Southeast Asia Composition, Cloud, Climate Coupling Regional Study (SEAC^{4}RS) Planning Document

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1. Introduction

The Southeast Asia Composition, Cloud, Climate Coupling Regional Study (SEAC^{4}RS) offers the opportunity to address science questions that bridge the full spectrum of interests for the component programs of the Atmospheric Composition Focus Area. Broadly stated, these interests are to facilitate "progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition." Southeast Asia defines a region which stands out globally in satellite observations. For instance, during the Asian monsoon (July-September), MLS CO observations are consistently enhanced over southern Asia each year. These observations point to the region's unique sensitivity to rapidly changing emissions of gas phase and aerosol pollutants in Asia. Simultaneously, this region also hosts one of the most complex meteorological and observing environments in the world. Understanding the sensitivity of this region to changes in climate and air quality requires knowlege of how dynamical, physical, chemical, and radiative processes are influenced by these emissions.

SEAC^{4}RS will take place in August and September of 2012. This deployment will address key questions regarding the influence of Asian emissions on clouds, climate, and air quality as well as fundamental satellite observability of the system. Science observations will focus specifically on the role of the Asian monsoon circulation and convective redistribution in governing upper atmospheric composition and chemistry. Satellite observations suggest a strong impact of the Asian Summer Monsoon on Tropopause Transition Layer (TTL) composition and a direct relationship to surface sources including pollution, biogenic emissions, and biomass burning. Attention will also be given to the influence of biomass burning and pollution, their temporal evolution, and ultimately impacts on meteorological processes which in turn feed back into regional air quality. With respect to meteorological feedbacks, the opportunity to examine the impact of polluting aerosols on cloud properties and ultimately dynamics will be of particular interest. To accomplish the goals of SEAC^{4}RS, multiple aircraft are required. The NASA DC-8 will provide observations from near the surface to 12 km, and the NASA ER-2 will provide high altitude observations reaching into the lower stratosphere as well as important remote sensing observations connecting satellites with observations from lower flying aircraft and surface sites. A critical third aircraft needed to sample convective outflow and slow ascent of air above the main convective outflow level (~12 km) has been identified as the NSF/NCAR GV (HIAPER). Participation by the GV will be through a collaboration in which the DC-8 will participate in the NSF-sponsored DC3 mission. Details of this collaboration are discussed in more detail later in this document. Basing the aircraft in Thailand is optimal for achieving science objectives with a preferred base in Surat Thani, Thailand (9.1° N 99.1 ° E), although options in Bangkok (13.6 ° N, 100.7 ° E) are also under consideration.

To maximize scientific return, SEAC^{4}RS is pursuing multiple international and interagency collaborations. Of these, the most well established is 7SEAS (7 Southeast Asian Studies), a regional partnership of scientists from throughout Southeast Asia and the United States aimed at addressing the specific issue of how aerosol particles impact meteorological processes, and precipitation in particular. Under 7SEAS, surface observations across the region will be conducted over several years, and SEAC^{4}RS will provide key intensive observations over a short period that will contribute to improving the interpretation of these longer-term observations and their connection to well established satellite datasets. Mature collaboration plans have also developed regarding NSF's DC3 (Deep Convection, Clouds, and Chemistry) experiment. Proposed for the May-June 2012 period over North America, DC3 seeks to investigate the impact of deep, midlatitude continental convective clouds, including their dynamical, physical, and lightning processes, on upper tropospheric (UT) composition and chemistry. These goals are in strong alignment with those of SEAC^{4}RS. Since the GV aircraft will be instrumented to address the sampling of convective outflow, its deployment in SEAC^{4}RS as the third aircraft needed to characterize the full tropospheric column is ideal. Conversely, the DC-8 will be appropriately instrumented to participate in DC3, alleviating the need for NSF to field a second aircraft. This collaboration is both a cost-effective use of the research aircraft and an efficient way to engage the atmospheric science community that both NASA and NSF rely on to accomplish SEAC^{4}RS and DC3 science objectives. European colleagues have also expressed a desire to collaborate with SEAC^{4}RS as they intend to deploy to the region. The German HALO research aircraft, also a GV, is the primary candidate for deployment. This activity is in the proposal stages, but collaboration in the form of shared planning documents is already underway. Discussions are also taking place with colleagues in Nepal to possibly extend the geographic reach of SEAC^{4}RS. Engagement of Nepalese scientists could enable flights over the interior of the Asian continent which would greatly improve sampling of the Asian monsoon anticyclone. Finally, SEAC^{4}RS recognizes the need to integrate with ongoing observing programs which provide an important long-term perspective. This includes the SHADOZ ozonesonde network led by Anne Thompson, which has two sites in the domain of interest (Kuala Lumpur, Malaysia and Watukosek, Java) with another soon to be added in Hanoi, Vietnam. CARIBIC and MOZAIC observations from commercial aircraft are another valuable source of complementary data useful for pre-mission planning as well as extending observations of key variables during the experiment. Official collaborations with these groups will be negotiated. While many of these opportunities need to mature, it is clear that substantial collaboration is expected and will play an important part in the success of SEAC^{4}RS.

2. Background

Much remains to be understood regarding atmospheric composition and the processes controlling its evolution and distribution. Continual progress in our ability to simulate current and future atmospheric composition is critical to reducing uncertainties in anthropogenic influences and the expected impacts on climate and air quality. As we focus on the role of field observations, which provide important detail but are necessarily limited in time and space, it is important to capitalize on what satellite observations can tell us about regions of high sensitivity to change. One region that stands out in recent observations is the UT/LS (upper troposphere/lower stratosphere) over Asia during the summer monsoon (June-August). While ozone and water vapor in the Asian summer monsoon anticyclone have been previously evaluated using HALOE and SAGE observations [*Rosenlof et al.*, 1997; *Jackson et al.*, 1998; *Dethof et al.*, 1999], more recent MLS observations of CO have highlighted an important pollution component to the composition of air trapped within this closed circulation pattern [*Li et al.*, 2005a, *Fu et al.*, 2006; *Jiang et al.*, 2007; *Park et al.*, 2007]. Onboard Canada's SCISAT, ACE (Atmospheric Chemistry Experiment) observations of elevated HCN (a biomass burning tracer) and hydrocarbons (i.e., C_2H_6 and C_2H_2) provide additional evidence for pollution entering this circulation [*Park et al.*, 2008; *Randel et al.*, 2010]. In this same region, considerable attention has also been attracted by severe biomass burning events in Indonesia, typically occurring in the August-October timeframe but also having significant interannual variation in timing and intensity [*Heil and Goldammer*, 2001; *Duncan et al.*, 2003a; *van der Werf et al.*, 2008]. Both of these phenomena are expected to respond to and have potential feedbacks on climate and meteorology from local to global scales. For instance, upper tropospheric outflow from this region followed by downwelling over the Middle East appears to be a major contributor to the large tropospheric ozone maximum observed there, representing an important case of teleconnection in chemistry-climate interactions [*Li et al.*, 2001].

Figure 1 [*Park et al.*, 2007] shows the climatological location of the Asian monsoon anticyclone and contours of OLR (outgoing longwave radiation) indicating the pattern of convection during the Asian monsoon. As noted by Park et al., satellite observed tracers within the anticyclone (e.g., CO, O_3, and H_2O) correlate best with changes in OLR within the region of ~60-120°E and 15-30°N (see highlighted box in figure 1), suggesting that the main region of convection delivering pollution into the UT/LS is located just outside and to the southeast of the anticyclone.

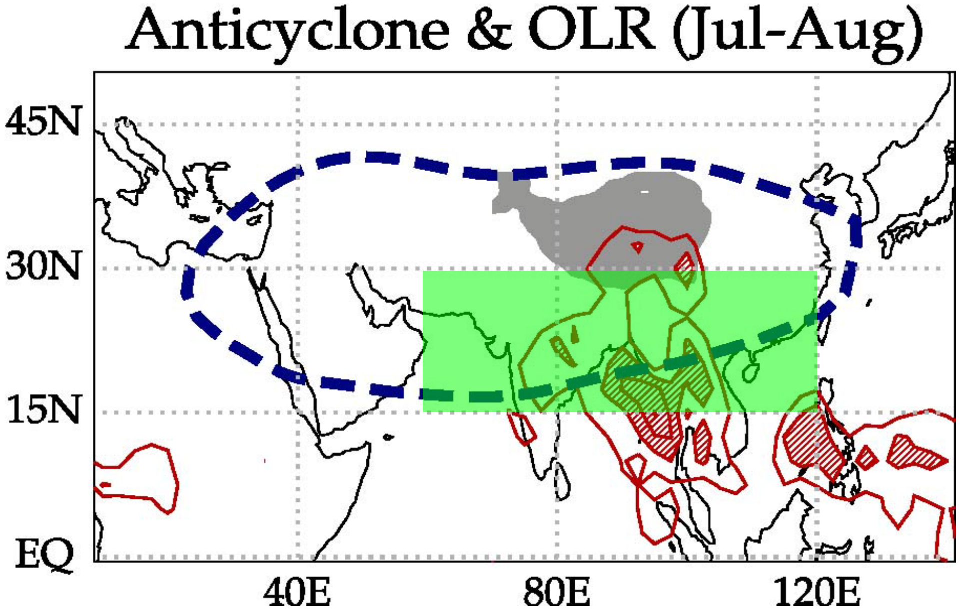

Figure 1. Climatological location of the monsoon anticyclone (blue dashed line; defined as a streamfunction calculated from NCEP horizontal winds, contour: 400 m^2 s^{-1}) averaged in July-August 2005. Red contours indicate deep convection (OLR contours of 205, 195, 185… W m^{-2}, with values below 195 hatched red), and Tibetan plateau is shown as gray shading where elevation is ≥3 km. Green shaded area is region for which OLR most closely correlates with tracer observations within the anticyclone at 100 hPa. (Figure taken from *Park et al.*, 2007)

Figure 2 [*Livesey et al.*, 2008a] shows the seasonal and interannual variability of IWC (ice water content), CO, and O_3 as observed by MLS in the upper troposphere at 215 mb (~11 km) over Southeast Asia for a four year period between July 2004 and October 2008. IWC observations clearly show the consistency in Asian monsoon convection over Southeast Asia each year from June to September. By contrast, observations over Indonesia indicate significant, but variable, convective activity year-round. CO observations show an upper tropospheric maximum in CO that is coincident with the enhancements in IWC over Southeast Asia. This CO maximum stands out both regionally and globally as the largest consistently observed perturbation to UT/LS composition. Larger enhancements can be seen in October-November associated with biomass burning over Indonesia in 2006, but this is not a consistently observed feature. Finally, O_3 exhibits a distinct annual minimum associated with the Asian monsoon. This is presumably due to the convection of ozone-poor air from the boundary layer, but this contrasts sharply with the observed increase in O_3 due to convection within the anticyclone associated with the North American summer monsoon [*Li et al.*, 2005b; *Cooper et al.*, 2006, 2007]. The reasons for this difference are unclear but one can conjecture that differences in boundary layer conditions and/or the abundance of lightning NO_x might play a role.

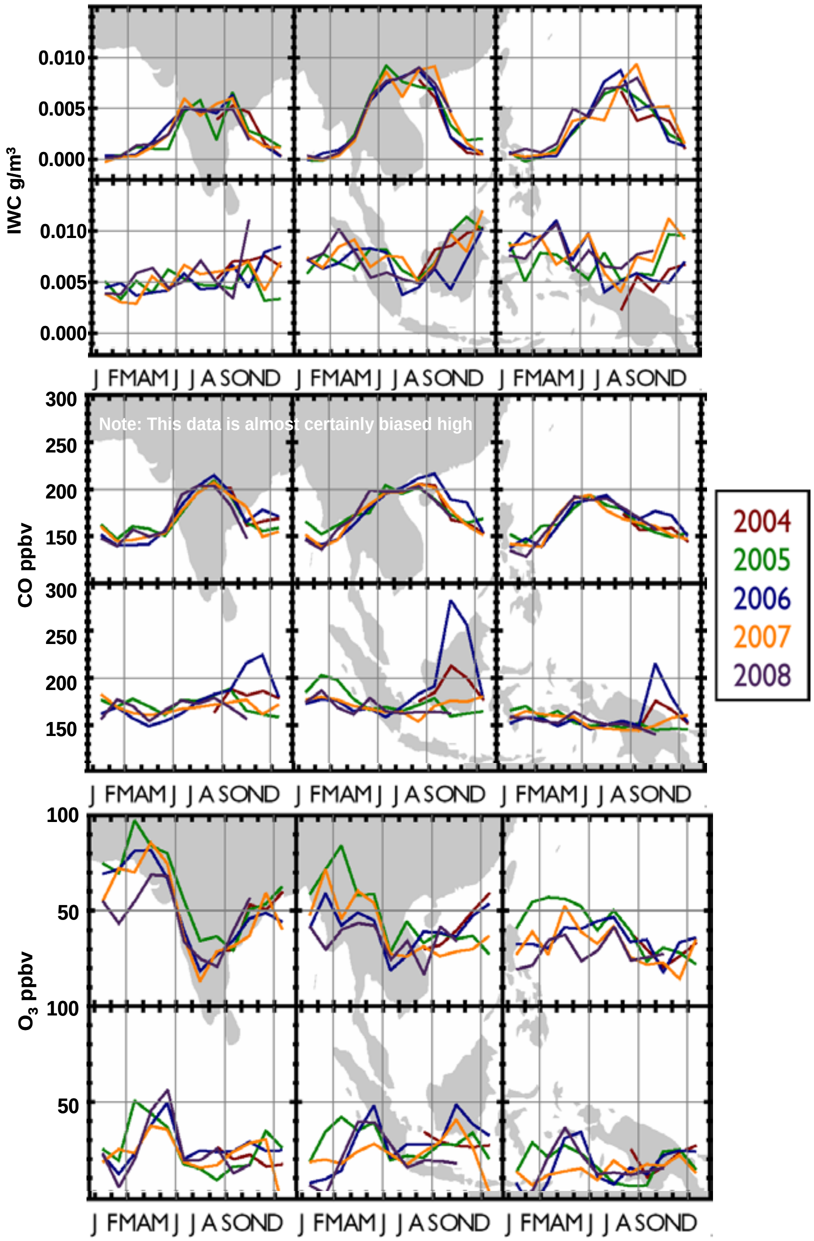

Figure 2. Seasonal and interannual variability in MLS observations of IWC, CO, and O_3 at 215 hPa from July 2004 to October 2008. (Figure extracted from *Livesey et al.*, 2008a)

Figure 3 [*Jiang et al.*, 2007] shows how the enhancement in MLS CO during July overlaps well with Asian monsoon convection at 215 mb with a shift at higher altitudes (147 and 100 mb) towards the anticyclone. While the July data might give the impression that the convection preferentially feeds the Asian monsoon anticyclone, Jiang et al. also provides observations (not shown here) of long-range transport eastward over the Pacific. In contrast to the anticyclone, however, these transport events are transient and thus are not as apparent in a monthly average. During October, enhancements in CO appear to relate more closely to biomass burning over Indonesia and show more overlap vertically. CO at the highest level (100 mb) during October tends to exhibit transport eastward into the TTL (Tropical Tropopause Transition Layer) over the western Pacific.

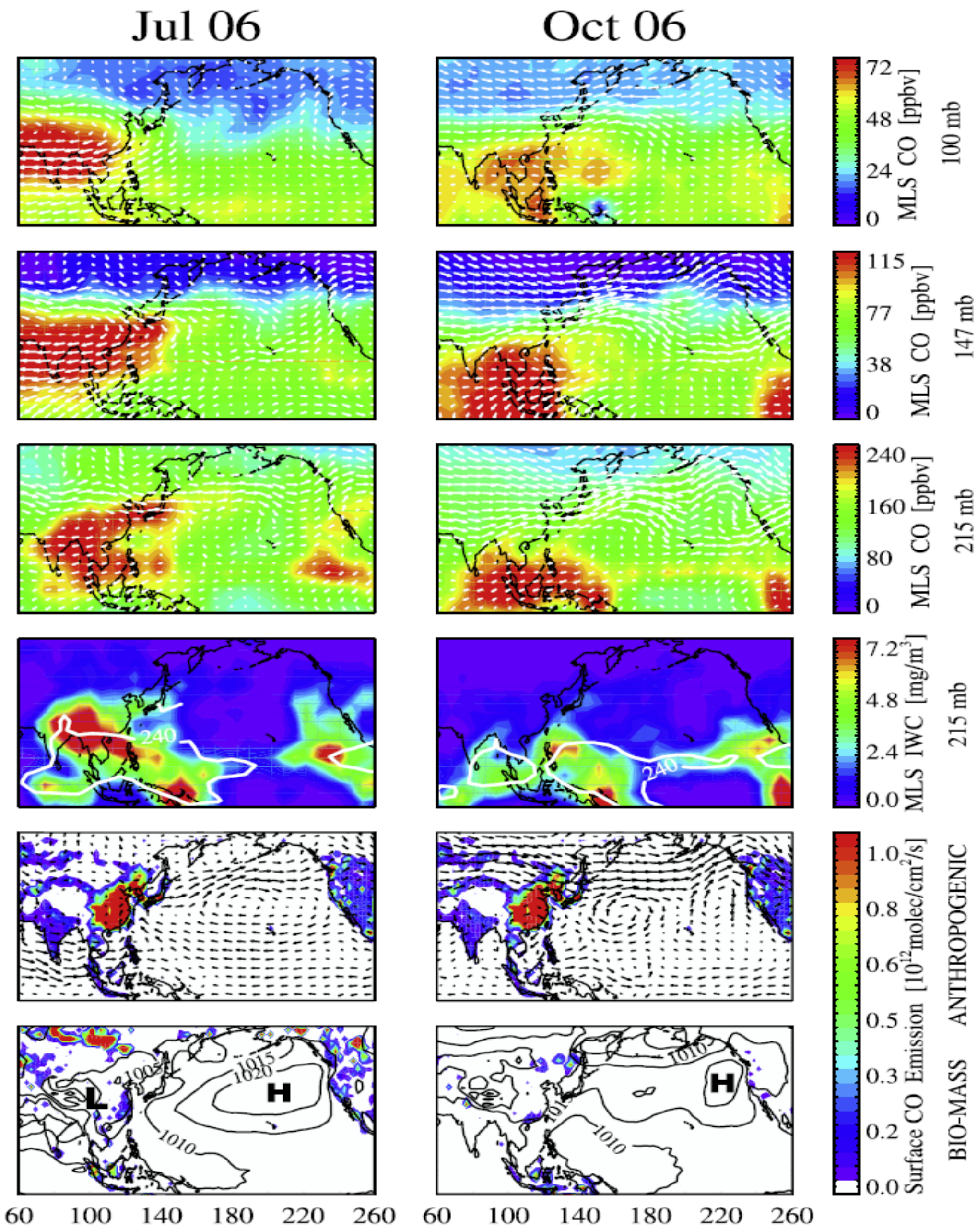

Figure 3. Monthly mean values (July and October 2006) averaged on 8°×4° longitude by latitude grids. MLS CO values are overplotted by NCEP vector winds at the pressure level of the observations. IWC is overplotted with the 240 W/m^2 OLR contours from NCEP. Anthropogenic CO emissions are overplotted by NCEP 900 hPa vector winds. Biomass burning emissions are overplotted by NCEP sea-level pressures. (Figure extracted from *Jiang et al.*, 2007)

3. Scientific Rationale

The reasons for seeking to better understand the influence of the Asian monsoon circulation, anthropogenic emissions from Southeast Asia and Indonesian biomass burning on atmospheric composition are multi-faceted:

The Asian monsoon anticyclone is believed to be a dominant pathway for transport from the troposphere into the stratosphere. A modeling study by *Gettelman et al.* [2004] suggests that transport within the anticyclone could account for as much as 75% of the total net upward water vapor flux in the tropics at tropopause levels between July and September. Based on convective cloud top statistics (see Figure 4), *Fu et al.* [2006] argue that the primary impact on the lower stratosphere comes from overshooting convection over the Tibetan plateau and its southern slope. *Park et al.* [2007] contend that slower ascent of convective outflow from lower altitudes could also play an important role, although large uncertainties in vertical velocities for the UT/LS prevent a definitive judgement.

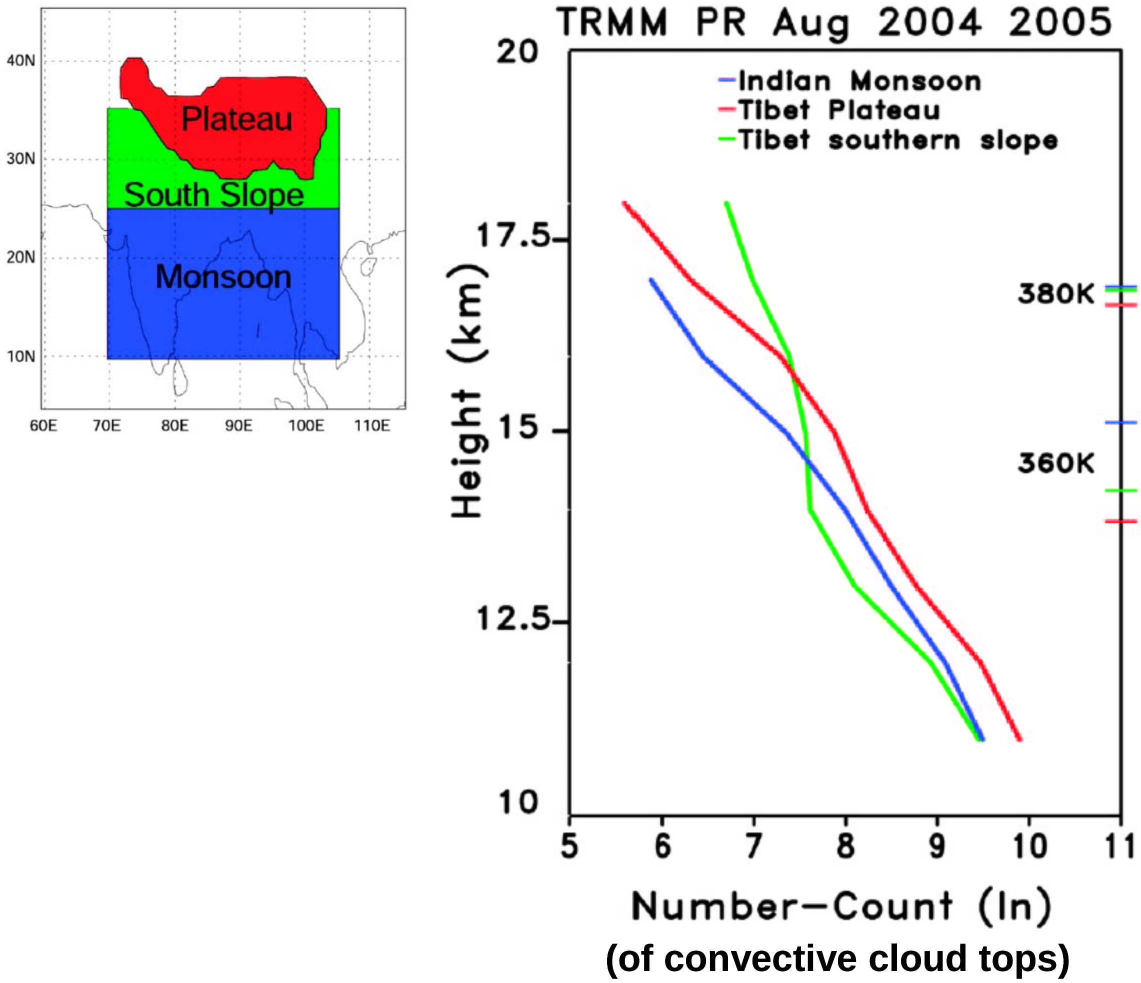

Figure 4. Number counts of convective tops >10 km as a function of altitude over the Tibetan Plateau (red), Tibet southern slope (green), and monsoon region (blue) during the period of August 2004 and 2005 derived from TRMM PR rain rate (product 2A25). The tropopause (380 K) and 360 K in these three regions are indicated on the right axis with the same color as defined for the profiles. (Figure taken from *Fu et al.*, 2006)

More recently, Randel et al.[2010] presented observations of elevated HCN (a biomass burning tracer) from ACE (Atmospheric Chemistry Experiment) onboard Canada's SCISAT. As shown in Figure 5, these observations provide clear evidence for pollution entering the stratosphere, bypassing the tropical tropopause.

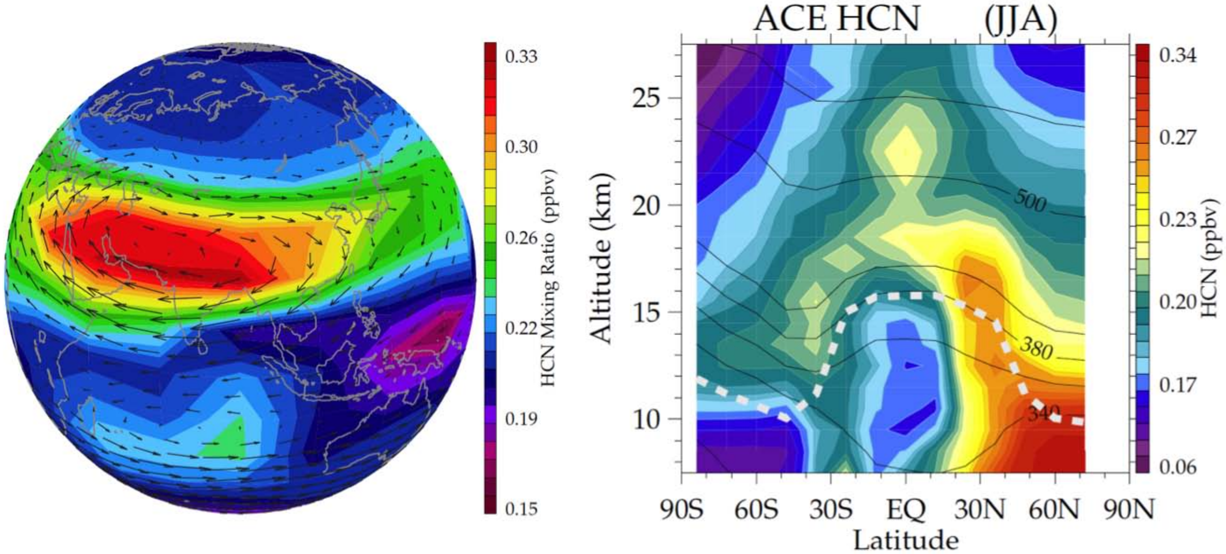

Figure 5. (left) Climatological mixing ratio of hydrogen cyanide (HCN) near 16.5 km during NH summer season (JJA) derived from ACE satellite measurements (color contours), together with wind vectors highlighting the Asian monsoon anticyclone. (right) Latitude-height cross section of HCN from ACE data, showing extension of the HCN plume across the tropopause (white dashed line) into the stratosphere. [Randel et al., 2010].

Convection over Southeast Asia and Indonesia is associated with uniquely diverse and rapidly changing emissions. Much attention has been paid to rising emissions in Asia [*Streets et al.*, 2001, 2003; *Richter et al.*, 2005; *Akimoto et al.*, 2006; *Zhang et al.*, 2009], which are tied to both its high population density (see figure 6) and potential for economic growth. *Zhang et al.* [2009] estimate that between 2001 and 2006, Asian anthropogenic emissions increased by 33% for SO_2, 44% for NO_x, 18% for CO, 25% for NMVOC and 11% for BC. Uncertainty in emissions over Southeast Asia is exacerbated by widespread use of biofuels within the residential sector which add significantly to emissions of CO, VOCs, and carbonaceous aerosols. Additional pollution sources in the local maritime environment due to ship traffic are concentrated throughout the South China Sea and across the southern end of the Bay of Bengal [*Wang et al.*, 2008]. These anthropogenic emissions overlap with large biogenic emissions from tropical rainforests across Southeast Asia and Indonesia as well as marine emissions of sulfur and halogen compounds that lead to the expectation of a uniquely diverse chemistry both near the surface as well as throughout the troposphere after convective redistribution. Lightning generated NO_x is associated with deep convection in the region. Widespread volcanism throughout Indonesia adds additional complexity. Although volcanic emissions constitute a small contribution to the sulfur and aerosol budgets across the region [*Spiro et al.*, 1992], there is potential for large local influences. Finally, biomass burning is a highly variable but potentially dominant source of pollution over Indonesia each fall [[e.g., *van der Werf et al.*, 2006; 2008; *Giglio et al.*, 2006; *Field et al.*, 2008; 2009; *Reid et al.*, 2009].]. The onset of burning in August overlaps with the end of the Asian monsoon (see figure 7) and evidence of continued influence on UT/LS composition due to ITCZ convection is evident in MLS observations for October 2006 (see figure 3).

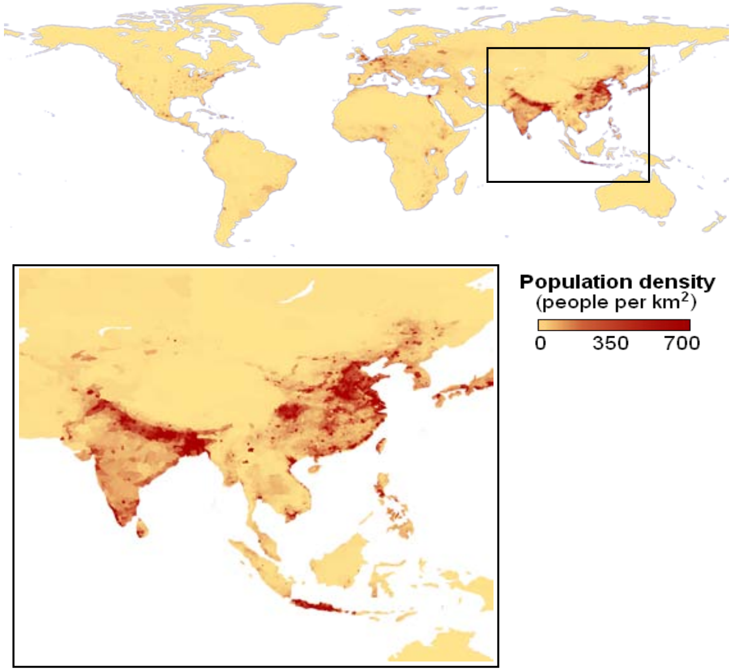

Figure 6. Global population density in 1994 as reported by the National Center for Geographic Information and Analysis. The data were derived from population records based on political divisions such as states, provinces, and counties. Because the resolution of the data from different nations varies, some small areas with high populations (such as Rio de Janeiro, Brazil) appear to have moderate population density spread over large areas.

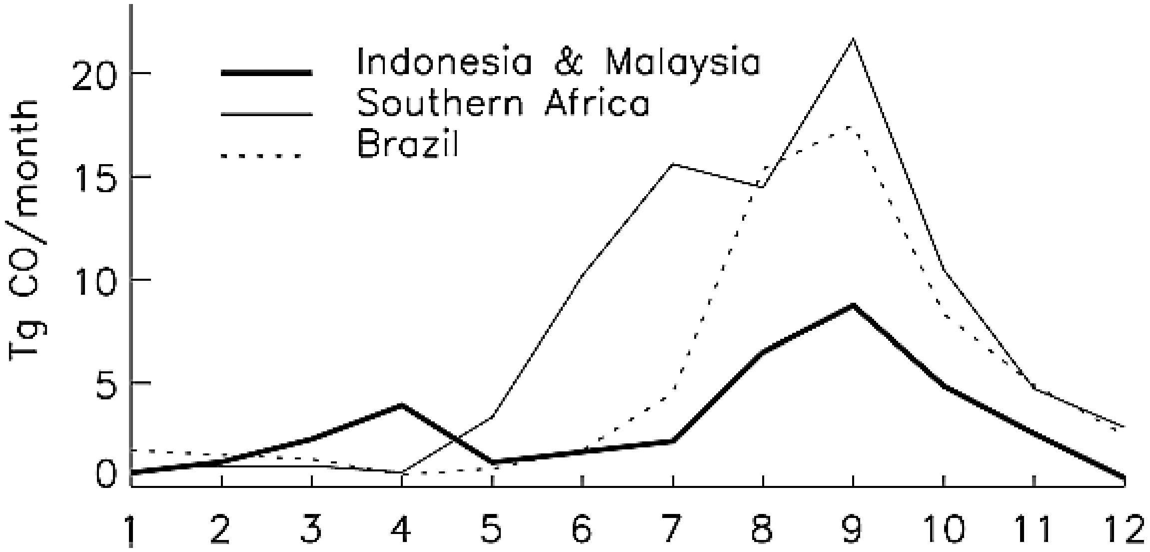

Figure 7. Average biomass burning emission rate (Tg CO per month) for Indonesia, Southern Africa, and Brazil. (Figure taken from *Duncan et al.*, 2003a)

Asian monsoon convection and surface emissions from multiple sources in Southeast Asia have relevance to both climate and air quality. The climatic impact of polluting gases and aerosols over Southeast Asia is directly influenced by Asian monsoon convection. Convective pumping of pollutants into the UT/LS influences the photochemistry of ozone at altitudes where its greenhouse forcing potential is greatest [*Lacis et al.*, 1990; *Gauss et al.*, 2006]. Teleconnection to the Middle East delivers high ozone to that region where clear skies and high surface temperatures result in particularly effective ozone radiative forcing [*Li et al.*, 2001]. Properties of cirrus anvils (e.g., persistence and ice particle radius) may also be influenced by pollution [*Jiang et al.*, 2008 and references therein]. Although widespread burning in Indonesia is driven by human activities (e.g., small and large-scale agriculture and logging), annual severity can be closely tied to local climate influences on precipitation [*Field and Shen*, 2008]. In turn, smoke aerosols from these fires can have a large influence on the tropical radiation budget, cloud properties, and tropospheric oxidation chemistry [*Duncan et al.*, 2003b]. While air quality is most visibly impacted by regional fires, air quality will continue to degrade with growth in anthropogenic emissions across Southeast Asia and the increasing concentration of population within megacities throughout the region (e.g., Jakarta, Bangkok, Calcutta, Dhaka, and Manila). At tropical latitudes, local pollution effects are also more pronounced as more intense sunlight and higher humidity allow pollution chemistry to proceed at a faster pace. In contrast to mid-latitudes, where frontal passages play a dominant role in the clearing of pollution, deep convection takes on a prominent role in ventilating the tropical polluted boundary layer, leading to long-range transport of pollution at higher altitudes.

Regional aerosol forcing could alter large-scale climatological features such as the Migration of InterTropical Convergence Zone (ITCZ), drought effects of the El Nino Southern Oscillation (ENSO), and the propagation of the Madden Julian Oscillation (MJO). The migration of the ITCZ, ENSO and the MJO are strongly linked to convective precipitation onset and intensity[Chang et al. 2004; Zhang, 2005; Field and Shen, 2008]. Relative to these large dynamical features, the significance of aerosol and cloud impacts is unclear. At regional scales, atmospheric radiation feedbacks between aerosol absorption and shallow cloud cover are also complicated in the tropical atmosphere (e.g., *Mcfarquhar and Wang*, 2006). With respect to cloud developments, there have been suggestions of both increased lighting severity (*Hamid et al.,* 2001) and decreased ice crystal size and perhaps precipitation (*Jiang et al.*, 2008). However, it is possible that there are scale relationships between the meso- and long-wave scales. It has been noted that strong, warm ENSO years result in increased smoke in Southeast Asia. It has also been hypothesized that smoke intensifies ENSO precipitation, thus creating a positive feedback mechanism [e.g., *Graf et al.*, 2009]. Simultaneously, model simulations suggest smoke enhancements of drought conditions [*Tosca et al.*, 2010]. Others have speculated that a radiative tipping point exists which allows rapid migration of the ITCZ [e.g, *Xian and Miller*, 2008]. A fundamental question is whether aerosol particles can influence this tipping point and delay migration for days to weeks, or are aerosol micro and mesoscale impacts too weak to cause large meteorological shifts in the region. Given the general lack of field data and poor satellite observability of SE Asia coupled with the fact that meteorological models often have difficulty replicating even basic features of the region, these hypotheses are largely speculative. SEAC^{4}RS data on basic smoke and pollution transport, microphysical properties and optical efficiencies will be imperative to help constrain and interpret the satellite and model data necessary to answer these questions.

Satellite observations over this region require both validation and correlative observations to maximize their utility for understanding influences of convective redistribution, changing emissions, and biomass burning on atmospheric composition. While the morphology of MLS CO (version 2) is believed to be robust, observations at 215 hPa exhibit a positive bias of about a factor of two when compared to observations from NASA field campaigns and MOZAIC observations from commercial aircraft [*Livesey et al.*, 2008b]. This is corroborated by in situ observations shown in Figure 8 from CARIBIC flights [*Brenninkmeijer et al.*, 2007] which exhibit a clear enhancement in CO over India at 10.5 km (~245 hPa), although peak values are in the range of 100-110 ppbv. More importantly, the CARIBIC observations of other VOCs show a complex mixture of pollution within the Asian monsoon anticyclone. Validation of MLS CO is critical to appropriately scaling the impact of convection on UT/LS composition. Additionally, detailed observations of convective impacts on UT/LS composition are needed to assess the utility of CO observed from space as a proxy for expected enhancements in other related pollutants. Additionally, satellite observations from Glory, CALIPSO, MODIS, and MISR will benefit from detailed aerosol and radiation measurements to better understand the direct radiative impact of aerosols and enable better application of techniques to differentiate "polluted" and "clean" clouds in satellite analyses (e.g., *Jiang et al.*, 2008 and references therein). Despite the recent setback experienced by OCO, observations of the vertical distribution of CO_2 along with detailed composition are needed to aid current (e.g., JAXA's GOSAT) and future satellites in the interpretation of carbon sources and sinks in this region of diverse anthropogenic and biogenic influences.

Future satellite missions such as those proposed in the Decadal Survey require data collection opportunities to refine science, algorithm, and hardware requirements. Several important satellite missions are in a science definition phase, including the National Research Council's Decadal Survey recommended Aerosol Clouds Ecosystems (ACE) and Geostationary Coastal and Air Pollution Experiment (Geo-CAPE). Scientists working on mission designs for these satellites require suitably scaled data collection to develop appropriate algorithms and hardware requirements. Examples of critical programs include: 1) Unifying CO_2, CO and aerosol satellite products to better constrain emissions; 2) Developing satellite-based remote sensing data products (combining new and existing sensors and retrieval algorithms) to meet the requirements of constraining aerosol lifecycle budgets as well as direct, semi-direct and indirect forcing; and 3) Developing remote sensing data products to support joint atmosphere and ocean investigations. The tropical coastal environment of Southeast Asia is a superb location to push the technological envelope in these and other mission support areas.

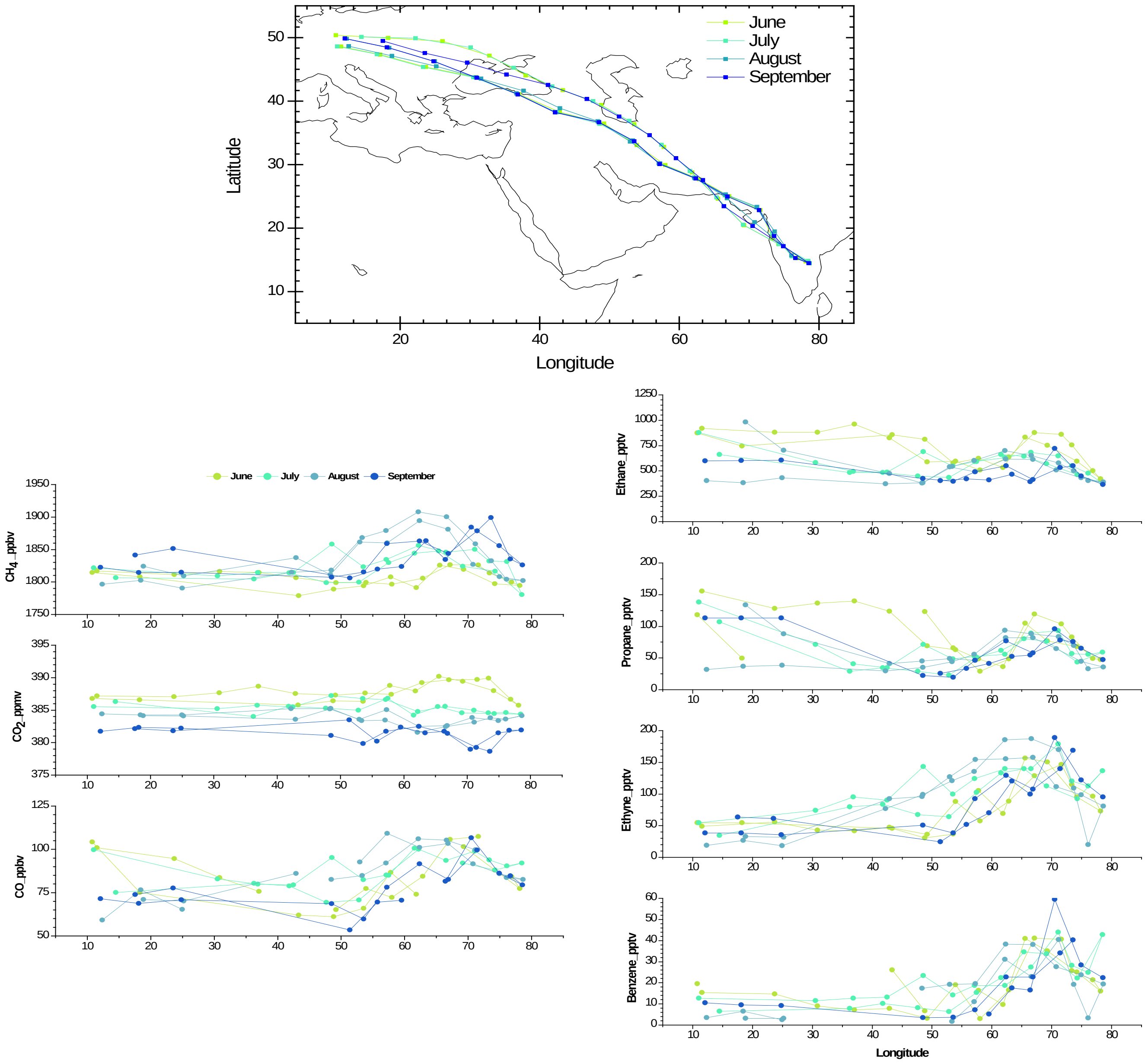

Figure 8. Observations from CARIBIC flights [Brenninkmeijer et al., 2007] between Frankfurt and Madras showing enhancements in pollution tracers at 10.5 km within the Asian monsoon anticyclone from June to September.

4. Science Questions

Given the realities of political and logistical limitations, it is clear that this region cannot be studied to the level warranted by purely scientific motives. For instance, the Asian monsoon anticyclone often develops, in part, over areas for which overflight clearance has a very low probability of being granted. On the other hand, much of the region of Asian monsoon convection responsible for delivering surface emissions into the anticyclone is either over water or in areas of medium-to-high probability of permission for overflight. Likewise, regions of biomass burning are expected to be largely accessible to research aircraft. For this reason, the science questions addressed by this experiment will emphasize convection and the connection it establishes between surface sources and UT/LS conditions. Specific questions to be addressed are listed below and discussed in the following section.

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1. How are pollutant emissions in the tropics redistributed via deep convection throughout the troposphere?

- **1a. What fraction of boundary layer air reaches the UT/LS region?**
- **1b. What is the convective transport efficiency of individual gas and aerosol constituents?**
- **1c. How do surface inflow conditions influence convective transport?**

2. What is the evolution of gases and aerosols in deep convective outflow and what are the implications for UT/LS chemistry?

- **2a. What constituents have the greatest influence on ozone and oxidation chemistry in convectively perturbed air masses?**
- **2b. How does the presence/absence of lightning generated NO_x influence the ozone and oxidation chemistry of convectively perturbed air masses?**
- **2c. What is the evolution of aerosol in deep convective outflow and what are the implications for the upper tropospheric aerosol?**
- **2d. What is the role of convective cirrus in modifying the chemistry of the upper troposphere?**
- **2e. What are the vertical gradients of ozone, aerosols, and related species across the UT/LS?**

3. What influences and feedbacks do aerosol particles from anthropogenic pollution and biomass burning exert on meteorology and climate through changes in the atmospheric heat budget (i.e., semi-direct effect) or though microphysical changes in clouds (i.e., indirect effects).

- **3a. What altitude dependent heating rates do absorbing aerosol induce in SE Asia?**
- **3b. What are the basic microphysical properties of smoke and pollution particles in the region and are there any relationships between cloud properties and aerosol supply?**
- **3c. Based on the mechanisms of 3a, b, are there any impacts of aerosol particles on convection distribution, onset, and vertical development?**
- **3d. How do aerosol-cloud interactions modify the distribution and transport of aerosol?**

Question 1. How are pollutant emissions in the tropics redistributed via deep convection throughout the troposphere?
There is abundant evidence for convective perturbation of the UT/LS in various airborne and satellite observations. Nevertheless, evaluations of convective redistribution based on concurrent observations from the surface to the altitude of convective outflow are extremely rare and have often been challenged by shortcomings in either the suite of measurements or the altitude range over which observations were conducted. The intent during SEAC^{4}RS will be to characterize the pre and post-convective condition over the full column of convective influence using multiple aircraft with complementary measurements. This approach will allow investigation of the following related questions.

Question 1a. What fraction of boundary layer air reaches the UT/LS region?
Convective outflow is the result of complex transport and mixing due to entrainment and detrainment at various levels throughout a convective storm. While this question may seem oversimplified, it is fundamental to the question of how effectively convection redistributes surface emissions. For very short-lived species, convection is the only mechanism by which they might exist in the upper atmosphere. It is that same short lifetime that requires observations to be made in the vicinity of fresh outflow. For some species, transport to the UT/LS can lengthen lifetime (aerosols) or drive chemistry (gases). Inert or very long-lived species can also be useful to assess convective influence. For instance, depressed CO_2 in convective outflow over a region of biogenic uptake can be an excellent indicator of transport from the surface. The connection between ozone in the boundary layer and UT/LS, as reflected in the MLS data (Figure 2) is intimately tied to deep convection.

Question 1b. What is the convective transport efficiency of individual gas and aerosol constituents?
Wet removal associated with convective precipitation plays a critical role in controlling the distribution of soluble species and atmospheric cleansing. Many of these soluble species are intermediate or reservoir species that are critical to controlling atmospheric oxidation chemistry (e.g., H_2O_2, ROOH, CH_2O, HNO_3). Since these species originate from photochemistry, it is again important to collect observations in the vicinity of fresh outflow to obtain an initial condition from which wet removal and subsequent influence on UT/LS chemistry can be evaluated. Similarly, observations are needed to assess the efficiency of removal for various aerosol types (e.g., sulfate, black carbon, and organics) and the rate of new particle formation in convective outflow. The effect on scavenging of cloud riming and ice crystal formation at higher altitudes in the convective column is another major area of uncertainty deserving attention.

Question 1c. How do surface inflow conditions influence convective transport?
While this is a particularly difficult question to address, there are clear expectations that boundary layer composition (e.g., clean, polluted, smoky, dusty, etc.) has relevance to convective intensity and in some instances may even suppress it through local atmospheric heating and the creation of stable layers. The abundance, size distribution, and chemical characteristics of aerosol drawn into a system might impact the physics of the convection,

modifying updraft velocities, tower heights and precipitation fields (impacting scavenging). An important goal with respect to this question will be to target a diverse set of boundary layer conditions providing inflow to different convective storms. The study region should allow for a combination of conditions spanning marine/terrestrial and clean/polluted conditions.

Question 2. What is the evolution of gases and aerosols in deep convective outflow and what are the implications for the UT/LS chemistry?
This second broad question acknowledges the increased chemical activity associated with delivering short-lived polluting gases and ozone precursors into the UT/LS and the need for observing a comprehensive suite of trace gases and aerosol chemical and physical properties to understand the ultimate impact of convection on UT/LS composition. The intent during SEAC^{4}RS will be to sample UT/LS air of various ages after convection to allow investigation of the following related questions.

Question 2a. What constituents have the greatest influence on ozone and oxidation chemistry in convectively perturbed air masses?
Given the role of water vapor and ozone in primary production of radicals, convective influence on these two quantities alone is fundamental to establishing the oxidative environment. However, the relative importance of other radical sources (e.g., acetone and convected radical reservoirs) is often maximized in the upper troposphere. Furthermore, it is expected that ozone photochemistry would proceed through a series of stages as precursors of various lifetimes are consumed. Very short-lived VOCs could provide an intense initial burst of radical activity that would subside well within the first day. While somewhat speculative, substantial convection of isoprene (~500 pptv) to an altitude of 10 km was observed during the recent ARCTAS campaign during a flight over central Canada during summer. Given the extremely short lifetime of isoprene (~1 hour), it is imperative that measurement of these species occur at the appropriate altitudes and proximities to fresh convective outflow. Similarly, convected formaldehyde would be expected to exert influence on radical levels for about a day on average before settling into photochemical equilibrium with the ongoing decay of convected VOCs. To the extent that peroxides are convectively enhanced, they could remain perturbed for a few days, depending on ambient NO_x conditions. Convected halogen species may also be found to play an important role. The ultimate effectiveness of these convected species is tied to the NO_x abundance, which is discussed in the question below.

Question 2b. How does the presence/absence of lightning generated NO_x influence the ozone and oxidation chemistry of convectively perturbed air masses?
NO_x ($NO+NO_2$) plays a central role in ozone photochemistry. In the upper troposphere, the role of NO_x in controlling radical abundances is increased due to several factors. First, the partitioning of NO_x is shifted in favor of NO due to the temperature dependence of the O_3+NO reaction. As NO_x loss is primarily through reactions involving NO_2, this shift in partitioning is largely responsible for extending the lifetime of NO_x to as long as one week in the upper troposphere in contrast to a lifetime that is generally less than one day at the surface. The yield of radicals from OVOCs (e.g., acetone) and the oxidation of other hydrocarbons is increased in the presence of NO_x, which favors the production of

formaldehyde rather than organic peroxides. HO_x recycling is also enhanced in the presence of NO_x, leading to the regeneration of OH at the expense of peroxy radical reactions leading to formation of peroxide reservoir species. Finally, NO_x enhancement can result from both direct convection as well as in situ production due to lightning. In contrast to observations of convectively enhanced O_3 over North America during summer, MLS observations show O_3 in the upper troposphere over Southeast Asia to be depressed due to convection. It is important to understand this difference and how it might be related to differences in boundary layer composition, lightning generation, and chemistry in the convective outflow. Assessing the reactive nitrogen budget will also be of importance. Quantifying the contribution of NO_x released from PAN injected to the UT over the course of the Walker circulation loop is a key objective. Past missions have also shown that HNO_3/NO ratios in the UT are much lower than simulated by standard photochemical models [*Hudman et al.*, 2007]. Given the utility of this ratio as a photochemical clock [Bertram et al., 2006], it is important to understand why models have difficulty with this quantity.

Question 2c. What is the evolution of aerosol in deep convective outflow and what are the implications for the upper tropospheric aerosol?

Understanding the formation and evolution of particles in deep convective outflow is of great importance for the aerosol budget in the UT/LS and in subsiding regions of the tropics. Water-soluble particles are expected to be efficiently scavenged in deep convection, but the fate of less soluble black carbon (BC) or dust particles is more uncertain. Fast nucleation of new particles is frequently observed in deep convective outflow but the mechanisms are not clear. Complex evolution of the aerosol may take place as the outflow ages, due notably to gas-aerosol exchange of organic compounds at the very low temperatures. Limited observations in the upper troposphere suggest that ammonia may escape convective scavenging, possibly because of low retention efficiency during drop freezing, and this would have profound implications for nucleation and growth of particles in the convective outflow. In addition, the mixture of boundary layer gases transferred to the UT by convection will interact with preexisting aerosol. Marine biogenic sulfur compounds may add to the mass of UT/LS aerosol, or play a role in nucleation. Perhaps more importantly, organic compounds detrained from deep convection may coat UT aerosol and modify their radiative and CCN/IN properties. It is likely that the impact of organics on aerosol in the UT/LS will vary depending on the mixture of BL sources (e.g., clean versus polluted, oceanic versus terrestrial, biomass burning) entrained into the convective system.

Question 2d. What is the role of convective cirrus in modifying the chemistry of the upper troposphere?

Results from a recent cloud-scale model intercomparison of convective transport of trace species highlight the uncertainty surrounding the role of cirrus ice particles [*Barth et al.*, 2007]. While the comparison showed fairly good agreement for insoluble tracers (CO and ozone) and lightning NO_x, results for H_2O_2, CH_2O, and HNO_3 varied widely showing both enhancement and depletion with respect to background values at outflow altitudes. The major reason for these differences related to assumptions regarding droplet freezing and whether these species are retained or degassed. Resolving this discrepancy is of major importance since these and other soluble species are important radical reservoirs that, if convected, would substantially influence radical concentrations and ozone photochemistry in the upper troposphere. A further complication is the lack of measurements for these species in fresh convective outflow. The need for observations at the point of convective outflow is especially important given the rapid evolution of these species due to short lifetimes (e.g., 2-6 hours for CH_2O) and/or continued photochemical production (e.g., HNO_3 from lightning NO_x). Once transported to the anvil, adsorption of soluble gases to ice particle surfaces can continue to influence chemistry by repartitioning reservoir species between the gas and particle phases, enabling heterogeneous loss and/or recycling between radicals and their reservoirs, and influencing actinic flux and associated photolysis frequencies.

Question 2e. What are the vertical gradients of ozone, aerosols, and related species across the UT/LS?

Park et al. [2007] use ACE data to demonstrate that within the Asian monsoon anticyclone, enhancements in tropospheric tracers and depressions in stratospheric tracers are maximized in the 13-15 km altitude range. This is somewhat higher than the expected level of maximum convective outflow at 12 km. As noted by Park et al., “The mechanism(s) of vertical transport above 12 km are a subject of ongoing research, but likely involve large-scale circulation in the anticyclone (*Park et al.*, 2007), overshooting deep convection (*Dessler and Sherwood*, 2004), or the dynamical divergence mechanism discussed in *Folkins et al.* (2007).” Profiling observations across this region would contribute greatly to understanding those transport mechanisms and the time-scales for delivering air from convective cloud tops through the upper troposphere and into the lower stratosphere and the degree of chemical evolution that takes place during such ascent.

Question 3. What influences and feedbacks do aerosol particles from anthropogenic pollution and biomass burning exert on meteorology and climate through changes in the atmospheric heat budget (i.e., semi-direct effect) or though microphysical changes in clouds (i.e., indirect effects).

Our goal in this science question is to understand the complicated relationships between aerosol radiative and microphysical impacts on tropical clouds. That is, to study the so called semi-direct [*Ackerman et al.,* 2000] and indirect effects [*Vonnegut,* 1950; *Twomey et al.,* 1984; *Albrecht,* 1989], respectively. It will be essential to characterize the variability in aerosol physical, optical, and chemical properties from the multitude of SE Asian sources, including natural, urban, biomass burning, and shipping emissions. These detailed observations will be made under both clear and overcast conditions to determine direct radiative forcing/heat budget, as well as in cloud to determine microphysical impacts. These measurements will be combined with satellite data and model simulations to understand the relative influences of aerosol particles on tropical clouds compared to large scale meteorological forcing.

Question 3a. What altitude dependent heating rates do absorbing aerosols induce in SE Asia?

A fundamental objective will be to quantify how absorbing aerosol particles impact the atmospheric diabatic heating rates and hence change the lapse rate or intensify inversions. Southeast Asia presents a complicated environment with a variety of absorbing and non-absorbing particles, as well as complicated ocean and land surfaces, coupled with a variety of small to mid sized cumulus. The coupled use of an in situ and a remote sensing aircraft allows for a more detailed evaluation of diabatic heating rates in tropical environments. The in situ aircraft will make detailed measurements of spectral absorbing properties of aerosol particles which can then be related to the aerosols' evolving physical, chemical and thermodynamic properties. Determining these heating rates is particularly important in the vicinity of clouds which redistribute absorbing aerosol particles in the vertical. This question is particularly germane to the ACE and Glory+ CALIPSO algorithm development needs so that diabatic heating rates can be assessed globally.

Question 3b. What are the basic microphysical properties of smoke and pollution particles in the region and are there any relationships between cloud properties and aerosol supply?

Apart from the external radiation and heat budget issues, aerosol can influence clouds through microphysical processes during droplet nucleation. These nucleation impacts influence cloud droplet size spectra, and consequently cloud albedo [*Twomey et al.*, 1984]. Precipitation may also be influenced [*Vonnegut*, 1950; *Albrecht*, 1989; *Feingold et al.*, 2001]. In warm clouds, it has been hypothesized that aerosols retard precipitation as additional CCN reduce drop size and inhibit auto-coalescence processes. However, for clouds with sufficient vertical development, inhibition of warm rain enhances the liquid water flux aloft where cold processes take place, leading to a net increase in precipitation. In the complicated Southeast Asian aerosol environment, it is unclear how aerosols influence these processes. SE Asia contains some of the most clean and polluted environments in the world, resulting in large differences in cloud droplet size distributions (see Figure 9). Cloud droplet size distributions measured in regions of similar meteorological forcing but very different aerosol loading/composition will provide insight into fundamental microphysical processes. Coupled together, in situ observations with airborne remote sensing from above can work synergistically to determine how environmental conditions impact local scale cloud field microphysical properties. These measurements will also lead to improved retrieval algorithms for satellite instruments. Remote sensors can then be used to infer cloud effective radius and liquid water content over larger areas.

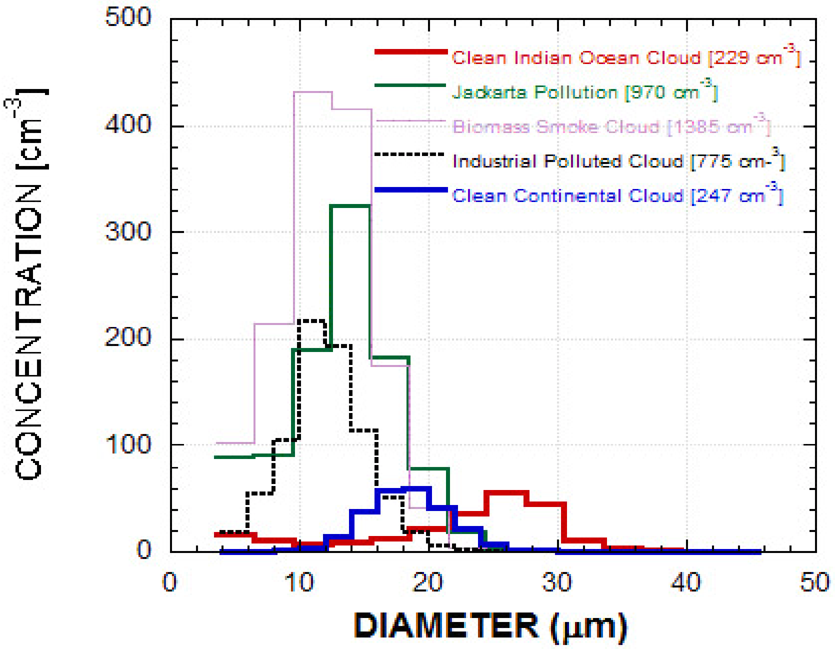


Figure 9. Southeast Asia measured cloud droplet size distribution for clean and polluted environments. Courtesy Roelof Bruinjes, NCAR

Question 3c. Based on the mechanisms of 3a, and b what is the impact of aerosol particles on convection distribution, onset, and vertical development? To what degree would these impacts feed back into the atmospheric heat budget?
The relative impact of these processes on clouds may come in numerous forms, such as the time of day boundary layer clouds begin to develop or grow vertically. Aerosol impacts may also retard the development of small cumulus which, while not able to develop into larger convective systems, nevertheless have a significant influence on regional radiative and heat budgets. Ultimately, the aerosol-cloud relationships are based around feedbacks, and any cloud impact will result in a change in the diabatic heating, surface heat balance and microphysical impacts. Modeling studies suggest that the amount of convective mixing to cloud tops is crucial in determining the impact of smoke on further cloud development (e.g, *Feingold et al.*, 2005). In regions of small to medium cumulus, the SEAC^{4}RC aircraft will be able to determine absorbing aerosol layering and hence diabatic heating rates. Aircraft data combined with remote sensing and modeling data are required to evaluate the impact of aerosol light absorption and thermodynamic properties on clouds.

Question 3d. How do aerosol-cloud interactions modify the distribution and transport of aerosol?
Aerosol have been shown to modify clouds in many ways but it is also apparent that clouds and processes within them modify aerosol abundance and composition, thus forming another feedback layer. Perturbations to the surface heat flux and atmospheric lapse rate influence boundary layer heights and dynamics. Similarly, as described in question 2, moderate to large convection can redistribute boundary layer pollutants aloft and hence ventilate boundary layer air. Shallow convection may enhance chemical evolution processes and precipitation can reduce particle concentration below clouds. Ultimately, these processes have a significant impact on particle properties and transport patterns. While Lagrangian studies are extremely difficult to implement, bulk characteristics of aerosol particles can be monitored by aircraft, such as aerosol properties before and after passage through cloud. Such information can then be used in the post mission analysis of model and satellite data to estimate the relative importance of feedback mechanisms.

5. Satellite Connections: Calibration/Validation and Test Bed for Future Missions

Another important objective of SEAC^{4}RS is satellite calibration and validation. This effort will be applicable to the relatively new sensors on Glory and NPP as well as the more mature sensors of the A-Train and Terra satellites. The focus will include radiance measurements for calibration of satellite sensors as well as in-situ and remote sensing measurements from aircraft and surface sites of aerosols, clouds, trace gases and radiation for validation of satellite data products. In addition, these observations will be used for intercomparison of radiation flux measurements and scene characterization by satellite sensors.

Aerosol measurements of interest include: AOD, light polarization, scattering and absorption, as well as concentration, size distribution, shape, composition and vertical distribution. Cloud measurements of interest include: cloud presence, particle (droplet) number concentration, size distribution and shape, as well as optical properties and vertical distribution. Trace gas measurements of interest include O_3, H_2O CO, CH_4, CO_2, $N0_2$, HNO_3, and, at lower priority, HCHO and SO_2.

SEAC^{4}RS will also benefit future missions intended to fulfill the recommendations of the National Research Council (NRC) decadal study panel (NRC, 2007) by providing an important opportunity for defining the instruments, evaluating the measurement techniques, and developing and testing the retrieval algorithms under consideration for these future satellite missions. In particular, airborne aerosol, chemical, and radiation measurements would be particularly important for the NASA Aerosol, Cloud, Ecosystems (ACE) and Geostationary Coastal and Air Pollution Events (GEO-CAPE) satellites. The highly absorbing and partially cloudy atmosphere coupled with complex ocean and land surfaces of Southeast Asia are ideal for testing key mission hypotheses and stressing potential sensor technologies.

ACE

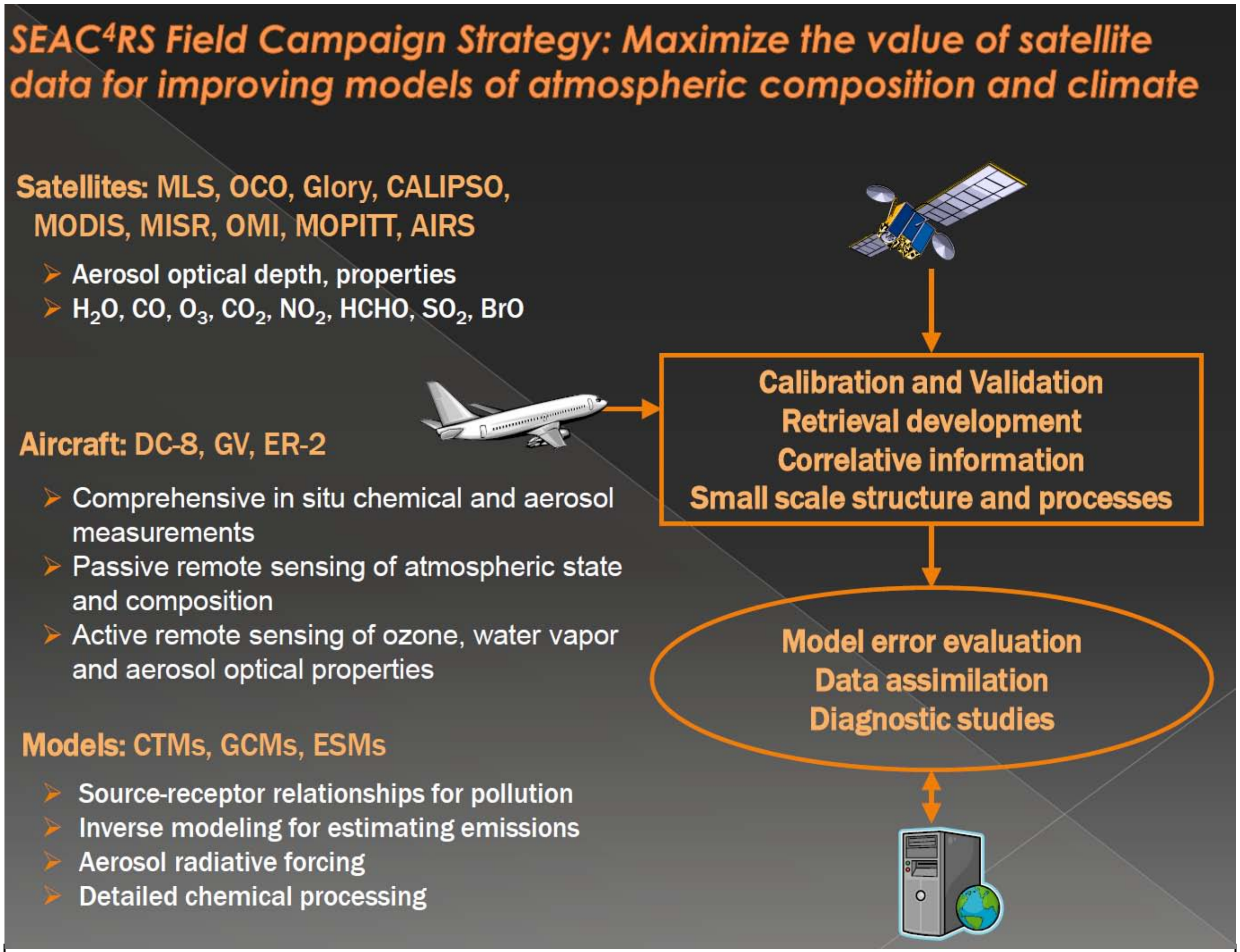
The ACE mission is designed to address many of the same regional questions regarding aerosols and clouds that are objectives for SEAC^{4}RS, but on a global scale. One of the major goals of ACE is to reduce uncertainties in climate forcing associated with aerosol-cloud interactions. ACE measurements are designed to examine the aerosol indirect effect; that is, how cloud radiative (e.g. albedo), macrophysical (e.g. areal coverage, height, thickness), and microphysical (e.g. water/ice content, drop size distribution) properties vary in response to the aerosol macrophysical (e.g. layer height, thickness) and microphysical (e.g. particle size, composition, shape) properties. ACE will also investigate the “semi-direct” effect by measuring aerosol radiative heating in the atmosphere due to absorbing aerosols, and how this heating affects cloud development and precipitation processes. In addition, ACE will go beyond the current “A-train” capabilities by determining the direct aerosol radiative forcing at the surface and within the atmosphere, for all-sky as well as clear-sky conditions. Since SEAC^{4}RS and the associated 7 Southeast Asian Studies (7-SEAS) program will include surface platforms, two aircraft with full complement of in-situ instrumentation capable of sampling the full depth of the troposphere, and a high altitude aircraft serving as a proxy for ACE satellite measurements, this joint mission will present an excellent opportunity to test remote sensing instrument designs, measurement techniques, retrieval algorithms, and methods of merging suborbital and satellite observations using data that captures a wide variety of aerosol physical, optical, and chemical properties in complex aerosol-cloud scenarios. Lastly, SEAC^{4}RS will be a venue for the atmospheric science community to work with the adjoining oceanography component of ACE. Traditionally separate communities, ACE provides an opportunity for the atmosphere and ocean programs to cooperate on many relevant issues such as simultaneous atmosphere characterization for cloud and chemistry research as well as atmospheric correction for oceanography. SEAC^{4}RS can form a core dataset for joint ocean/atmosphere retrieval development for both passive and active sensors.

Geo-CAPE

Geostationary Coastal and Air Pollution Events (Geo-CAPE) satellite is a proposed geostationary satellite centered in the western hemisphere to carry out two key missions 1) a ~5 km shortwave hyper-spectral resolution spectrometer to measure the diurnal loading of key ozone precursors and aerosol particles, and 2) a ~250 m resolution coastal shortwave hyper-spectral imager. The synergistic use of the atmosphere and ocean sensors can provide powerful tools for understanding air and water pollution in coastal environments. That said, coastal remote sensing is extremely challenging, and developmental data sets are required to bridge between the atmospheric and oceanographic research focus. Even though Geo-CAPE is slated to be stationed in the western hemisphere, Southeast Asia is an excellent environment for studying pollution in coastal environments. Hence, as for ACE, SEAC^{4}RS provides an excellent opportunity for compiling substantive interdisciplinary relevant data sets. Concentrations of ozone precursors and aerosol particles are high, providing good signal to noise, which, when coupled with complicated ocean color and bottom features, provides retrieval challenges for both atmosphere and ocean communities.

6. Experimental Design

The SEAC^{4}RS field campaign enables the unique opportunity to combine observations from satellites, aircraft, balloons, and grounds sites to provide an unprecedented view of atmospheric composition over Southeast Asia as influenced by the Asian monsoon and regional biomass burning. Atmospheric models of meteorology and atmospheric composition (e.g., CTMs and GCMs) will also play a critical role during the campaign as an aid to flight planning. Direct participation by satellite and modeling teams in pre-mission planning and the execution of science flights during the deployment increases the relevance of the field observations to post-mission analyses. The ultimate goal is to improve our ability to use satellites to diagnose atmospheric conditions as they are influenced by human-induced and natural forcings. Likewise, for atmospheric models, field observations are expected to improve the ability to characterize current atmospheric conditions and predict future response to changes in these forcings. These connections are illustrated in Figure 10.



SEAC^{4}RS Field Campaign Strategy: Maximize the value of satellite data for improving models of atmospheric composition and climate

Satellites: MLS, OCO, Glory, CALIPSO, MODIS, MISR, OMI, MOPITT, AIRS

- Aerosol optical depth, properties
- H_2O, CO, O_3, CO_2, NO_2, HCHO, SO_2, BrO

Aircraft: DC-8, GV, ER-2

- Comprehensive in situ chemical and aerosol measurements
- Passive remote sensing of atmospheric state and composition
- Active remote sensing of ozone, water vapor and aerosol optical properties

Models: CTMs, GCMs, ESMs

- Source-receptor relationships for pollution
- Inverse modeling for estimating emissions
- Aerosol radiative forcing
- Detailed chemical processing

Calibration and Validation
Retrieval development
Correlative information
Small scale structure and processes

Model error evaluation
Data assimilation
Diagnostic studies

Figure 10. SEAC^{4}RS strategy for integrating satellites, aircraft, and models to improve understanding of atmospheric composition and climate.

Airborne Platforms: A minimum of two airborne platforms are required to adequately sample the atmosphere from the surface to the lower stratosphere; thus linking surface inflow conditions to high altitude convective outflow. For SEAC^{4}RS, the NASA DC-8 and ER-2 aircraft will be used for this purpose. Both aircraft have similar range and duration with nominal flights lasting about 8 hours. For rough purposes of defining operational ranges, an operating radius of ~2000 km requires about 6 hours of flight for each aircraft, leaving about 2 hours of loiter time. The NASA DC-8 is capable of extensive profiling from the surface to 12 km. This ceiling is sufficient to sample outflow from the majority of convective cloud tops (see Figures 3 and 4); however, satellite observations from ACE show that enhancements in tropospheric tracers maximize around 13-15 km and reach as high as 20 km [*Park et al.*, 2008]. The NASA ER-2 provides the capability to span the observed enhancements, although ER-2 cruise altitude of 18-21 km limits sampling from 12-18 km to profiles on ascent and descent away from active convection. To more adequately cover these altitudes, the NSF/NCAR GV (HIAPER) is currently planned to satisfy this requirement. The GV has a range and endurance compatible with the DC-8 and ER-2 and has an effective ceiling of 14 km. This ceiling is high enough to reach the maximum enhancements observed by ACE within the Asian monsoon anticyclone.

Aircraft Payloads: The following table outlines measurement priorities for the three research platforms. The DC-8 payload is expected to allow for comprehensive composition measurements (gas and aerosol) useful for studying transport and chemical evolution as well as measurements to assess aerosol impacts on radiation. For the ER-2, the desire is for sufficient capability to assess basic chemical tracers and aerosol properties as well as provide remote sensing to assess aerosols and radiation over regions where the DC-8 is sampling. The GV payload has been articulated in the DC3 proposal to NSF and is noted in this table without assigning a priority.

Payload Priorities and Definitions for SEAC^{4}RS
1 = required; 2 = desired; 3 = useful
X=planned for GV in DC3

Gas Phase In Situ	**DC-8**	**ER2**	**GV**
O3	1	1	**X**
H2O	1	1	**X**
CO	1	1	**X**
CO2	1	1	**X**
NO	1	2	**X**
OH/HO2/RO2	1	2	**X**
HCHO	1	2	**X**
H2O2	1	2	**X**
CH3OOH	1	2	**X**
NMHCs	1	2	**X**
OVOCs	1	2	**X**
BrO	2	2	**X**
Halocarbons	2	2	
NOy	2	2	**X**
CH4	2	2	**X**
NO2	2	3	
HNO3	2	3	**X**

PANs	2	3	
HO2NO2	2	3	**X**
HCN	2	3	
CH3CN	2	3	
SO2	2	3	**X**
N2O	3	3	
HOBr, ClO, HOCl	3	3	
RONO2	3	3	
NH3	3	3	
Organic Acids	3	3	**X**
Speciated Mercury	3	3	
H2SO4			**X**
Aerosol and Cloud In Situ	**DC-8**	**ER2**	**GV**
Aerosol number	1	N/A	
Aerosol size distribution	1	N/A	**X**
Optical properties (scattering/absorption)	1	N/A	
Aerosol hygroscopicity, f(RH)	1	N/A	
Aerosol composition, inorganic	1	N/A	
Aerosol composition, organic	1	N/A	
Aerosol gravimetric mass	2	N/A	
CCN	1	N/A	
Aerosol volatility	3	N/A	
Aerosol composition, BC	1	N/A	
Size-resolved aerosol composition	2	N/A	
Cloud particle size distribution	1	N/A	**X**
Condensed water content	1	N/A	**X**
Cloud water chemistry	3	N/A	
Radionuclides (Rn222, Be7, Pb210)	3	N/A	
Remote Sensing and Radiation	**DC-8**	**ER2**	**GV**
UV spectral actinic flux	1	N/A	**X**
O3 lidar (nadir/zenith)	1	N/A	
Hyperspectral solar flux	1	1	X
Broad band flux (Nadir/Zenith Solar and IR)	1	1	
Multi-spectral optical depth	2	2	
Aerosol extinction profile (nadir/zenith on DC8, nadir on ER-2)	1	1	
Aerosol backscatter (nadir/zenith on DC8, nadir on ER-2)	1	1	
Aerosol depolarization (nadir/zenith on DC8, nadir on ER-2)	1	1	
Multiangle, multiwavelength, polarized radiances	3	1	
Multiwavelength imager for combined land, ocean and cloud use	2	1	
Cloud Radar	3	2	
Microwave Temperature Profiler			**X**
Meteorology	**DC-8**	**ER2**	**GV**
Vertical State	1	1	
Vertical Wind	2	2	
SST	2	NA	

Deployment sites and flight space considerations: Figure 11 defines nominal operations from a deployment to Surat Thani, Thailand. Possible deployment to Bangkok would compromise as much as one-fourth of the flight hours should Myanmar deny overflight to reach the Bay of Bengal. Even if based in Surat Thani, successful science flights will require negotiation of airspace controlled by as many as 12 countries and 17 separate FIRs (Flight Information Regions). These requirements and priorities are presented in figure 12. The possible use of suitcase locations is also under consideration to extend the reach of aircraft across the Southeast Asian domain (e.g., Kathmandu and Manila). Given the need for three transit flights to reach Southeast Asia, a total of 154 flight hours is required for each aircraft to complete the deployment. This would be divided into roughly 10 hours of test flight, 24 hours of transit flight in each direction, and 96 hours of science flight which would allow for 12 science flights of 8 hour duration. The total length of the deployment would be 40-45 days across a yet to be determined window in the August-September timeframe.

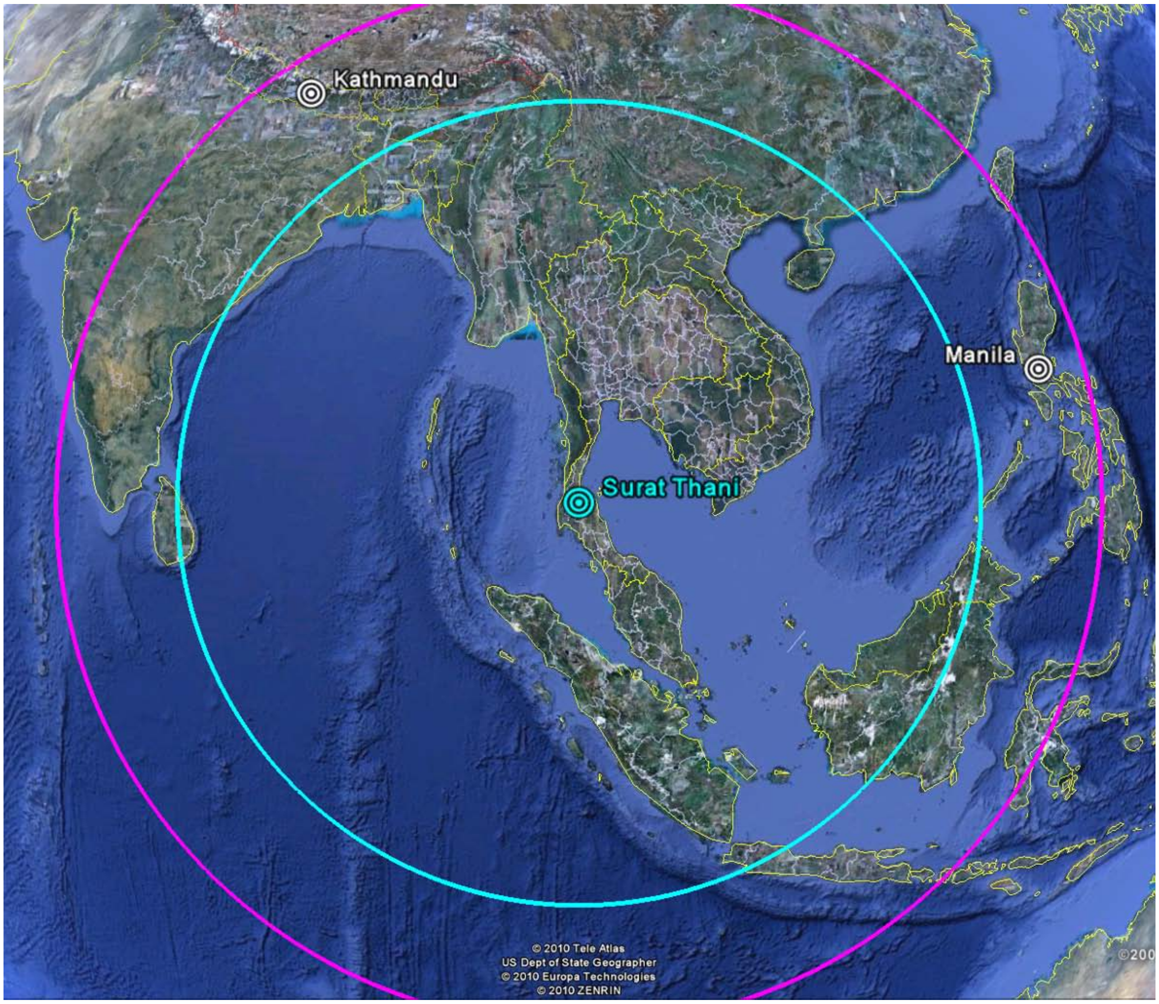


Figure 11. Nominal deployment and operational area for SEAC^{4}RS Inner circle encompasses the nominal operational area across which aircraft could be expected to fly directly to the edge of the operational area and return in 6 hours, leaving 2 hours to loiter for a typical 8-hour flight.

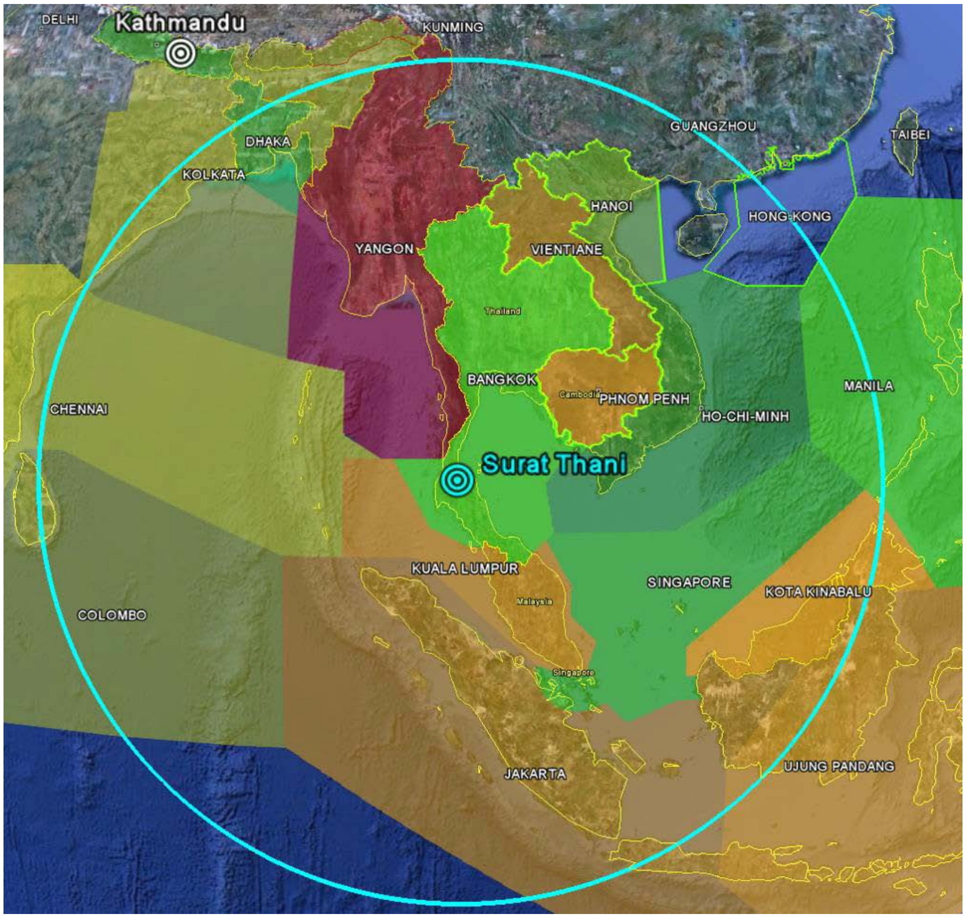


Figure 12. Flight Information Region priorities for SEA^{4}CRS (map above and table below).

Country	FIR	Over Water	Over Land
Bangladesh	Dhaka	Important	Important
Cambodia	Phnom Penh	NA	Desired
India	Chennai	Critical	NA
	Kolkata	Critical	Important
	Colombo	Critical	NA
Indonesia	Jakarta	Important	Desired
	Ujung Pandang	Desired	Desired
Laos	Vientiane	NA	Desired
Malaysia	Kuala Lumpur	Critical	Desired
	Kota Kinabalu	Desired	Desired
Myanmar	Yangon	Desired	Desired
Nepal	Kathmandu	NA	Important
Philippines	Manila	Critical	Desired
Singapore	Singapore	Critical	Desired
Thailand	Bangkok	Critical	Critical
Vietnam	Ho Chi Minh	Critical	Desired
	Hanoi	Desired	Desired

Measurement Objectives and Nominal Flight Scenarios

Three broad measurement objectives are described below to indicate the modes of flight needed to address the science questions posed by SEAC^{4}RS. Nominal flight scenarios are then described to provide further detail on how these measurement objectives might be accomplished. Each of the three measurement objectives is planned to use one-third of the total flight hours or nominally 4 flights of ~8 hours duration.

> (1) Characterize the chemical gradients associated with the dynamical background of the Asian Monsoon Anticyclone. This includes both the horizontal gradients across the southern edge of the anticyclone boundary as well as the vertical gradients within the region of slow ascent.
>
> (2) Characterize the chemical composition of convective outflow and microphysical properties of anvil cirrus, including the contrast between fresh and aged outflow. Chemical composition includes trace gas and aerosol observations contrasted between boundary layer inflow regions, convective outflow regions, and downwind of convection. Anvil cirrus properties include ice crystal size distribution and habit, relative humidity, and radiative heating.
>
> (3) Characterize the chemical and meteorological impact of biomass burning plumes. This includes trace gas and aerosol composition resulting from biomass burning mixtures with various surface emission sources, impact of smoke on atmospheric temperature profiles, and potential impact of convected smoke on cirrus anvil properties.

Flight Scenario 1. Anticyclone Survey

The Asian Monsoon anticyclone is shown by the satellite measurements to be a region of strong horizontal gradients in the UTLS chemical composition. However, the detailed structure of the anticyclone confinement is not known. In situ measurements of a suite of chemical tracers will provide detailed information about the relationship of chemical tracers and the dynamical field. This includes the chemical gradient across the edge of the anticyclone as defined by the wind field gradient, the vertical gradients of the tracers, and their relationship with the convective outflow over the Bay of Bengal.

Figure 13 shows a conceptual flight track. The aircraft will sample high altitude gradients across the southern edge of the monsoon anticyclone in a coordinated fashion. The GV has the cruising altitude to sample the center of the gradient, which is around 12-14 km. In this flight scenario, the aircraft will also profile outside the anticyclone and the inner most edge that can be reached, contrasting the vertical gradient in the chemical tracers and the background dynamical field.

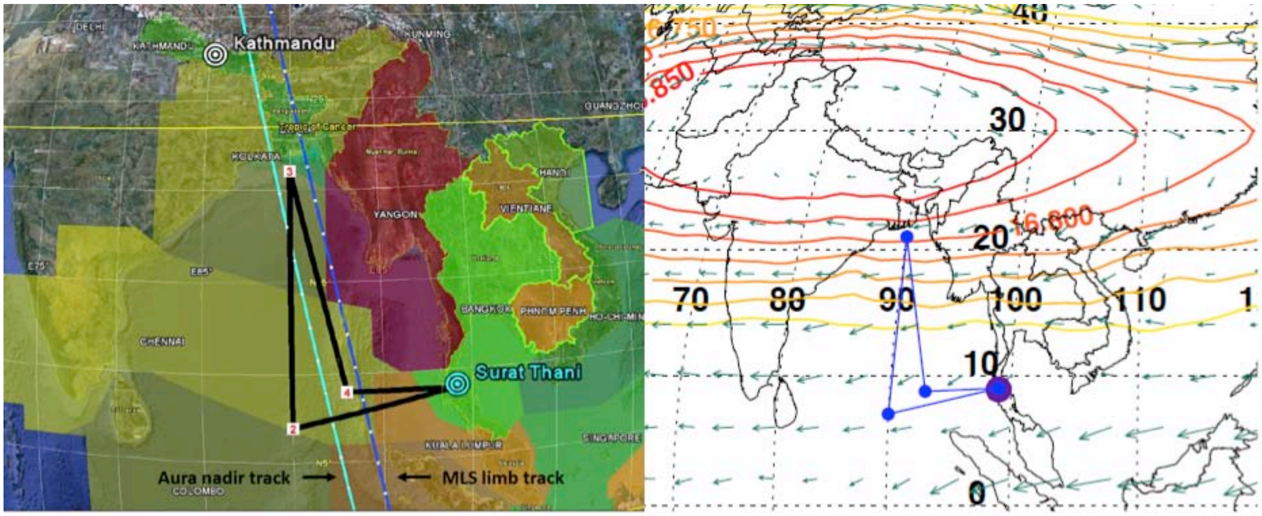


Figure 13. Conceptual flight track for scenario 1 is shown with FIRs (left) and the location of the anticyclone (using August 4th 2009 as an example).

Flight Scenario 1a. Anticyclone Suitcase

If flights over Nepal are possible, the GV and DC-8 will sample the horizontal chemical gradient across the edge of the anticyclone (ER-2 would return to Thailand after reaching Bangladesh, dashed line) and contrast airmass inside/outside the anticyclone. In this scenario, both local flights and suitcase transits to Nepal will be explored. Figure 14 shows a conceptual flight pattern of the scenario of a suitcase flight. The GV, in coordination with the DC-8, will perform vertical profiles from 8-14 km inside the anticyclone, as well as the surface to 14 km during takeoff and landing.

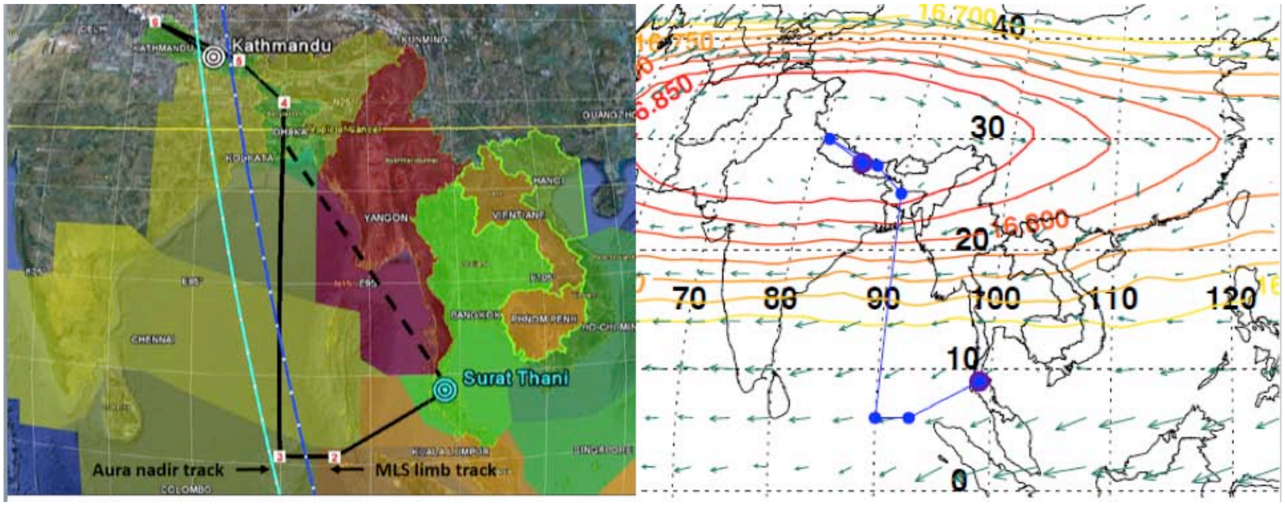


Figure 14. As in figure 13 but for scenario 1a.

Flight Scenario 2. Convective transport and anvil cirrus

Scenario 2a. Aged, detached anvil

Very few direct measurements of anvil cirrus properties in southeast Asia are available. The evolution of anvil microphysical properties in the high relative humidity environment of the Asian monsoon region upper troposphere will likely be very different from anvil cirrus sampled in previous field campaigns (e.g., CRYSTAL-FACE, TC4). It may be possible to determine the impact of biomass-burning aerosols on anvil cirrus properties. In addition, by sampling the anvil cirrus, we will necessarily be making measurements of the chemical composition of convective outflow, thus providing valuable information about convective transport of pollutants to the upper troposphere. The impact of convective transport on specific constituents will be influenced by factors such as their solubility and atmospheric lifetime.

The safest way to sample the anvil cirrus will be to identify locations where the clouds are persisting but the convection that generated them has completely died away. The rapid-scan satellite imagery will be necessary to identify these regions. Racetrack patterns would be flown along the wind, stepping up or down through the depth of the anvils on each turn with 2000 ft increments. The GV would be used to sample the uppermost part of the anvil while the DC-8 samples the middle and lower parts of the anvil. Either before or after the anvil sampling, the DC-8 would sample the aerosols, thermodynamic environment, and chemical composition of the troposphere from the boundary layer up to the height of the anvils. During some of these sampling periods, the ER-2 would be as close as possible to directly above the anvil-sampling aircraft, flying the same racetrack pattern, to provide coincident remote-sensing and in situ measurements of cloud properties.

Flight Scenario 2b. Young anvils

The detached anvils persisting after convection has ceased (described above) would generally be relatively aged. Sampling of younger anvils is desirable to determine the full evolution of cloud microphysical properties as well as the evolution of chemical composition. Some models hypothesize a brief but intense period of photochemical processing and ozone production following convection of short-lived hydrocarbons and radical precursors in the presence of lightning NO_x. Sampling of fresh outflow would facilitate determination of the influence of a particular convective system rather than the combined impact of many systems. Therefore, flight plans will be designed to sample anvils at a safe distance downwind of active convection. The flight patterns would be similar to those described above for scenario 2a. The anvil-sampling aircraft would start well downwind of the convection and slowly work their way toward it. Close monitoring of the rapid-scan satellite imagery will be required to safely conduct these flights. The HIAPER Cloud Radar (HCR), requested to be onboard GV, will complement the satellite information by identifying the edge of the cloud and the motion field with a forward scanning pattern. This capability will enhance the GV’s ability to sample the anvils away from the active region.

Flight Scenario 3. Evolution of smoke/pollution

Biomass burning activity is expected to increase across Indonesia and Borneo during the deployment period. While routine agricultural practices will ensure a minimum level of burning, ENSO-related influences on precipitation will determine the level of severity and amplification of these fires. The figure below shows a typical smoke distribution (in blue) from the NAAPS model as well as the EDGAR NOx flux across the region. This is to demonstrate that smoke emission from fires will not be isolated. Instead, these fire emissions will be intermingled with any number of anthropogenic and natural sources across both the marine and terrestrial environment. These fire emissions are expected to be most dominant in the lower troposphere. In the case of deep convection, observing the impact of fire emissions would fall under scenario 2.

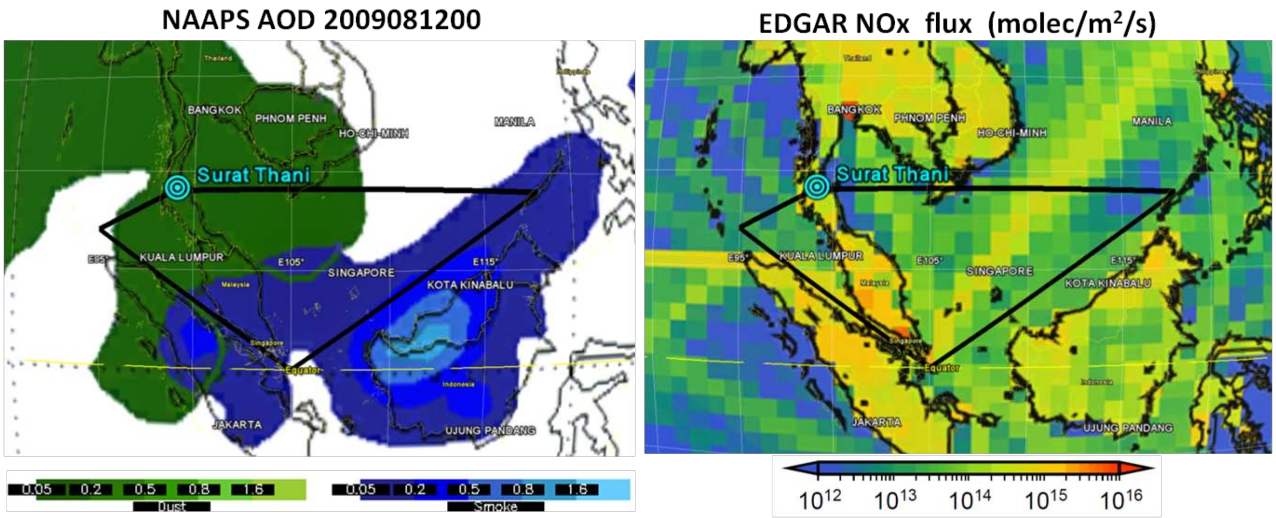


Figure 15. Distribution of dust and smoke from the Navy Aerosol Analysis and Prediction System (NAAPS) and the distribution of NOx sources from the EDGAR emissions database. Note the strong signal from shipping over the South China Sea where smoke emissions are often transported.

In this scenario, both the GV and DC-8 would sample more extensively in the lower atmosphere, characterizing the radiative and meterological impact of smoke. This would include radiation transects both above and below smoke layers and sampling with cloud probes within areas of intermingling between clouds and smoke. Coordinated sampling of radiation by the DC-8 and GV above and below smoke layers would also be pursued. The ER-2 would conduct both active and passive remote sensing of smoke and clouds from high altitude.

7. Research Partners and Leveraging Opportunities

NASA's interest in Southeast Asia is shared by others who want to understand the region and the changes taking place across a wide range of related issues: atmospheric composition and chemistry, climate, meteorology, land use/land change, ocean biology, etc. The following groups represent identified partners where collaborations are being negotiated. This list is not comprehensive and is expected to grow as plans for SEAC^{4}RS are publicized and shared with interagency and international colleagues.

7SEAS (Seven Southeast Asian Experiments): To help understand how aerosol particles impact the Southeast Asian atmosphere and climate, the 7 Southeast Asian Studies (7SEAS) project has been initiated. A regional partnership of scientists from throughout Southeast Asia and the United States, 7SEAS wishes to address the specific issue of how aerosol particles impact meteorological processes, and precipitation in particular. Taking place over a several year time period, 7SEAS will be composed of a series of approaches including long term monitoring, small field campaigns, and research vessel deployments. Specific details can be found at http://7-seas.gsfc.nasa.gov/. While SEAC^{4}RS will contribute to specific science and process studies, the nature of aerosol-meteorology interaction will require long term monitoring through the 7SEAS effort. SEAC^{4}RS can help improve that monitoring capability by improving the utility of satellite measurements through a series of goals that include:

1) Providing data to help develop methods for the monitoring of atmospheric heating through remote sensing means.
2) Advancing the development of joint or joint parameter aerosol and ocean retrievals.
3) Understanding and reconciliation of the significant difference in MODIS and MISR aerosol optical depth retrievals.
4) Cal/Val of Glory and NPP.

The Deep Convective Clouds and Chemistry (DC3) Experiment: Interest in deep convection and its influence on atmospheric composition is also the focus of a field experiment proposed to NSF for the May-June 2012 period. The DC3 experiment seeks to investigate the impact of deep, midlatitude continental convective clouds, including their dynamical, physical, and lightning processes, on upper tropospheric (UT) composition and chemistry. These goals are in strong alignment with those of SEAC^{4}RS. Details on the science objectives and experimental design of DC3 can be found at http://utls.tiimes.ucar.edu/science/dc3.html In order to adequately sample the influence of convection over the full tropospheric column, the experiment requires two platforms. Originally proposed as a two platform experiment utilizing the NSF/NCAR GV (HIAPER) and C-130 aircraft, the experimental plan documents the preference for participation of the DC-8 in place of the C-130 if possible. As noted in the DC3 Experimental Design document, the NASA DC-8 would provide for, "larger payload capacity; longer flight durations; higher altitudes; closer match of aircraft speeds with GV during intercomparsions, and an existing extensive instrument infrastructure." Similarly, if participating in SEAC^{4}RS, the GV would fill an important gap for sampling the atmosphere at altitudes of convective outflow and immediately above. This would provide for continuity in extending observations above the DC-8 ceiling of 12 km. The participation of the DC-8 and GV in both experiments would also allow for a higher level of consistency between the datasets for comparing and contrasting the impact of deep convection over each environment. As already noted in the discussions above, there are distinct differences in the expected influence of convection on upper tropospheric ozone over North America versus Southeast Asia. There are also expected to be differences in the role of lightning NO_x, boundary layer composition, and other factors that will allow convection to be assessed over a broader range of conditions and more completely than either plane can accomplish without the help of the other.

SHADOZ and other networks: The SHADOZ ozonesonde network (http://croc.gsfc.nasa.gov/shadoz/) led by Anne Thompson, has two sites in the domain of interest (Kuala Lumpur, Malaysia and Watukosek, Java) with another soon to be added in Hanoi, Vietnam. More importantly, her leadership within the international ozone and sonde communities has the potential to entrain strong interest in providing additional launches from existing and temporary sites of interest. Given the low expectation for access to some regions influenced by the Asian monsoon, ozonesondes provide one of the most promising ways to get a broad view of the temporal and spatial evolution of ozone across the region of both monsoon convection and the anticyclone circulation.

CARIBIC and MOZAIC: Observations from commercial aircraft offer another important source of information that will be invaluable in providing a broader view of atmospheric composition across the Southeast Asia and the anticyclone circulation (see Figure 8). Past observations and observations during the timeframe leading up to the deployment will be invaluable to mission planning. Possible data sharing with CARIBIC (http://www.caribic-atmospheric.com/) and MOZAIC (http://mozaic.aero.obs-mip.fr/web/) for the experiment period will be pursued.

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