the DC-8 would provide unprecedented information on atmospheric composition over Korea, and providing space onboard for Korean colleagues to conduct their own measurements or participate as collaborators with NASA instrument teams would enhance the development of the Korean airborne science community.

More specific requirements for a successful field study and desirable enhancements should funding be available are described in more detail in the section of this document discussing experimental design.

Scientific Questions

A well-designed field study integrating information from the elements described above (i.e., satellites, aircraft, ground sites, and models) can lead to progress in our understanding of satellite performance, fundamental understanding of atmospheric composition, and improvement of models in the simulation of the current atmospheric state and possible future scenarios. The following science questions provide a framework for elaborating on these areas and are discussed individually in the following section.

Question 1. What are the challenges and opportunities for satellite observations of air quality?
  Question 1a. How do synoptic conditions (outflow, convection, stagnation, etc.) affect the vertical distribution of trace gases and aerosols?
  Question 1b. How do pollutant distributions relate to cloud cover?
  Question 1c. How does aerosol abundance and vertical distribution influence trace gas retrievals?
  Question 1d. How does the land/water boundary influence aerosol retrievals?

Question 2. What are the most important factors governing ozone photochemistry and aerosol evolution?
  Question 2a. How does ozone photochemistry respond to the various mixtures of upwind versus local pollutant emissions, biogenic emissions, and marine emissions?
  Question 2b. What do aerosol physical, optical, and chemical properties reveal about the interaction between ozone photochemistry and secondary aerosol formation?

Question 3. How do models perform and what improvements are needed to better represent atmospheric composition over Korea and its connection to the larger global atmosphere?
  Question 3a. Are modeled gradients across the Korean peninsula consistent with local/upwind sources, transport, and chemistry?
  Question 3b. Are air quality and atmospheric chemistry forecasting systems prepared to utilize GEO observations?

Question 1. What are the challenges and opportunities for satellite observations of air quality?

The applications potential for geostationary satellite observations of air quality raises the bar on readiness to exploit the data as soon as possible after launch. Detailed observations of atmospheric trace gas and aerosol distributions under a wide range of conditions from polluted to clean provide valuable information to inform retrieval studies. This information also helps define the best mix of ground-based observations to complement satellite observations and improve interpretation. Some of this important work is already being accomplished through campaigns such as DISCOVER-AQ, which is showing that there are common factors affecting satellite observations of air quality as well as factors that are location dependent. The following questions and discussion emphasize the unique factors associated with Korea and the observational strategies needed to improve the geostationary constellation of air quality satellites.

Question 1a. How do synoptic conditions (outflow, convection, stagnation, etc.) affect the vertical distribution of trace gases and aerosols?

Vertical distributions of trace gases and aerosols depend heavily on synoptic conditions and associated impacts on chemistry and transport of emissions. Stagnant conditions will favor trapping of emissions near the surface, while outflow conditions along the Pacific Rim can introduce strong perturbations in the middle troposphere for both aerosols and trace gases. Local convection will act to smooth profiles for most passive constituents, while upwind convection could lead to enhanced concentrations in the upper atmosphere affecting satellite observations of ozone, NO_2, and HCHO. Capturing these impacts on the vertical structure of atmospheric composition would be best accomplished through survey flights covering the same locations under a variety of synoptic conditions.

Satellite observations of column concentrations of trace gases have been extremely successful in detecting changes in anthropogenic emissions and even useful as top-down constraints to update bottom-up emission inventories with inverse modeling techniques. The retrieved vertical column concentrations, however, are very sensitive to the air mass factor (AMF), which is used to convert slant columns into vertical columns (see discussion under Question 1c for more detail). Specification of the AMF depends on the assumed vertical profile of a retrieved species, which is often obtained from CTMs. Thus, the validation of modeled vertical profiles of species is critical for the success of satellite observations. Information for such validation is sparse. The profile validation is particularly important for geostationary satellites measuring diurnal variation of atmospheric composition. This also raises the requirement for *a priori* information of species profiles with hourly resolution. The validation of these *a priori* profiles would be an important contribution that could be provided by this field study.

Recent comparisons of modeled and measured aerosol extinction profiles during recent NASA and DOE field missions over the U.S. have revealed systematic differences in aerosol distributions. For example, during the CARES and CalNex missions over California during 2010, profile comparisons revealed systematic model overpredictions of aerosol extinction in the free troposphere and underpredictions in the boundary layer [Fast et al., 2014]. The overprediction bias in the free troposphere was found to somewhat offset the underprediction of boundary layer aerosols, reducing differences between the measured and modeled aerosol optical depths [Fast et al., 2014]. These comparisons demonstrate the importance of assessing model representations of aerosol profiles in the free troposphere as well as in the boundary layer in order to evaluate *a priori* assumptions derived from regional scale AOD simulations

Spaceborne observations of near-surface aerosols are additionally challenged by several factors unique to the region. The wide variety of aerosol species including dust, black carbon, and inorganic and organic compounds mixed in various sizes, as observed during TRACE-P and

ACE-Asia [Clarke et al., 2004], complicates the interpretation of the remote sensing products for aerosol microphysical and chemical properties. The frequent presence of dust particles aloft, sometimes carrying industrial and urban pollutants, hampers satellite-based monitoring of the near-surface air quality. Airborne in situ, remote-sensing, and column-integral measurements of aerosols would help address these challenges and study the link between the near-surface aerosol characteristics and satellite products.

Question 1b. How do pollutant distributions relate to cloud cover?

Clouds pose a major impediment to satellite observations, but they are also intimately related to atmospheric redistribution and transport. This can be of particular importance in outflow regions along continental margins. For instance, during the TRACE-P campaign, frontal clouds along the Asian Pacific Rim were found to contain large enhancements in CO and other trace gases [Crawford et al., 2003]. Enhancements were also noted above and below clouds compared to clear sky observations. Clouds also have photochemical impacts, affecting both oxidation rates and the partitioning of NO_x through the perturbation of photolysis frequencies. Geddes et al. (2012) demonstrated a bias in long-term averages of OMI NO_2 in the Toronto area that varied from 12% (+/-6%) over urban sites to 40% (+/-10%) over rural locations due to both changing photochemical conditions and a correlation between cloud cover and transport of emissions. While important, these impacts on satellite observations are difficult to study and demand that field observations include both cloudy and clear conditions. Survey flights of the type mentioned above should be designed to take advantage of opportunities to profile through clouds to contrast with clear periods. Observing gradients in composition along cloud edges and before or after cloud passage could also provide insight into whether satellite observations near cloud boundaries can provide any insight on diagnosing pollution transport.

Question 1c. How does aerosol abundance and vertical distribution influence trace gas retrievals?

The standard space-borne trace-gas retrieval algorithms used, for example, in OMI [Chance, 2002], GOME [Valks et al., 2011] and SCIAMACHY for NO_2, HCHO, and BrO, are based on the DOAS fitting window method to derive the total slant column density (SCD) of these gases. To get vertical column density (VCD), SCD is divided by an airmass factor (AMF), which is derived from radiative transfer calculations based on various auxiliary inputs such as terrain pressure, cloud fraction and properties (top height, albedo), surface albedo, trace gas profile shapes (O_3 and NO_2) and aerosol properties (amount, vertical distribution and radiative properties). In retrieving stratospheric amounts, or in clean regions, the aerosol background is small and its influence on the retrieval is often neglected [Chance, 2002]. This is not the case for tropospheric trace gas retrievals in polluted regions, where the AMF uncertainty represents a large fraction of the error in the retrieved trace gas concentrations [Boersma et al., 2007]. In the case of NO_2 retrievals, AMF is affected by the a-priori assumed NO_2 vertical profile, which is tightly related to aerosol loading in polluted regions [Lin et al., 2014], further complicating the retrievals.

The widely used DOMINO v2 [Boersma et al., 2011], and the OMNO2 [Bucsela et al., 2013] OMI NO_2 products do not explicitly account for the effects of aerosols in their AMF calculations, but rather assume that the cloud corrections account for aerosols (Lin et al., 2014).

In recent comparison of MAX-DOAS with OMI NO_2 over China and Russia, Kanaya et al., (2014) found that OMI presents low biases of ~50% when a layer with high NO_2 is located close to the surface and associated with high aerosol loading. Other recent sensitivity studies [Lin et al., 2014] suggest that aerosol scattering will enhance the NO_2 AMF if the aerosol layer is below or within the NO_2 layer, and will reduce the NO_2 AMF if the aerosol layer is above the NO_2 layer, or the aerosol is highly absorbing, as can be the case for polluted or sometimes pure dust aerosols. The presence of highly absorbing aerosol will generally cause significant underestimations in standard NO_2 column retrievals.

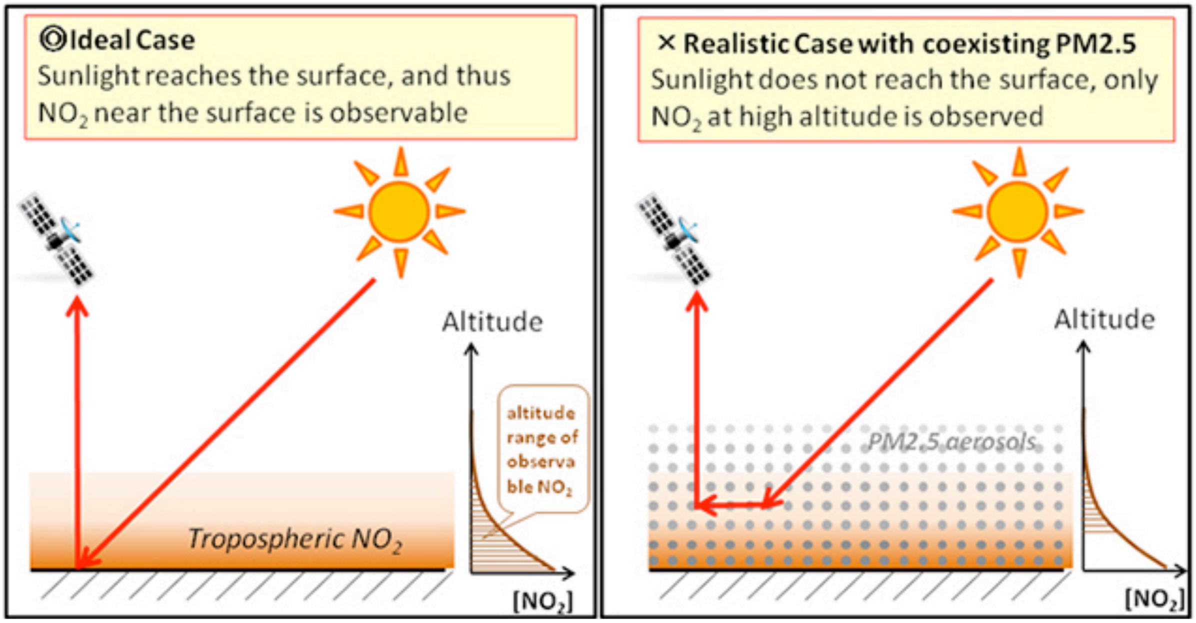

Figure 10. Conceptual diagram of shielding effect caused by co-existing PM2.5 aerosols. Co-existing PM2.5 aerosols prevent sunlight from reaching the earth's surface. As a result, satellite observation fails to detect NO_2 near the Earth's surface.
Taken from Kanaya et al. (http://www.jamstec.go.jp/e/about/press_release/20140811/)

Solutions for the challenges due to aerosols in satellite trace gas retrievals include model-based estimations (e.g. GEOS-CHEM) of aerosol amount, vertical distribution, and properties constrained by satellite observations (e.g. Lin et al., 2014) that are incorporated explicitly in the AMF calculations. Others include a combination of aerosol-specific satellite retrievals (e.g. MISR, POLDER) combined with gas-specific satellite retrievals (e.g., GOSAT for CO_2) [e.g., Frankenberg et al., 2012]. As we are moving toward geostationary satellite monitoring of air quality and emissions, aerosol property distributions of higher spatial and temporal resolution and improved accuracy are needed to assess the impact of co-varying gas concentrations and aerosol properties (e.g. scattering, absorption, vertical distribution) on retrievals; current single pixel, coarse-resolution satellite retrievals, such as the OMI retrievals at 13x24 km^2 resolution (and the GOME and SCIAMACHY retrievals at coarser resolutions yet), would benefit from the sub-pixel variability measurements as well.

KORUS-AQ, with a capability to concurrently measure NO_2, O_3, HCHO, and aerosol properties at high spatial and temporal resolution can be used to improve satellite trace gas retrievals and to contribute to air quality monitoring by characterizing differences in the chemical composition of airmasses affected by fresh and aged pollution [Segal-Rosenheimer et al., 2013]. Specific strategies to address the trace gas retrieval challenges described above should include small-scale sampling of aerosol and trace gas 3-D inhomogeneity for areas analogous to satellite footprints, sampling of elevated aerosol layers of different composition to examine their impacts on trace gas retrievals (from satellite, aircraft, and ground instrumentation), and seeking to gather these observations at different times of day.

Question 1d. How does the land/water boundary influence aerosol retrievals?

Given the retrieval differences over land versus ocean, detecting the evolution of aerosol properties during transport across the sea/land boundary presents a significant challenge for satellite retrievals and hence an exciting opportunity for assessment in an airborne campaign. The challenges in satellite aerosol retrievals over land stem from the dominating contribution of surface reflectance. Over dark oceans, the spectral surface reflectance is much better constrained than over land, resulting in significantly better retrievals of spectral aerosol optical depth (AOD, e.g., Levy et al., 2013) and the extinction Angstrom exponent, a measure of the slope of AOD with wavelength in log-log space. The Angstrom exponent in turn is related to the aerosol fine mode fraction (FMF, the fraction of aerosol optical depth due to fine mode aerosol), which has been used as a proxy for anthropogenic aerosol contributions (Anderson et al., 2005; Redemann et al., 2009). In particular, the satellite observations of AOD, Angstrom exponent and FMF over dark oceans in the West Sea have the potential to contribute significantly to the monitoring of Asian dust outbreaks and pollution events upwind of Korea. However, to be useful for actual monitoring of these events and for quantitative testing of CTM's, the quality of the over-ocean aerosol retrievals has to be assessed, as the aerosols evolve chemically during their transport towards Korea. Because the satellite aerosol retrievals are challenged with ocean sediments in the Korean coastal zone and the impact of gaseous pollutants concomitantly with the aerosol chemical evolution during transport, an airborne campaign that assesses aerosol chemical and optical properties during transport is the only way to assess the utility of geostationary and polar-orbiting satellite aerosol observations for AQ monitoring in Korea and elsewhere.

Question 2. What are the most important factors governing ozone photochemistry and aerosol evolution?

Korea's air quality is driven predominantly by local emissions from cities, forests, and the nearby oceans, but is heavily influenced by emissions from the west, including industrial pollution and dust from China and biomass burning from Asia. Because Korea has such a wide range of emission sources, from fresh to aged and from marine and biogenic to anthropogenic, the interactions of these emissions will be as important as the emissions themselves in determining the ozone production and aerosol evolution. Ozone photochemistry and aerosol evolution are strongly coupled and several different oxidants (OH, NO_3, O_3, halogens) likely play a role in driving the chemical mechanisms. The balance of these emissions and oxidants determines the sensitivity of ozone production and aerosol evolution to nitrogen oxides and to VOCs (see Figure 3). Thus, while the basic air quality processes are generally known from air quality studies primarily in the US and Europe, Korea provides an excellent laboratory to more fully explore the range of NO_x-VOC relationships affecting our understanding of these chemical and dynamical processes in a quite different environment from those encountered in previous studies. Significant recent advances in airborne observing capability (e.g, hydrocarbon measurements and their oxidation products as well as speciated reactive nitrogen) would enable further understanding of these issues.

Question 2a. How does ozone photochemistry respond to the various mixtures of upwind versus local pollutant emissions, biogenic emissions, and marine emissions?

The diverse mixture of sources, from megacities, agriculture and forests, and also ship traffic, leads to the formation, at poorly quantified rates, of ozone and secondary organic and inorganic aerosols over the Korean peninsula.

As awareness of air pollution problems in East Asia has grown, a number of tropospheric photochemistry process studies have been conducted in the region along with modeling studies to assess ozone and secondary organic aerosol (SOA) production. These results have consistently reported the importance of isoprene (C_5H_8) photochemistry even in the polluted metropolitan areas in East Asia, such as in the Japan Kansai region (including Kyoto, Kobe and Osaka) where a 25% increase in the afternoon ozone peak was attributed to isoprene photochemistry [Bao et al., 2010]. Kim et al. (2013) reported a similar level of additional ozone production from isoprene photochemistry at the Taehwa Forest Observatory (TFO), located at the southeastern edge of the Seoul. The trace gas observational results at the TFO also clearly indicate that isoprene accounts for most of the midday OH reactivity (11 am to 3 pm). Reported observations from the suburban regions of megacities in China show that isoprene provides a significant component of the OH reactivity [e.g., Ran et al., 2011; Lu et al., 2012; Tie et al., 2013]. Considering that most Asian megacities consist of densely populated city centers surrounded by forests, the roles of biogenic VOCs are expected to be critical for the atmospheric chemistry and composition throughout the East Asian region.

This experiment provides an opportunity to answer questions regarding the evolution of gas-phase reactivity over the urban-to-regional scale transition in the unique East Asian environment. While urban reactivity is widely understood in terms of primary pollutants such as NO_x and a multitude of VOCs, the reactivity of the aging outflow encountered in this environment will often be enhanced by fresh biogenic emissions from surrounding forests. Previous studies in the southeastern US and elsewhere have found that under favorable meteorological conditions, this mix can lead to high oxidant formation [e.g. Goldan et al., 2000]. In recent work at Taehwa Forest, Kim et al. (2014) highlighted uncertainties in the radical pool (OH, HO_2, RO_2) as the dominant factor limiting current understanding of the relative importance of NO_x and VOCs to ozone formation.

Chemical measurements along the outflow would enable the evaluation (and improvement) of models, including the concentrations of major oxidants (e.g. O_3, H_2O_2, organic peroxides, acids), longer-lived species that contribute to the global budgets of odd nitrogen (PANs, organic nitrates) and odd hydrogen (photo-labile organics such as ketones and aldehydes), aerosols, as well as physical controlling variables such as temperature, pressure, specific humidity, and spectral actinic fluxes. These measurements would help establish whether the chemistry of the outflow from the urban centers proceeds at a vigorous pace for only a short time after encountering the biogenic influence or persists for a longer period of time. The impact on the regional and global environments would partially be gauged by the observation of NO_x and HO_x reservoir species (e.g., HNO_3, PANs, $RONO_2$, HOOH, ROOHs, RCHOs) formed in the outflow.

For instance, recent analyses of NASA ARCTAS observations [Browne et al. 2014] establish that $RONO_2$ are the major sink of NO_x at concentrations characteristic of rural and remote locations. Similarly ROOH are the dominant sink of HO_x radicals in these regimes.

The composition of the air encountered downwind is expected to be dominated by a large number of intermediates produced by the photo-oxidation of the initial compounds. This intermediate chemistry is complex and arguably the most uncertain regime in our understanding of the atmospheric life cycle of anthropogenic and biogenic emissions. The fully explicit chemistry, expected to involve thousands of intermediate species based on laboratory kinetic/mechanistic data, has so far been considered only in box (zero-dimensional) models such as the NCAR and Leeds Master Chemical Mechanisms. These detailed chemical models predict that elevated concentrations of partially oxidized VOCs persist in the atmosphere for days and can even dominate the gas phase reactivity. As discussed above with respect to isoprene, these intermediate VOCs are important precursors for SOA formation.

Question 2b. What do aerosol physical, optical, and chemical properties reveal about the interaction between ozone photochemistry and secondary aerosol formation?

Isolating the impact of chemical evolution on aerosols and trace gases is complicated by the continuous input of emissions, mixing between air masses during transport, and removal by deposition and scavenging. Nevertheless, the physical separation and transport times between sources upwind of the Korean peninsula, in Seoul, rural areas downwind, and into the East Sea represent regimes that should demonstrate clear differences in atmospheric composition that can be attributed to chemical evolution.

Megacities are strong sources of both primary and secondary aerosols. While much aerosol evolution (e.g. emission, nucleation, coagulation, growth) occurs rapidly within the urban core, questions remain regarding how much additional processing occurs downwind. Precursors of inorganic aerosol, such as SO_2, H_2SO_4, NO_x, HNO_3, and NH_3 are known to persist for some time in the outflows from urban areas. Furthermore, many secondary VOCs are expected to contribute to aerosol evolution, through condensation, uptake and surface reaction. Downwind of Seoul, the mixing between urban NO_x emissions and biogenic VOCs is expected to enhance organic aerosol formation. Continued oxidation and aging of aerosols will increase hygroscopicity. In addition, as particles age, they mix internally by coagulation and growth. Information on the relative importance of these processes can be obtained by observing aerosol distributions and their chemical properties. These many processes ultimately determine the optical properties of aerosols (and therefore their direct impact on radiative budgets) and their microphysical characteristics (with potential impacts on clouds and precipitation).

Aerosols affect chemistry by removing some species from the gas phase, transforming others through surface reactions, and modifying (by scattering and/or absorption) the ultraviolet radiation field driving gas phase photochemistry. Scattering and absorption of sunlight by dense aerosol layers can decrease the photolysis of NO_2 and ozone. Uptake of potential ozone precursors onto the particles is a potential chemical impact. Aerosol layers dominated by dust, secondary inorganic (pollutant derived) aerosol, and secondary organic (both pollutant and biogenic derived) may be expected over Korea, as well as complex mixtures of these particle types. Characterizing the physical, chemical, and optical characteristics of the aerosol layers coupled with actinic flux measurements above and below would constrain the photolytic impact on ozone photochemistry.

Measurements of aerosol chemical and physical properties across the domain, simultaneously with the gas phase measurements, would help quantify the degree of chemical processing in various air masses and the resulting influence on primary and secondary aerosol abundances. Aircraft surveys upwind, across, and downwind of the peninsula would be able to capture these detailed changes in composition, which would provide valuable context for future geostationary observations which will provide unprecedented continuity across these regimes.

Question 3. How do models perform and what improvements are needed to better represent atmospheric composition over Korea and its connection to the larger global atmosphere?

Models represent our best knowledge of the factors controlling atmospheric composition by integrating the impact of emissions, transport, and chemistry. Understanding model strengths and weaknesses in representing the current atmosphere is critical since these models are also used to predict the future atmospheric state based on different scenarios. These results can then be used to support policy decisions. As noted earlier, models also play a role in defining the assumptions for satellite retrievals. During the campaign, daily flight decisions would rely on forecasts from both regional and global models to identify the meteorological scenarios and expected gradients in atmospheric composition that can best be used to test the models. Comparisons with observations would aid in model development by identifying features that are well captured versus inconsistencies that indicate potential areas of improvement.

Question 3a. Are modeled gradients across the Korean peninsula consistent with local/upwind sources, transport, and chemistry?

Understanding atmospheric composition over Korea requires the deconvolution of episodic trans-boundary influences from the more persistent influences of local emissions. The difficulty in modeling the impact of upwind sources on temporal and vertical variability of pollutants in Korea is illustrated by the attenuated lidar backscattering observations at the Seoul National University station for the two-week period from April 26th to May 9th 2012 (see Figure 11). During this period the air quality in Korea was impacted by dust from the Gobi desert, anthropogenic pollution, and biomass burning smoke coming from boreal fires in south-eastern Russia. There is significant variability in the vertical profiles, which needs to be better understood. Sampling the full atmospheric column is critical to understanding how material lofted from the ground by different processes is transported and how and where it subsequently impacts the surface. The model predictions show that current models have some capacity to capture this variability in the vertical profiles, but that further model improvements are clearly needed which can be driven by field experiment activities.

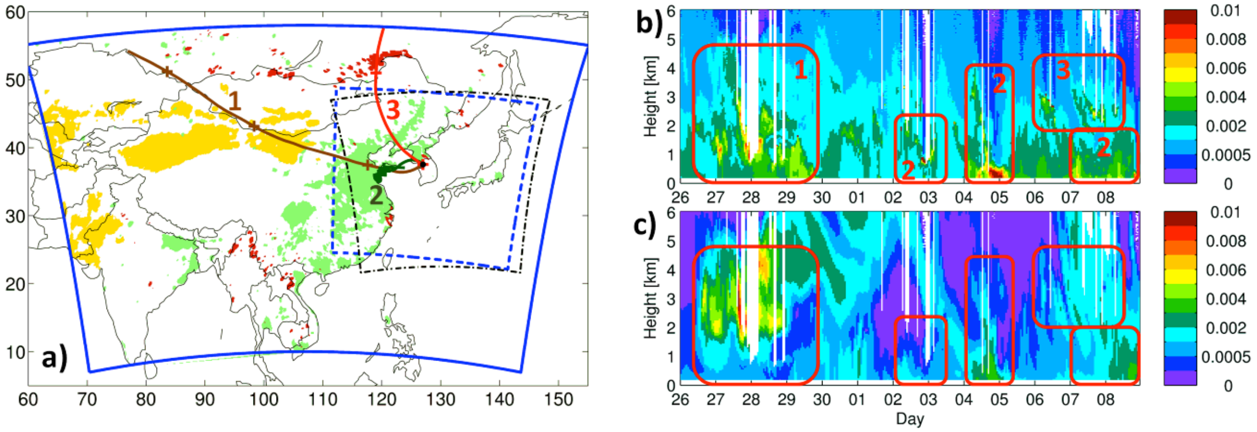

Figure 11. Left panel: Source and trajectory paths for the types of pollution episodes expected during KORUS-AQ. Boxes outline the GOCI field of view (dashed black) and proposed modeling domains (blue). These sources affected Korea for a 2-week period during April-May 2012 and correspond to dust (yellow), anthropogenic pollution (green) and biomass burning smoke (dark red), with corresponding representative trajectories in brown (1), dark green (2) and red (3). Plus signs mark 1-day increments along the trajectories. Right panels: Observed (b) and modeled (c) attenuated Lidar backscattering at Seoul National University station (black circle on the map). Red boxes represent the different pollution episodes associated with each numbered source trajectory. From Saide et al., 2014.

The effect of upwind sources on air quality in Korea is determined by synoptic-scale meteorological transport, including the highly unpredictable Asian monsoon system. Upwind anthropogenic emissions are difficult to distinguish from local influences. Soil dust aerosols from arid and semi-arid regions such as the Gobi and the Taklimakan deserts cause serious concern for human health and industry in Korea every spring. The direct impact of dust on health in Korea is compounded by the fact that the transport route out of Asia passes over major urban and industrial regions before reaching the West Sea. As a result, the dust is frequently mixed with pollution. Satellite measurements of aerosol optical depth (AOD) have recently been shown to be promising over the highly reflective deserts, and they can be used to constrain the geographical locations and timings of soil dust mobilization in models. If the dust layers are optically thick enough they can also be tracked across eastern Asia and then the West Sea enroute to Korea.

Local processes also have a strong influence on gradients. Mountains and other vegetative areas, where natural biogenic VOCs emissions are dominant, surround Seoul and other large cities in Korea. O_3 concentrations in Seoul are typically low due to titration by high NO_x from the heavy traffic, but it sometimes increases rapidly when high NO_x in polluted air is mixed with natural VOCs from surrounding areas. Thus, O_3 simulations show high sensitivity to emissions of natural biogenic VOCs, which are often parameterized using surface types and meteorological variables. Significant errors in surface type specification in Seoul and South Korea are often found in current databases, leading to large uncertainties in natural VOC emissions, which affect both O_3 and organic aerosol simulations. Extensive observations of VOC species would be very helpful to better estimate biogenic emissions and deepen the understanding of their roles in O_3 and PM air quality in Seoul and surroundings.

Survey flights including routine sampling legs over the West Sea and over the Korean peninsula would be critical to separating upwind and local influences for comparison with models. These flights would include full vertical profiling to capture elevated dust layers as well as any associated pollution layers.

Question 3b. Are air quality and atmospheric chemistry forecasting systems prepared to utilize GEO observations?

The applications potential for geostationary satellite observations of air quality raises the bar on readiness to exploit the data as soon as possible after launch. This is true for air quality forecasts. However improvements depend not only on the quality of the models but also on the assimilation system used to optimally integrate the observations and the predictions. The goal is to derive the maximum information from the retrievals (as many pixels and time periods as possible) for all satellites available (LEO and GEO). It would be important to evaluate the extent to which this new information can be used to improve the forecasts, and how does it complement the information provided by other components of the observing system (e.g., surface based concentrations of PM mass, AERONET sites and lidar backscattering profiles).

Forecasting models including assimilation systems with the capability to utilize observations from all these sources are available and will be in use in Korea at the time of the experiment (e.g., Saide et al., 2013). These systems can be used in pre mission and post mission mode to help determine the capability of assimilating different datasets to improve forecasts. Detailed airborne and ground-based observations can be used as independent observations to assess these improvements and to identify gaps in the observing system.

Relevance and Benefit to NASA

KORUS-AQ would contribute to NASA priorities in the areas of: 1) NASA Atmospheric Composition Program science goals, 2) Pre-launch studies and algorithm development for planned air quality satellites in development, 3) International collaboration through the Committee on Earth Observations Satellites (CEOS), and 4) NASA Applied Sciences Program goals.

Benefits to NASA's science goals under the Atmospheric Composition Focus Area are most closely related to the following two overarching questions: "How is atmospheric composition changing?" and "What are the effects of global atmospheric composition and climate changes on regional air quality?" With respect to these two questions, KORUS-AQ provides an exciting opportunity to observe a part of the globe undergoing rapid changes in atmospheric composition that have immediate importance to the need to understand human impacts. Previous campaigns in the region (e.g., TRACE-P, ACE-Asia, PEM-West A/B) offer an opportunity for comparisons to assess long-term changes and to provide valuable data for assessing models focused on quantifying the long-term trends in Asian emissions, air quality, and greater global influence. As satellites will play an increasingly important role in assessing these changes, KORUS-AQ directly addresses the goals of the Tropospheric Chemistry Program which "seeks to improve the utility of satellite measurements in understanding of global tropospheric ozone and aerosols, including their precursors and transformation processes in the atmosphere." and has relevance to the Radiation Science Program which "supports studies to improve the theoretical understanding of radiative transfer as well as field measurements of aerosol and cloud particle concentration, composition, microphysics, and optical properties."

In addition to addressing the broadly stated questions and goals of the Atmospheric Composition Focus Area and its component programs, KORUS-AQ also responds to community priorities set forth by the recent workshop at NASA Ames to determine "Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics, and Radiation for the Coming Decade." Specific outcomes are still being drafted and can be found at:

https://espo.nasa.gov/home/content/NASA_SMD_Workshop

Under the group charged to address current understanding of tropospheric composition, the top priority was determined to be "What is the future of air quality in a changing world?" (question 2.1.1). Under this question, particular mention was given to Asia and Africa as regions where rapidly increasing emissions and limited controls have importance for both future air quality and global composition (question 2.1.1.1). Emphasis was also placed on developing a space-based observing system for global air quality (question 2.1.1.2). KORUS-AQ would directly contribute to both of these priorities by providing important information for assessing the current factors controlling air quality in a developing region and apply these observations to pave the way for a successful system of satellites to observe global air quality.

KORUS-AQ will directly aid retrieval algorithm development for current and future air quality satellites. Accurate retrieval of tropospheric trace gas and aerosol amounts from passive remote sensing observations depends on several assumptions, including vertical distribution of the species in the atmosphere and spectral reflectance of the underlying surface. Trace gas retrievals are also influenced by scattering from aerosol. Basic trace gas retrievals are relatively mature, having been developed and applied to observations from a series of satellites in low Earth orbit beginning with GOME in 1995 [e.g., Martin 2008; Fishman et al., 2008; Liu et al., 2010]. Sources of error in the retrieval of tropospheric partial columns include knowledge of the stratosphere/troposphere separation and errors associated with the Air Mass Factors (AMF) used to convert measured total slant column density to the inferred tropospheric vertical column density [Streets et al., 2013]. Over continental regions of pollutant emissions, AMF error dominates the total error, and the largest contributors to AMF error include incorrect assumptions about the vertical profile shape, surface reflectivity, cloud parameters, and aerosols [Streets et al., 2013]. These influences are accounted for using relationships, or climatologies, that have been derived from available observations and/or global model predictions. A major challenge for the upcoming retrievals from the geostationary sensors is that the AMF relations will need to be established at much finer spatial resolution than has been done with the LEO sensors and also for all hours of the day (in contrast to the 1 or 2 times per day that have been available from LEO sensors). All of the key parameters in the AMF are sensitive to spatial resolution and time of day. The vertical profile shape and the vertical distribution of aerosols can change rapidly due to diurnal growth and collapse of the planetary boundary layer. Surface reflectivity depends on viewing geometry and sun angles, and the high heterogeneity in urban areas will need to be represented to retain retrieval accuracy at finer spatial resolution. The DISCOVER-AQ campaigns have acquired data over four different regions of the US that are helping to refine the retrieval algorithms (including AMF) in preparation for the GEO sensors.

KORUS-AQ would greatly extend the range of data (stronger signals of pollutants, stronger gradients, wider range of surface types including land/water boundaries) for developing these algorithms and relationships. Also, the hourly multispectral GOCI data available over the Korean region will provide useful constraints on the diurnal variation of aerosol and surface reflectance. Finally, because TROPOMI will have comparable spatial resolution to the GEO sensors, conducting the campaign with TROPOMI in orbit would provide additional value for algorithm development and also provide early validation data for TROPOMI.

In support of Group on Earth Observations (GEO) objectives and as a space component of the Global Earth Observation System of Systems (GEOSS), CEOS has developed the concept of virtual space-based Constellations. The goal of a Constellation is to demonstrate that added value can result through partnerships among the space agencies and their supported institutions to coordinate existing and future international space assets. The Atmospheric Composition Constellation (ACC) focuses on observations needed to improve monitoring, assessment and predictive capabilities for changes in the ozone layer, air quality and climate forcing associated with changes in the environment. The need for international collaboration on a virtual constellation for air quality is currently of high priority given the need for geostationary satellite instruments that can only view a portion of the globe. Collaborative activities in preparation for this constellation are outlined in the CEOS ACC document, "A Geostationary Satellite Constellation for Observing Global Air Quality: An International Path Forward" which is available online at http://www.ceos.org/images/ACC/AC_Geo_Position_Paper_v4.pdf. This planning document calls for international collaboration on a wide range of topics that include retrieval algorithms, OSSE studies, data protocols and accessibility, approaches to cal/val, improvement of air quality models, and data assimilation techniques. Observations collected during KORUS-AQ would contribute to each of these areas of emphasis. The linked development of the GEMS and TEMPO instruments, both of which are being delivered by Ball Aerospace, further elevates the need for developing strong relationships with colleagues in Korea focused on air quality.

The NASA Applied Sciences Program (ASP) seeks to promote and accelerate the adoption of NASA-sponsored Earth science and observations by external organizations to increase tangible near-term societal benefits. NASA's commitment to the application of satellite data to air quality is being demonstrated through the Air Quality Applied Sciences Team (AQAST). This group works to exploit the current air quality observing system (see Figure 8), taking advantage of satellite data, suborbital data, and models to inform forecasting, monitoring, assessment, emissions quantification, source attribution, trans-boundary influence, and climate-air quality interactions. AQAST is already closely aligned with research teams from NASA's GEO-CAPE, TEMPO, and DISCOVER-AQ efforts. The ASP increasingly recognizes that engaging the user community during the development of future satellite missions is essential for expanding and accelerating the ultimate use of the data, thereby increasing societal benefits of the missions. KORUS-AQ would increase readiness for applied use of data from the geostationary constellation in several ways. It would help mature the satellite retrieval algorithms and, importantly, establish confidence in them. It would contribute to evaluation and future development of operational air quality forecasting models in both Korea and the US. It would also provide improved fundamental scientific understanding of pollutants originating in Asia that ultimately may impact US air quality and climate, an issue of rapidly growing importance to air quality managers particularly in the Western US.

Experimental Design

Timing for the study: Based on the seasonality of air quality in Korea, conducting a field study sometime during April-June would be the best choice. As shown in the figure below, urban ozone statistics reveal peak ozone in Korea occurs over the months of April to June. This is also the period of strongest influence from upwind sources via strong frontal transport, including dust outbreaks and biomass burning, which is peaking in East Asia at this time [Cheng et al., 2014]. Additionally, this period overlaps with early planting and growth of rice and corn crops as well as harvesting of winter wheat [Wang and Mauzerall et al., 2004].

Based on the time needed for proper planning, the study could feasibly be accomplished as early as 2016, a target shared by our Korean collaborators. By this time, cal/val activities would be possible in support of the once-daily data from the European LEO S5P mission. This would help establish continuity of the data record from OMI. Because the S5P instrument and data products will have much in common with the GEMS and the other geostationary chemistry missions (e.g., same spectral ranges, similar spectral and spatial resolution, similar retrieval algorithms and data products), any experience and improvements gained from the S5P cal/val would also have direct application to the data from the GEO missions. This should ultimately improve initial quality of data products from the GEO missions and foster readiness for applied use of the data rapidly after launch.

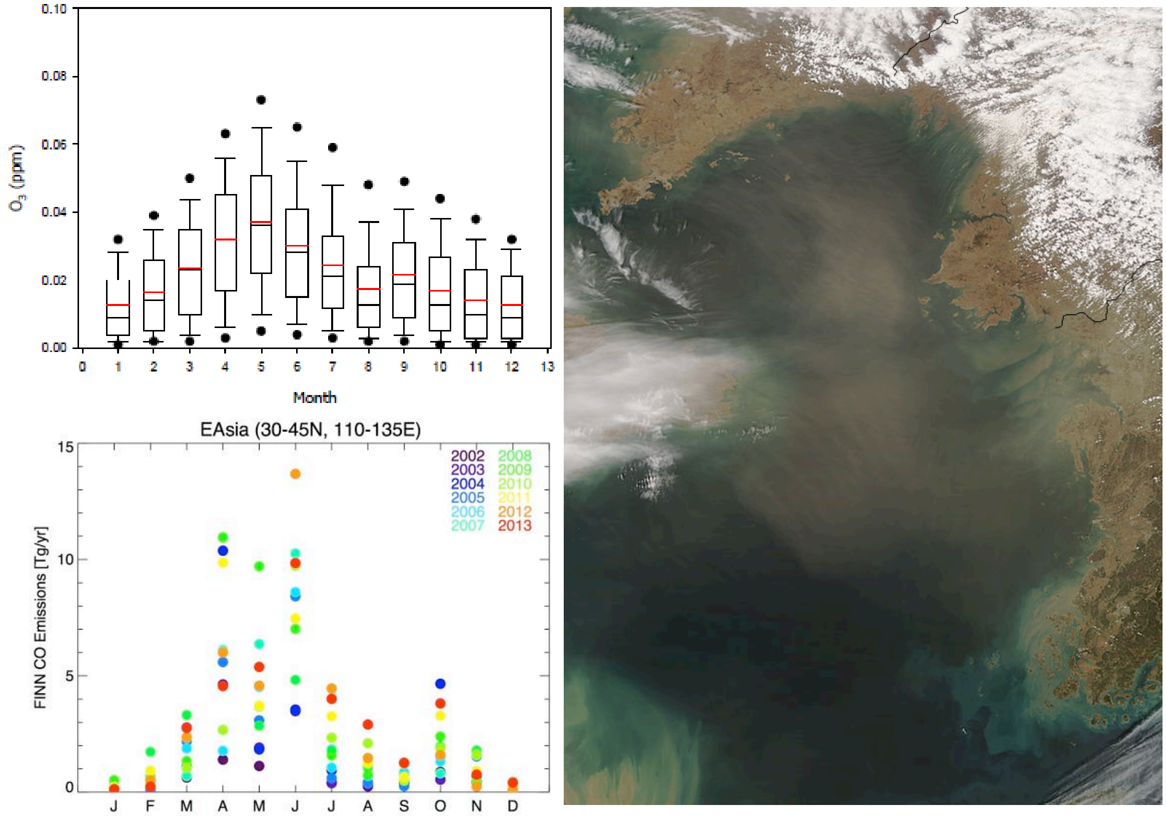

Figure 12. Top left: Monthly ozone statistics for urban areas of Korea (taken from Dr. Jongcoon Kim, 2011 presentation to 4th Tripartite Workshop on Scientific Research of Photochemical Oxidant). Bottom left: Monthly average biomass burning CO emissions from the Fire INventory at NCAR (FINN), summed over East Asia (L. Emmons, NCAR). Right: MODIS image of dust transport across West Sea in April 2005 (courtesy of NASA's Visible Earth Image Gallery)

Airborne measurements: For this field study, the NASA DC-8 is the desired research aircraft due to the need for a complex payload and space for collaborating Korean scientists. The following table outlines measurement priorities for the payload. Priorities are expressed as follows: 1 = required, 2 = desired, 3 = useful. Detection limit and resolution specifications must be met or exceeded for a measurement to be useful. The suite of measurements identified as Priority 1 is sufficient to fully address the science described under Question 1 relating to satellite observability. Priority 1 measurements also enable a high-level assessment of Questions 2 and 3 addressing chemical evolution and its representation in models. Priority 2 measurements would allow for a more detailed examination of chemical evolution (Question 2) by adding information on radical chemistry, reservoir species for reactive compounds, and source-specific tracers. These measurements would also enable a deeper assessment of model calculated gradients (Question 3) by enabling an assessment of the underlying chemical processes affecting tracer distributions. 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 beyond what is required by the science questions.

Gas Phase In Situ	Priority	Detection Limit	Resolution
O3	1	1 ppbv	1 s
H2O	1	10 ppmv	1 s
CO	1	5 ppbv	1 s
CH4	1	10 ppbv	1 s
CO2	1	0.1 ppm	1 s
NMHCs	1	<10%	1 min
NO	1	10 pptv	1 s
NO2	1	20 pptv	1 s
HCHO	1	50 pptv	1 s
OH, HO2, RO2	2	0.01/0.1/0.1 pptv	30 s
OH reactivity	2	1 s^{-1}	10 s
H2O2	2	50 pptv	10 s
ROOH	2	50 pptv	10 s
HNO3	2	50 pptv	10 s
PANs	2	50 pptv	10 s
RONO2	2	50 pptv	10 s
SO2	2	10 pptv	1 s
CH3CN	2	10 pptv	1 min
NOy	3	50 pptv	1 s
Halocarbons	3	variable	1 min
HCN	3	10 pptv	1 min
NH3	3	30 pptv	1 min
N2O	3	1 ppbv	10 s
Organic Acids	3	10 pptv	1 min
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 dist.	2	0.05-1000 µm	1 s
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
Ozone lidar (nadir/zenith)	1	5 ppbv or 10%	300 m
Trace Gas Columns (O_3, NO_2, C_2HO)	1	variable	variable
Multi-spectral optical depth	1	0.01	1 s
Aerosol profiles of extinction	1	10 Mm^{-1} or 10%	300 m
Aerosol profiles of backscatter	1	3%	30 m
Aerosol profiles of depolarization	1	3%	30 m
High Resolution Met (T, P, winds)	2	0.3K, 0.3 mb, 1 ms^{-1}	1 s
Hyperspectral solar flux	3	4%	1 s
Broadband flux	3	5%	1 s

Ground measurements: Close integration with ground measurements is critical to the study. The nucleus of any ground effort should necessarily leverage the existing air pollution monitoring networks administered by the Korean Ministry of the Environment and major research sites discussed earlier. For instance, proposed coordination of flights over sites near Seoul as well as upwind and downwind at multiple distances would help put transport and chemical evolution in context.

During the study period, it would be of great value to augment existing ground sites with remote sensors. Passive ground-based spectrometers and sunphotometers for column-integrated measurements would be particularly useful for providing information on the relationship between air quality conditions on the ground versus those aloft and how that would likely influence satellite observations of key air quality constituents. Augmenting the existing Korean active remote sensing network with ceilometers, aerosol lidars and/or ozone lidars at carefully chosen locations would provide valuable information on lower atmospheric structure and mixing of pollution, which is fundamental to remote sensing as well as the nonlinear chemistry of emissions. Other opportunities for augmentation of in situ instrumentation at ground sites, especially for measurements complementing the connection between the airborne observations and the surface should be considered.

Satellite observations: Given the overarching goal of maximizing the utility of satellite data, satellite teams should be both key contributors to and primary beneficiaries of the study. Close interaction with satellite data teams is required in all phases of the study. Satisfying satellite validation requirements requires detailed consideration of the characteristics of each satellite instrument and its data products during the study planning phase. During the study, near real-time satellite data are desirable to help develop daily flight plans and even to optimize flights in progress. The hourly aerosol and cloud products from the GOCI instrument provided by Korean collaborators would be a focus of the study. Observations from the TROPOMI instrument on the ESA Sentinel-5 Precursor mission, expected to launch in early 2016, are another likely emphasis. Daily TROPOMI measurements of O_3, NO_2, HCHO, SO_2, and aerosol will be made at similar horizontal resolution to the hourly measurements expected from the geostationary GEMS, TEMPO, and Sentinel-4 missions later in the decade. The NASA OCO-2 mission is expected to be in operation during this campaign, meaning that CO_2 observations can also be a campaign focus if desired. The TCCON FTS in Anmyeon, providing more continuous remote sensing would provide an anchor for connecting airborne data with satellite information. Atmospheric composition data from many mature NASA instruments (including OMI, TES, MODIS, MLS, MISR, CALIPSO, MOPITT, and AIRS) could be available for flight planning (assuming continued operation) and would benefit from new validation data that would be obtained.

Models of Atmospheric Composition and Air Quality: Model simulations for both forecasting and analysis are critical to a successful study. Therefore, a modeling system combining pre-existing CTMs with regional or global weather forecasting models that are best suited for East Asian climate is needed. This system is needed for pre-flight planning to predict pollution pathways as well as for post-mission data interpretation to understand source-receptor relationships. It is important to have an ensemble of models including but not limited to the operational and research models mentioned above that are in use by the Korean community. These models must focus both regionally and globally to address the hemispheric nature of air quality as Korea both contributes to and is impacted by its connection to the changing hemispheric background and associated trans-boundary transport issues.

Flight Scenarios and Sampling Approach

In order to develop adequate plans for scientific flights, information on flight restrictions must be addressed. Broad details provided in the Figure 13 demonstrate that Korea and its surrounding waters are blanketed by special use airspace. To be successful, scientists do not need unrestricted access to all airspace, but it is important to establish how scientific goals can be satisfied within airspace constraints.

The red lines on the top left panel of Figure 13 depict potential flight lines along which survey sampling could be conducted without impinging on restricted airspace. The length of the lines is based on the assumption of an 8-hour flight for the DC-8 with four transects along each direction at various altitudes. While this establishes the distance that can be covered by the DC-8, sampling on any given day could be extended (see yellow line) or repeated along any of these lines depending on the specific synoptic situation or expected gradients in pollution. A closer look at restrictions on low altitude flight also indicate that boundary layer sampling of the Seoul megacity outflow as it is transported downwind is also conceptually feasible both during the week as well as on weekends. This is represented by the yellow meandering track sampling to the southeast of Seoul on the map in the lower left of Figure 13, but the direction of this track would ultimately depend on the actual transport path on the chosen flight day. These two modes of sampling are sufficient to address the scientific questions posed above, but the reduced flight restrictions on weekends also offer the option for more exploratory flight plans if, for instance, models indicate interesting features or survey flights indicate the influence of anomalous sources worthy of direct sampling.

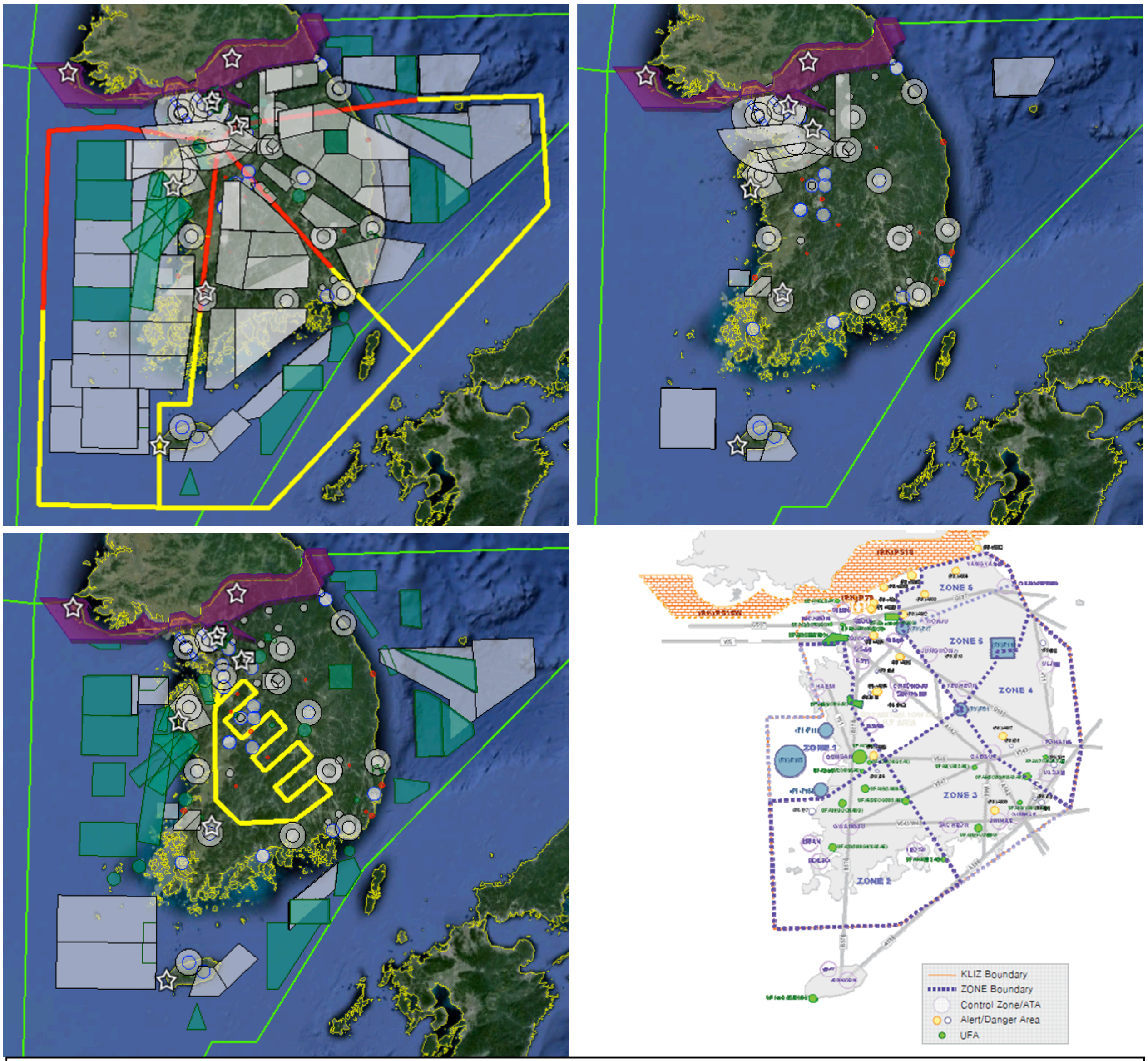

Figure 13. Special use airspace within the South Korean FIR (green border) for weekdays (top left) and weekends (top right). Flight areas to support military operations and training are not active on weekends, offering greater flexibility for sampling. Flight lines (shown in red and yellow) indicate potential lanes for survey sampling that should be feasible on any day (see discussion in text). Low altitude flight (below 3000 ft) to sample near-surface pollution is more broadly feasible as only a subset of special use airspace extends to the surface (bottom left). Instead, low altitude flight is regulated by the ROK Air Force across six zones (bottom right).

The importance and value of fostering international collaboration

Successful international collaboration necessarily requires strong communication and involvement by both countries in the development, execution, and analysis of field study observations. The following areas of collaboration will be emphasized by the NASA team.

Joint development of the field study definition

While this white paper articulates NASA's conceptual plans, similar planning documents will be developed by our Korean partners. Harmonization of these plans is an important function of the Steering Group identified at the beginning of this document. It is also desirable to invite input from scientists in Japan, China, and other East Asian countries.

Hosting of foreign scientists on the NASA DC-8

The NASA DC-8 research aircraft is capable of hosting a large number of investigators and instruments. For this field study, at least five racks would be set aside for use by Korean investigators. While NASA cannot directly fund foreign investigators, there is a long history of foreign investigator participation on NASA airborne field studies. Through international agreements, NASA assumes responsibility for installing the instrument on the aircraft while the home country financially supports the scientist. Hosting need not be limited to those scientists with existing aircraft instruments. Preference would also be given to instrument teams having strong US-Korean collaboration. Collaboration with US scientists experienced in airborne measurements could be valuable to Korean scientists interested in developing similar capability. These activities would be especially important to the continued development of airborne research capability in Korea.

Data Sharing

Maximizing the utility of the data collected and fostering collaboration relies on open data access. NASA commits to full sharing of data during both the execution of the field study and post-mission analysis. Sharing is accomplished through a central data repository that is password protected while data is still in a preliminary stage. Access to this data repository would be available to all participants including those making measurements from the plane and on the ground as well as those using models to interpret the data. NASA would also require the data produced by its scientists to become publically available one year after the completion of the field deployment.

Joint analysis and publication of results

To fully exploit the field study observations, thorough analysis and modeling activities are needed. While Korean and US scientists would secure funding for these activities from their respective countries, joint science team meetings would allow scientists to prioritize work and apply appropriate models. It is customary for the science team to arrange for publications to appear in a special journal issue and appropriately recognize contributions of measurements or analysis of data with co-authorship on papers.

References:

Anderson T. L., Y. Wu, D. A. Chu, B. Schmid, J. Redemann, O. Dubovik (2005) Testing the MODIS satellite retrieval of aerosol fine-mode fraction, *J. Geophys. Res.,*110, D18204, doi:10.1029/2005JD005978.

Arimoto, R., Y. J. Kim, Y. P. Kim, P. K. Quinn, T. S. Bates, T. L. Anderson, S.Gong, I. Uno, M. Chin, B. J. Huebert, A. D. Clarke, Y. Shinozuka, R. J. Weber, J. R. Anderson, S. A. Guazotti, R. C. Sullivan, D. A. Sodeman, K. A. Prather, and I. N. Sokolik (2006) Characterization of Asian Dust during ACE-Asia, *Global and Planetary Change*, 52, 23-56, doi:10.1016/j.gloplacha.2006.02.2013.

Bao, H., Shrestha, K. L., Kondo, A., Kaga, A., and Inoue, Y. (2010) Modeling the influence of biogenic volatile organic compound emissions on ozone concentration during summer season in the Kinki region of Japan, *Atmos. Env.*, 44, 421-431, doi:10.1016/J.Atmosenv.2009.10.021.

Boersma, K. F., Eskes, H. J., and Brinksma, E. J. (2004) Error analysis for tropospheric NO_2 retrieval from space, *J. Geophys. Res.*, 109, D04311, doi:10.1029/2003JD003962

Boersma, K. F., Eskes, H. J., Dirksen, R. J., van der A, R. J.,Veefkind, J. P., Stammes, P., Huijnen, V., Kleipool, Q. L., Sneep, M., Claas, J., Leitão, J., Richter, A., Zhou, Y., and Brunner, D. (2011) An improved tropospheric NO_2 column retrieval algorithm for the Ozone Monitoring Instrument, *Atmos. Meas. Tech.*, 4, 1905–1928, doi:10.5194/amt-4-1905-2011.

Browne, E. C., Wooldridge, P. J., Min, K.-E., and Cohen, R. C. (2014) On the role of monoterpene chemistry in the remote continental boundary layer, *Atmos. Chem. Phys.*, 14, 1225-1238, doi:10.5194/acp-14-1225-2014.

Bucsela, E. J., Krotkov, N. A., Celarier, E. A., Lamsal, L. N.,Swartz, W. H., Bhartia, P. K., Boersma, K. F., Veefkind, J. P.,Gleason, J. F., and Pickering, K. E. (2013) A new stratospheric and tropospheric NO_2 retrieval algorithm for nadir-viewing satellite instruments: applications to OMI, *Atmos. Meas. Tech.*, 6, 2607–2626, doi:10.5194/amt-6-2607-2013.

Chance, K. (2002). OMI Algorithm Theoretical Basis Document Volume IV OMI Trace Gas Algorithms Edited by. OMI-ATBD, IV(August).

Cheng, Z., Wang, S., Fu, X., Watson, J. G., Jiang, J., Fu, Q., Chen, C., Xu, B., Yu, J., Chow, J. C., and Hao, J. (2014) Impact of biomass burning on haze pollution in the Yangtze River delta, China: a case study in summer 2011, *Atmos. Chem. Phys.*, 14, 4573-4585, doi:10.5194/acp-14-4573-2014.

Crawford, J., et al. (2003), Clouds and trace gas distributions during TRACE-P, *J. Geophys. Res.*, 108, 8818, doi:10.1029/2002JD003177.

Fast, J. D., Allan, J., Bahreini, R., Craven, J., Emmons, L., Ferrare, R., Hayes, P. L., Hodzic, A., Holloway, J., Hostetler, C., Jimenez, J. L., Jonsson, H., Liu, S., Liu, Y., Metcalf, A., Middlebrook, A., Nowak, J., Pekour, M., Perring, A., Russell, L., Sedlacek, A., Seinfeld, J., Setyan, A., Shilling, J., Shrivastava, M., Springston, S., Song, C., Subramanian, R., Taylor, J. W., Vinoj, V., Yang, Q., Zaveri, R. A., and Zhang, Q. (2014) Modeling regional aerosol variability over California and its sensitivity to emissions and long-range transport during the 2010 CalNex and CARES campaigns, *Atmos. Chem. Phys. Discuss.*, 14, 7187-7303, doi:10.5194/acpd-14-7187-2014.

Fishman, J., K. W. Bowman, J. P. Burrows, A. Richter, K. V. Chance, D. P. Edwards, R. V. Martin, G. A. Morris, R. B. Pierce, J. R. Ziemke, J. A. Al-Saadi, J. K. Creilson, T. K. Schaack, and A. M. Thompson (2008) Remote Sensing of Tropospheric Pollution from Space, *Bull. Amer. Met. Soc.*, 89(6), 805-821, doi:10.1175/2008BAMS2526.1.

Frankenberg, C., Hasekamp, O., O'Dell, C., Sanghavi, S., Butz, a., & Worden, J. (2012). Aerosol information content analysis of multi-angle high spectral resolution measurements and its benefit for high accuracy greenhouse gas retrievals, *Atmos. Meas. Tech.*, 5(7), 1809–1821. doi:10.5194/amt-5-1809-2012.

Hillbol, A., A. Richter, and J. P. Burrows (2013) Long-term changes of tropospheric NO2 over megacities derived from multiple satellite instruments, *Atmos. Chem. Phys.*, 13, 4145–4169, doi:10.5194/acp-13-4145-2013.

Kanaya, Y., H. Irie, H. Takashima, H. Iwabuchi, H. Akimoto, K. Sudo, M. Panchenko (2014) Long-term MAX-DOAS network observations of NO_2 in Russia and Asia (MADRAS) during the period 2007–2012: instrumentation, elucidation of climatology, and comparisons with OMI satellite observations and global model simulations. *Atmos. Chem. Phys.*, 14(15), 7909–7927. doi:10.5194/acp-14-7909-2014.

Geddes, J. A., J. G. Murphy, J. M. O'Brien, and E. A. Celarier (2012) Biases in long-term NO2 averages inferred from satellite observations due to cloud selection criteria, *Rem. Sens. Env.*, 124, 210-216, DOI: 10.1016/j.rse.2012.05.008.

Goldan, P.D., D.D. Parrish, W.C. Kuster, M. Trainer, S.A. McKeen, J. Holloway, B.T. Jobson, D.T. Sueper, F.C. Fehsenfeld (2000) Airborne measurements of isoprene, CO, and anthropogenic hydrocarbons and their implications, *J. Geophys. Res.*, 105, 9091-9105.

Kim, J., (2011), Current status of ozone management and policy in Korea, presented at the 4th Tripartite Workshop on Scientific Research of Photochemical Oxidant, http://www.acap.asia/event/ozone/index_2.html.

Kim, S.-W., I.-J. Choi, S.-C. Yoon (2010) A multiyear analysis of clear-sky aerosol optical properties and direct radiative forcing at Gosan, Korea (2001–2008), *Atmos. Res.*, 95, 279–287, doi:10.1016/j.atmosres.2009.10.008.

Kim, S., Kim, S.-Y., Lee, M., Shim, H., Wolfe, G. M., Guenther, A. B., He, A., Hong, Y., and Han, J. (2014) Urban-rural interactions in a South Korean forest: uncertainties in isoprene-OH interactions limit understanding of ozone and secondary organic aerosols production, *Atmos. Chem. Phys. Discuss.*, 14, 16691-16729, doi:10.5194/acpd-14-16691-2014.

Kim, S. Y., Jiang, X. Y., Lee, M., Turnipseed, A., Guenther, A., Kim, J. C., Lee, S. J., and Kim, S. (2013) Impact of biogenic volatile organic compounds on ozone production at the Taehwa Research Forest near Seoul, South Korea, *Atmos. Env.*, 70, 447-453, doi:10.1016/J.Atmosenv.2012.11.005.

Kurokawa, J., T. Ohara, T. Morikawa, S. Hanayama, J.-M. Greet, T. Fukui, K. Kawashima, and H. Akimoto (2013) Emissions of air pollutants and greenhouse gases over Asian regions during 2000–2008: Regional Emission inventory in ASia (REAS) version 2, *Atmos. Chem. Phys.*, 13, 11019-11058, doi:10.5194/acp-13-11019-2013.

Levy, R. C., S. Mattoo, L. A. Munchak, L. A. Remer, A. M. Sayer, F. Patadia, and N. C. Hsu (2013) The Collection 6 MODIS aerosol products over land and ocean, *Atmos. Meas. Tech.*, 6, 2989-3034, doi:10.5194/amt-6-2989-2013.

Lin, J.-T., R. V. Martin, K. F. Boersma, M. Sneep, P. Stammes, R. Spurr, and H. Irie (2014) Retrieving tropospheric nitrogen dioxide from the Ozone Monitoring Instrument: effects of aerosols, surface reflectance anisotropy, and vertical profile of nitrogen dioxide, *Atmos. Chem. Phys.*, 14(3), 1441–1461. doi:10.5194/acp-14-1441-2014.

Liu, X., P. K. Bhartia, K. Chance, R. J. D. Spurr, and T. P. Kurosu (2010) Ozone profile retrievals from the Ozone Monitoring Instrument, *Atmos. Chem. Phys.*, 10, 2521–2537, doi:10.5194/acp-10-2521-2010.

Lu, K. D., Rohrer, F., Holland, F., Fuchs, H., Bohn, B., Brauers, T., Chang, C. C., Häseler, R., Hu, M., Kita, K., Kondo, Y., Li, X., Lou, S. R., Nehr, S., Shao, M., Zeng, L. M., Wahner, A., Zhang, Y. H., and Hofzumahaus, A. (2012) Observation and modelling of OH and HO_2 concentrations in the Pearl River Delta 2006: a missing OH source in a VOC rich atmosphere, *Atmos. Chem. Phys.*, 12, 1541-1569, doi:10.5194/acp-12-1541-2012.

Martin, R.V. (2008) Satellite remote sensing of surface air quality, *Atmos. Env.*, 42, 7823-7843, doi:10.1016/j.atmosenv.2008.07.018.

National Research Council, Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution. Washington, DC, The National Academies Press, 2008.

Ohara, T., H. Akimoto, J. Kurokawa, N. Horii, K. Yamaji, X. Yan, and T. Hayasaka (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980–2020, *Atmos. Chem. Phys.*, 7, 4419–4444, doi:10.5194/acp-7-4419-2007.

Ran, L., Zhao, C. S., Xu, W. Y., Lu, X. Q., Han, M., Lin, W. L., Yan, P., Xu, X. B., Deng, Z. Z., Ma, N., Liu, P. F., Yu, J., Liang, W. D., and Chen, L. L. (2011) VOC reactivity and its effect on ozone production during the Hachi summer campaign, *Atmos. Chem. Phys.*, 11, 4657-4667, doi:10.5194/acp-11-4657-2011.

Redemann, J., Q. Zhang, J. M. Livingston, P. B. Russell, Y. Shinozuka, A. Clarke, R. Johnson, R. Levy (2009) Testing aerosol properties in MODIS Collection 4 and 5 using airborne sunphotometer observations in INTEX-B/MILAGRO, *Atmos. Chem. Phys.*, 9, 8159-8172, 2009.

Saide, P. E., Kim, J., Song, C. H., Choi, M., Cheng, Y., and Carmichael, G. R. (2014) Assimilating next generation geostationary aerosol optical depth retrievals can improve air quality simulations, Geophys. Res. Lett., 2014GL062089, 10.1002/2014gl062089, 2014.

Saide, P. E., G. R. Carmichael, Z. Liu, C. S. Schwartz, H. C. Lin, A. M da Silva, and E. Hyer (2013) Aerosol optical depth assimilation for a size-resolved sectional model: impacts of observationally constrained, multi-wavelength and fine mode retrievals on regional scale analyses and forecasts, *Atmos. Chem. Phys.*, 13, 10425-10444, 10.5194/acp-13-10425-2013.

Segal-Rosenheimer, M., P. Russell, B. Schmid, J. Redemann, J. Livingston, C. Flynn, R. Johnson, S. Dunagan, Y. Shinozuka, J. Herman, A. Cede, N. Abuhassan, J. Comstock, J. Hubbe, A. Zelenyuk, and J. Wilson (2013) Tracking Elevated Pollution Layers with a Newly Developed Hyperspectral Sun/Sky spectrometer (4STAR): Results from the TCAP 2012 and 2013 campaigns, *J. Geophys. Res.*, 119, doi:10.1002/2013JD020884.

Streets, D. G., T. Canty, G. R. Carmichael, B. de Foy, R. R. Dickerson, B. N. Duncan, D. P. Edwards, J. A. Haynes, D. K. Henze, M. R. Houyoux, D. J. Jacob, N. A. Krotkov, L. N. Lamsal, Y. Liu, Z. Lu, R. V. Martin, G. G. Pfister, R. W. Pinder, R. J. Salawitch, K. J. Wecht (2013) Emissions estimation from satellite retrievals: A review of current capability, *Atmos. Env.*, 77, 1011-1042, doi:10.1016/j.atmosenv.2013.05.051.

Sun, J., M. Zhang, and L. Tungsheng, Spatial and temporal characteristics of dust storms in China and its surrounding regions, 1960-1999, Relations to source area and climate, *J. Geophys. Res., 106*, 10,325-10,333, 2001.

Tie, X., F. Geng, A. Guenther, J. Cao, J. Greenberg, R. Zhang, E. Apel, G. Li, A. Weinheimer, J. Chen, and C. Cai, (2013) Megacity impacts on regional ozone formation: observations and WRF-Chem modeling for the MIRAGE-Shanghai field campaign, *Atmos. Chem. Phys.*, 13, 5655-5669, doi:10.5194/acp-13-5655-2013.

Valks, P., G. Pinardi, A. Richter, J.-C. Lambert, N. Hao, D. Loyola, M. Van Roozendael, and S. Emmadi (2011) Operational total and tropospheric NO_2 column retrieval for GOME-2, *Atmos. Meas. Tech.*, 4(7), 1491–1514, doi:10.5194/amt-4-1491-2011.

Wang, X. and D. L. Mauzerall (2004) Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020, *Atmos. Environ.*, doi:10.1016/j.atmosenv.2004.03.067.

Yum, S. S., G. Roberts, J. H. Kim, K. Song, and D. Kim (2007) Submicron aerosol size distributions and cloud condensation nuclei concentrations measured at Gosan, Korea, during the Atmospheric Brown Clouds–East Asian Regional Experiment 2005, *J. Geophys. Res.*, 112, D22S32, doi:10.1029/2006JD008212.

Glossary of Acronyms and associated URLs

ACE-Asia – Asian Pacific Regional Aerosol Characterization Experiment
AIRS – Atmospheric Infrared Sounder
AMF – Air Mass Factor
AOD – Aerosol Optical Depth
AQAST – Air Quality Applied Sciences Team
http://acmg.seas.harvard.edu/aqast/
ARCTAS - Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
https://espo.nasa.gov/arctas/
BB – Biomass Burning
CALIPSO – Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CalNex – California Nexus: Research at the Nexus of Air Quality and Climate Change
http://www.esrl.noaa.gov/csd/projects/calnex/
CARES – Carbonaceous Aerosols and Radiative Effects Study
http://campaign.arm.gov/cares/
CEOS – Committee on Earth Satellites Observations
http://www.ceos.org/
CINDI – Cabauw Intercomparison Campaign of Nitrogen Dioxide measuring Instruments
http://www.knmi.nl/samenw/cindi/
ClearfLo – Clean Air for London Project
http://www.clearflo.ac.uk/
CMAQ – Community Multi-scale Air Quality Model
CTM – Chemical Transport Model
DISCOVER-AQ – Deriving Information on Surface conditions from Column and Vertically-resolved observations relevant to Air Quality
http://discover-aq.larc.nasa.gov/
DOAS – Differential Optical Absorption Spectroscopy
DOMINO – Derivation of OMI tropospheric NO2
DRAGON – Distributed Regional Aerosol Gridded Observation Networks
http://aeronet.gsfc.nasa.gov/new_web/dragon.html
ESA – European Space Agency
FIR – Flight Information Region
FMF – Fine Mode Fraction
FTS – Fourier Transform Spectrometer
GEMS – Geostationary Environment Spectrometer
GEO – Geostationary Orbit
GEOS-Chem – Goddard Earth Observing System Chemical transport model
GOCI – Geostationary Ocean Color Imager
GOME – Global Ozone Monitoring Experiment
GOSAT – Greenhouse gases Observing Satellite
KARI – Korea Aerospace Research Institute
KMA – Korean Meteorological Agency
LEO – Low Earth Orbit
MAX-DOAS – Multi Axis Differential Optical Absorption Spectroscopy
MISR – Multi-angle Imaging SpectroRadiometer

MLS – Microwave Limb Sounder
MODIS – Moderate-resolution Imaging Spectroradiometer
MOPITT – Measurements of Pollution in The Troposphere
NIER – National Institute of Environmental Research
OCO-2 – Orbiting Carbon Obseratory-2
OMI – Ozone Monitoring Instrument
OMNO2 – OMI NO2 Aura Level-2 data product
OSSE – Observing System Simulation Experiment
PEM-West A/B – Pacific Exploratory Missions – West A and B
PM – Particulate Matter
POLDER – POLarization and Directionality of the Earth's Reflectances
REAS – Regional Emission inventory in Asia
S5P – Sentinel-5 Precursor
SCD – Slant Column Density
SCIAMACHY – Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
SOA – Secondary Organic Aerosol
TCCON – Total Carbon Column Observing Network
TEMPO – Tropospheric Emissions: Monitoring of Pollution
TES – Tropospheric Emission Spectrometer
TRACE-P – Transport and Chemical Evolution over the Pacific
http://www-air.larc.nasa.gov/missions/tracep/tracep.htm
VCD – Vertical Column Density
VOC – Volatile Organic Carbon
WRF-Chem – Weather Research and Forecasting model with Chemistry