An overview of mesoscale aerosol processes, comparison and validation studies from DRAGON networks

Brent N. Holben[1], Jhoon Kim[2], Itaru Sano[3], Sonoyo Mukai[4], Thomas F. Eck[1,5], David M. Giles[1,6], Joel S. Schafer[1,6], Aliaksandr Sinyuk[1,6], Ilya Slutsker[1,6], Alexander Smirnov[1,6], Mikhail Sorokin[1,6], Bruce E. Anderson[7], Huizheng Che[8], Myungje Choi[2], James H. Crawford[7], Richard A. Ferrare[7], Michael J. Garay[9], Ukkyo Jeong[1], Mijin Kim[2], Woogyung Kim[2], Nichola Knox[10], Zhengqiang Li[11], Hwee S. Lim[12], Yang Liu[13], Hal Maring[14], Makiko Nakata[15], Kenneth E. Pickering[1], Stuart Piketh[16], Jens Redemann[17], Jeffrey S. Reid[18], Santo Salinas[19], Sora Seo[20], Fuyi Tan[12,#], Sachchida N. Tripathi[21], Owen B. Toon[22], Qingyang Xiao[13]

[1] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2]Department of Atmosphere Sciences/IEAA BK 21 plus, Yonsei University, Seoul, Korea
[3] Faculty of Science and Engineering, Kindai University, Higashi-Osaka, Japan
[4] The Kyoto College of Graduate Studies for Informatics, Kyoto, Japan
[5]Universities Space Research Association, GESTAR, Columbia, MD, USA
[6]Science Systems and Applications, Inc., Lanham, MD, USA
[7]NASA LRC, Hampton, VA, USA
[8]Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China
[9]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[10]Namibia University of Science and Technology, Windhoek, Namibia
[11]Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[12]School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia
[13]Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA,
[14]NASA Headquarters, Washington, DC, USA
[15]Faculty of Applied Sociology, Kindai University, Higashi-Osaka, Japan
[16] North-West University, Potchefstroom, South Africa
[17]NASA Ames Research Center, Moffett Field, CA, USA
[18]Naval Research Laboratory, Monterey, CA, USA
[19]Singapore National University, Center for Imaging, Sensing and Processing, Singapore, Singapore
[20]Korea Polar Research Institute, Incheon, South Korea
[21]Indian Institute of Technology Kanpur, Kanpur, India
[22]University of Colorado, Boulder, CO, USA
USA
[#]Current affiliation: DISTED College, Penang, Malaysia

Correspondence to: Brent N. Holben (brent.n.holben@nasa.gov)

Abstract. The AErosol RObotic NETwork (AERONET) program has provided over the past 24 years highly accurate remote sensing characterization of aerosol optical and physical properties for an increasingly extensive geographic distribution including all continents and many oceanic island and coastal sites. The measurements and retrievals from the AERONET global network have addressed satellite and model validation needs very well, but there have been challenges in making comparisons to similar parameters from in situ surface and airborne measurements. Additionally, with improved spatial and temporal satellite remote sensing of aerosols, there is a need for higher spatial resolution ground-based remote sensing networks. An effort to address these needs resulted in a number of field campaign networks called Distributed Regional Aerosol Gridded Observation Networks (DRAGONs) that were designed to provide a database for in situ and remote sensing comparison and analysis of local to mesoscale variability of aerosol properties. This paper describes the DRAGON deployments that will continue to contribute to the growing body of research related to meso and microscale aerosol features and processes. The research presented in this special issue illustrates the diversity of topics that has resulted from the application of data from these networks.

1 Introduction

The AErosol RObotic NETwork project (AERONET, Holben et al, 1998) has provided significant contributions to remote sensing of aerosols during the course its 24-year history. Observations have largely been utilized to validate satellite retrievals of Aerosol Optical Depth (AOD) (e.g., Remer et al., (2002), Sayer et al, (2012), and many others), characterize aerosol absorption and size distributions (e.g., Dubovik et al. 2002 and others), evaluate model products (e.g., Kinne et al., 2003; Sessions et al., 2015) and more recently forecasts through assimilation (e.g., Randles et al., 2017; Rubin et al, 2017 among others) of aerosol properties. These investigations have largely been dominated by the highly accurate observations of extensive properties such as spectral AOD, and as more data became available, the intensive products retrieved from inversions of the radiative transfer equation such as complex index of refraction and particle size distribution have come to the fore. The accuracy of the ground-based AERONET quality assured (Level 2) point observations of aerosol optical depth is very high and therefore is considered a ‘ground truth’ for most satellite and model comparison purposes. AOD is a direct measure of a column integrated spectral property and can be derived from essentially an instantaneous measurement. Thus the only uncertainty arises from calibration and contamination from outside influences such as optical and digital contamination in the instrument in some rare cases and cirrus clouds (e.g., Chew et al., 2011). Given the accuracy of the calibration (Eck et al., 1999) and processing algorithms (Smirnov et al., 2000 and manual quality assurance assessment), the accuracy of Level 2 AOD is estimated to be ~0.01 in the visible and NIR for fully calibrated field instruments, when pre- and post calibrations have been applied. Further, analytic solution to the relative contributions of the fine and coarse modes to the AOD are provided by AERONET through the Spectral Deconvolution Method Algorithm (O’Neill et al., 2003), and verified by Kaku et al., (2014).

The accuracy of the intensive AERONET aerosol properties (single scattering albedo, particle size distribution and complex index of refraction) is less clear due to larger uncertainties of the inversion retrievals and difficulty in obtaining adequate verification data from other methodologies. These properties are extinction weighted atmospheric column integrated properties that exhibit different uncertainties than the wide variety of techniques associated with in situ measurements and estimates. The retrieval uncertainties of the column integrated aerosol properties inverted by the Dubovik and King (2000) algorithm are well discussed in Dubovik et al. (2000), however the additional uncertainty of the measurement techniques are very difficult to assess due to atmospheric variability during the time of observations. The uncertainties associated with in situ techniques are well discussed by Reid et al., (2003/2008b, 2005, 2006) for the size distributions of dust, smoke and sea salt aerosols, respectively. Andrews et al. (2017) found that, provided the AERONET guidelines of only using absorption or index of refraction data when 440 nm AOD>0.4, inversion products were within stated uncertainty bounds. The accuracy of the inverted parameters is predicated upon the atmosphere being stable and spatially uniform within the measurement space of the sky radiance measuring radiometer. For example, if we assume that the aerosol is in the lowest 2 km of the atmosphere and the solar zenith angle is 60°, the AERONET observation path would be 4 km long and a horizontal distance of approximately 3.5 km. Thus for this particular solar zenith angle and layer height geometry example, AERONET retrievals are assuming relative uniformity in an atmospheric cylinder of 7 km diameter, 2 km vertically and a measurement slant path of 4 km about the surface center point. Quality assurance algorithms and spatial averaging of measured sky radiance distributions have been utilized to minimize this uncertainty associated with spatial variance of aerosol (Holben et al., 2006).

AERONET and other ground-based remote sensing systems have the distinct advantage of the time domain with direct sun measurement frequencies of seconds to minutes through-out the day and in some instances at night. Nominally the AOD sampling frequency for AERONET network measurements is 15 minutes and more recently 3-minute intervals for sites with sufficient communication infrastructure. The measurements of sky radiance used to retrieve the inversion products are nominally taken hourly for AERONET but in some instances are taken more frequently such as early in the morning and late in the afternoon when optical airmass changes rapidly. Other networks such as the SKYNET network (http://atmos2.cr.chiba-u.jp/skynet/data.html; Hashimoto et al., 2012) make almucantar sky scan measurements at 10-minute intervals. These high frequency ground-based remote sensing measurements allow the opportunity to assess aerosol properties diurnally as well as provide a higher probability of making valid aerosol observations under variable atmospheric conditions, such as in partial cloud cover and/or spatially or temporally varying aerosol. The temporal domain may be a powerful ally for assessing transport processes and in some instances a proxy for the spatial domain.

Individual ground -based systems inherently do not represent the spatial variation of aerosol properties. Thus they complement the satellite retrievals and regional and global model predictions. Typically a spatial scale bridge to the ground-based measurements (including in situ) to satellite and model assessments have been through aircraft observations. Aircraft flights occur over ground-based point observations from profiles and various altitude transects extending tens, hundreds and thousands of kilometers, and can provide spatial continuity during intensive field operations that enables scaling point location observations to the satellite observations and regional model simulations.

Field campaigns are of limited duration and aircraft flights are often discontinuous during the measurement campaign. The question arises, is there a need for continuous high spatial and temporal resolution aerosol data that neither a single point, airborne, satellite nor model results address? Furthermore is there an approach that will clarify the uncertainty in comparisons of in situ and remote sensing aerosol properties? In hindsight and with some foresight the answers have proven to be yes and yes.

The series of Distributed Regional Aerosol Gridded Observation Network (DRAGON) campaigns arose in 2011 primarily as a means to foster collaboration and comparison of the remote sensing community and in situ communities to close measurements and retrievals of the intensive properties of aerosol particles such as single scattering albedo, particle size distribution, complex index of refraction, etc. Note that earlier DRAGON like campaigns (e.g., UAE Unified Aerosol Eperiment, UAE^2 –Reid et al., 2008a; and TIGERZ, Giles et al., 2011) were performed to assess spatial and temporal intensive and extensive aerosol optical properties for comparison to satellite retrievals and thus provided further motivation for satellite and model intercomparisons with high resolution ground-based measurement systems. We therefore define a DRAGON campaign as a relatively high spatial and temporal network of ground-based sun photometers and other associated measurements. Typically these instruments are in a loose mesoscale grid with a two dimensional spacing of tens to hundreds of km for a period of 30 days or more with high frequency sampling in minutes (typically at 3 minute intervals for AOD) during daylight hours. Contrast a DRAGON network to the overall AERONET global spatial distribution of 100s to 1000s of km that developed out of individual PI and institutional contributor needs since 1993. An assessment of the published AERONET measurements from 1993 through 2011 showed very few in situ versus remote sensing comparisons many of which were of limited applicability, (see Table 1, also available from the AERONET website under DRAGON campaigns, https://aeronet.gsfc.nasa.gov/new_web/dragon.html). Indeed, clearer descriptions of aerosol types beyond these five generic multi-modal categories have been expressed in more recent literature. Many investigations have provided clarity in the definition of fine and coarse mode aerosols in terms of particle size and chemical composition of various aerosol types particularly from the in situ point of view. From a remote sensing perspective aerosol typing remains difficult but progress is moving forward primarily by assessment of fine/coarse partition, single scattering albedo, Angstrom Exponent (AE), and Absorption AE (AAE) ((O'Neill et al., 2008; Giles et al., 2012; Russell et al., 2014, among others). Table 2 is updated based in large part on contributions to this special issue and several other important studies using DRAGON data sets.

Table 1, Principle intensive parameters retrieved by sun and sky scanning spectral radiometers for five aerosol types. Sixteen published validations/comparisons of these retrievals against in situ measurements were made during field campaigns prior to 2010; these are Ra=Ramanathan et al, 2000; Re=Remer et al., 1997; H=Haywood et al, 2003; L=Leahy et al., 2007; B=Bergstrom et al., 2003; Chand et al., 2006; E=Eck et al., 2010; M=Müller et al., 2010, Mü= Müller et al., 2012, Rp=Reid et al, 2003; Ru=Reid et al., 2008; S=Smirnov et al., 2003; Sc=Schafer et al., 2008; T=Toledano et al., 2011; O=Osborne et al., 2008 and J=Johnson et al., 2009. Note that most categories are incomplete, most studies are regionally based, not updated for the current inversion algorithm and/or not relevant to total column ambient retrievals.

Parameter\Type	Urban	Biomass Burning	Dust	Sea Salt Maritime	Mixed
SSA (ω_o)	Ra$^{\dagger\#}$	H$^{@\#}$, L, B, C†, Sc$^{\&}$	T, M, Mü		O$^{@}$, J$^{@}$,E†
Size Distribution dV/dlnr, r_v	Re*	H$^{@\#}$	Rp$^{\#}$, Ru, Mü	S$^{\dagger\#}$	J$^{@}$
Real Index (n)					
Imaginary (k)					
Asymmetry (g)					J$^{@}$
% Sphericity					

†Regional comparisons
*Nakajima retrievals
#Version 1
@ Single point
& surface comparison

Table 2, The aerosol types detectable from remote sensing (RS) techniques and compared with in situ field measurements. We show only those direct RS/in situ comparisons. Unlike Table 1, here the aerosol type describes the properties of the aerosols rather than sources. We acknowledge that aerosol typing is difficult and still subjective and incomplete. (C=Corrigan et al., 2008; E=Esteve et al., 2012; Sc=Schafer et al., 2014, 2017 in preparation). Some studies appearing below are defined in Table 1.

Parameter\Type	Fine			Coarse			Mixed
	Inorganic Hygroscopic	Organic		Mineral	Organic	NaCl	
		B, C	Br, C				
SSA	Sc, E, A	C		T, M			O$^{@}$, J$^{@}$
Size Distribution dV/dlnr, r_v	Sc			Mü, Rp$^{\#}$, Ru			J$^{@}$
Real Index (n)		H$^{@\#}$					
Imaginary (k)							
Asymmetry (g)							J$^{@}$

The description of the aerosol size distribution is of primary importance as a first order physical and optical parameter corresponding to particle size and the associated concentration of various sized particles. Coarse mode aerosol is sometimes considered to have a particle radius of greater than 1 micron (μm) and the fine mode from 0.05 to 1 μm (in volume distributions), although definitions vary widely. This type of classification may be generally applied for remote sensing from sun and sky scanning radiometers that use inversion schemes to retrieve aerosol properties (Dubovik and King, 2000, Nakajima et al., 1996 among others). Different definitions of fine/coarse mode breakdown of the AOD are applied to the spectral de-convolution algorithm (O'Neill et al., 2003), while the Angstrom exponent computed from spectral optical depth is a general scaling of fine/coarse optical influence, although it varies considerably as a function of wavelength for fine mode dominated aerosols (Eck et al., 1999). Note that the AERONET retrieval scheme of Dubovik and King (2000) reports the size in terms of particle radius with the retrieved radius limits of

0.05 microns to 15 microns. The inflection point defining the upper limit of the fine mode sized particles of a retrieval lies between 0.44 to 0.99 micron radius in volume distributions that are composed of discrete particle sizes from a mixture of spheres and spheroids with a fixed shape distribution (Dubovik et al., 2006).

Generally natural sources for coarse mode hygroscopic sea salt aerosol are breaking waves and associated bursting water bubbles. These particles are nominally spherical at most ambient relative humidity over the ocean with AOD typically dominated by particles larger than 0.5 μm radius. Dust particles are highly non-spherical airborne mineral soil and typically have radii on average greater than 1 μm with numerous electron micrographs showing particles with lengths exceeding 10 μm yet sometimes with a dimension of submicron size. These dust sources from arid and semiarid regions often originate in dried lakebeds and intermittent waterways (Prospero and Carlson, 1972 among others). Other sources of coarse particles reported in the literature include diatomaceous earth from the Bodele Depression in Chad (Washington et al., 2005, Ben-Ami et al., 2010), intensive construction in mega cities causing localized, highly variable and largely unknown particle properties, dust from agricultural fields, pollen grains which are very large organic particles that are quickly settled from the atmosphere, fly ash from unfiltered coal combustion (WHO, 1999) and ash from episodic volcanic eruptions. Thus Table 2 has three categories for coarse mode aerosol, sea salt, mineral dust (such as particles that contain Hematite causing absorption in the blue and UV, diatomaceous earth and anthropogenic coarse particles) and pollen (organic). The chemistry of 'dust' particles is highly variable and is beyond the scope of this discussion however it is noteworthy that as chemical analysis of coarse particles is more geographically studied and better understood there will be greater opportunity to assess the response of remote sensing to the properties of these particles.

The fine mode (or accumulation mode) aerosols are sometimes loosely referred in the literature as either urban/industrial or biomass burning. These terms were convenient in the early days of remote sensing but are only a rough guide to our greater understanding of their diversity and properties. The range of fine mode aerosol types that contribute to remote sensing can be rather daunting and often don't exist in a single type distribution in the atmosphere. Artaxo et al (1994) in early work and continuing Fuzzi et al., (2007 among many others) have made extensive investigations of the smoke aerosol generated during the burning season in the Amazon basin that includes both black carbon particles from flaming phase burning and primarily brown carbon particles that are organic and from both flaming and smoldering combustion (Falkovich et al, 2005). Particle sizes are generally less than 1 micron in radius in volume distributions, although a distinct coarse mode of ash aggregates and suspended soils is also present (Reid et al. 2005). Both have been shown to have very different absorptive properties from each other and from other types of particles, thus we have added black carbon and brown carbon to Table 2 which typically range in volume median radius from 0.14 to 0.2 μm. Gas to particle conversion from nitrates, organic compounds and SO_2 can form fine mode aerosols. This process is enhanced in the presence of clouds and fog. Sometimes hydoxymethanesulphonate (HMS) may form within cloud/fog droplets when sulfur dioxide is present, whereupon after evaporation it can form large particles. These have been shown to have a variable modal range but typically have mean volume modal radius of ~0.45 μm, see Eck et al. (2012) and Li et al. (2014). Properties of these aerosol types require further evaluation. This complexity gives rise to three fine mode aerosol types in Table 2, black carbon, brown carbon and "other" that can be distinguished in principle by ground-based sun and sky scanning radiometers by combinations of size, shape and/or absorption magnitude.

Table 2 shows those studies that have objectively assessed all of the known AERONET to in situ direct comparisons of aerosol properties.

2 The DRAGON campaigns

The DRAGON field campaigns were developed in consideration of the spatial and temporal advantages and disadvantages of remote sensing systems and in situ systems for ground-based, aircraft-based and remote sensing systems. In the previous section we described generally the assets available for a typical AERONET deployment. Table 3 presents an overview of the DRAGON campaigns, including the dominate aerosol type, the time frame, the approximate range of aerosol characteristics from a remote sensing perspective and the principle contact for each campaign. We have attempted to provide an exhaustive list up to the time of this writing and this table will be maintained and updated on the AERONET website as new information is received.

The method of the DRAGON campaigns was to establish a high density of ground-based sun and sky scanning spectral radiometers within a local or mesoscale region to capture small-scale aerosol variations. For this discussion we present those distributions over tens to hundreds of kilometers and a time period of weeks to months. Very early studies dating back to the 1950s by Flowers et al, (1966) showed regional to continental scale variations across the US and in the 1980s sun photometry documented regional Sahelian aerosol loading during the drought (Holben et al., 1986). The 1990s brought AERONET regional measurements to the Amazon Basin (Holben et al., 1996), BOREAS in boreal Canada (Markham et al., 1997) and southern Africa in ZIBBIE (Eck et al., 2001), and SAFARI2000 (Swap et al., 2003; Eck et al. 2003). These and other regional investigations brought tremendous knowledge of aerosol properties over regions dominated by a single aerosol type, however they could not address variability of small-scale regional aerosol processes. They also came largely before the massive data collection ushered in by the EOS satellite era that began with Terra in 2000 and continues today from an expanding series of space borne quantitative Earth monitoring platforms. Figure 1 shows the location of DRAGON field experiments relevant to this paper.

2.1 United Arab Emirates -Unified Aerosol Experiment (UAE^2)

The UAE^2 was established across the northern UAE with 18 AERONET sites distributed over approximately 150,000 km^2 including islands in the Arabian Gulf (Reid et al., 2008a). The campaign was conducted in August and September 2004 with the objectives to assess the radiative properties of dust aerosols in a humid coastal environment from ground, airborne and satellite perspectives. Sites were selected to provide characterization of Arabian Gulf, coastal, and interior desert sites from satellite product validation-especially in locations of consistent changes in the lower boundary condition (e.g., soil albedo, Case II waters). UAE^2 was conducted in concert with an on-going weather modification assessment (NCMS/NCAR) in the region. Although Southwest Asia and the Middle East are often thought of as coarse mode dust dominated aerosol environments fine mode aerosol particles from the petroleum industry and urban pollution contribute equally to overall AOD (Eck et al., 2008). From a product verification point of view, the UAE^2 deployment provided the first conclusive evidence that dust size retrievals are consistent with in situ measurements (Reid et al., 2008b), and that dust retrievals including vertical homogeneity can be further constrained by the inclusion of UV and near infrared data (O'Neill et al., 2008).

2.2 CALIPSO And Twilight Zone (CATZ)

The CATZ campaign was the first AERONET Intensive Operation Period (IOP) to support CALIPSO aerosol retrievals. This was temporally synchronized with CALIPSO over-flights to assess the aerosol variability within the along track averaged CALIPSO retrieval. Up to 12 AERONET sites were placed along 230 km of the daytime Aqua track within the CALIPSO footprint on the Delmarva Peninsula on seven different dates from late June to mid-August 2007. Very low to high aerosol loadings occurred which were all fine mode dominated.

2.3 Transects: Indo-Gangetic aERosol Zone (TIGERZ)

The TIGERZ campaign was an effort during the pre-monsoon of May 2008 to characterize the complex and high loading aerosol environment in the Indo-Gangetic-Plain (IGP) of northern India in support of CALIPSO satellite borne lidar validation. The deployment of additional instruments was centered around the long term monitoring site on the IIT campus in the industrial city of Kanpur. The pre-monsoon aerosol environment is characterized by regional fine mode haze from fossil fuel emissions mostly from coal with episodic dust events both locally generated and regionally transported from the northwest. The local Kanpur City aerosol plume was enhanced by a megawatt power plant plume and numerous coal fired brick kilns dotting the region. Despite local strong sources, the Kanpur aerosol properties were similar to a village site 400 km downwind (Giles et al., 2011). Sites were established specifically to be in and very near the CALIPSO footprint during May captured the spatial variability and provide validation of CALIPSO retrievals. Sites were local to the descending CALIPSO track but ranged up to a 300 km radius of Kanpur.

2.4 Seven South East Asian Studies (7-SEAS)

The 7-SEAS interdisciplinary research program has a rich history of ground-based measurements in Southeast Asia beginning in 2007, including region wide deployments of AERONET sites throughout the Maritime Continent of (Indonesia, Malaysia, Philippines, Singapore) and Peninsular Southeast Asia (Laos, Thailand and Vietnam). Overall AERONET properties can be found in Reid et al., 2013. Specific to the DRAGON concept, the AERONET program collaborated with local scientists to develop two DRAGON programs during the August-September 2012 burning season: National University Singapore (NUS) for Singapore and Sains-Malaysia University for Penang, Malaysia.

2.4.1 Penang

Penang Island is mountainous with an eastern coastal plain from 2 to 15 km offshore from mainland peninsular NW Malaysia, within the Strait of Malacca. Its densely populated capital of Georgetown (2 million) is across the Penang Strait from industrial Butterworth while the Malacca Strait side of the island is rural. Anchored ships, industry and automobile traffic contribute to fossil fuel emissions while episodic pulses of biomass burning aerosols from Riau, Sumatra Indonesia added to a background of sea salt aerosol within the sampled 30 km transect. During September 2012, Univeristy Sains Malaysia staff maintained eight AERONET stations. In addition to satellite and model validation, research was conducted specific to coastal areas with these data sets utilized for air quality investigations (see Fuyi et al., 2015).

2.4.2 Singapore

Singapore is a highly industrialized urbanized center on an island with dimensions approximately 30 km east west by 20 km north south at the southern tip of the Malay Peninsula. The regional population including Johor Bahru is well over 5 million. Thus fossil fuel emissions from cars, petrochemical industries and ships constitute a major portion of the aerosol sources however maritime aerosol from the S. China Sea and the Straits of Malacca provide a rather constant but weak background regime. Biomass burning primarily from Sumatra and Kalimantan impose an episodic and at times massive aerosol burden on the region. This September 2012 DRAGON campaign in collaboration with NUS' Centre for Remote Imaging, Sensing and Processing (CRISP) afforded the opportunity to assess the variability of the aerosol loading in response to local and regional sources from six well distributed AERONET sites and a suite of detailed ground-based measurements across the region.

2.5 Deriving Information on Surface Conditions from Column and VERtically Resolved Observations Relevant to Air Quality (DISCOVER-AQ)

DISCOVER-AQ was a NASA sponsored Earth Venture Suborbital four-year campaign (2011 to 2014) to relate remote sensing measurements to air quality assessments at four selected sites across the United States (Central Maryland, Houston TX, San Joaquin Valley, CA, Denver-Front Range Region, Colorado;

https://discover-aq.larc.nasa.gov). For each campaign, this involved repeated in situ and remote sensing ground and airborne (NASA's P-3B and King Air) measurements during most days for the duration of the campaign. This involved a series of high and low airborne transects, targeted airborne profiles, high altitude down-looking lidar profiling plus passive remote sensing measurements, combined with in situ ground, ground-based lidar, ozonesonde releases and AERONET measurements configured in a mesoscale grid. As conditions warranted, flights would continue for approximately 8 hours/day on most days through the ~30 day campaign. This resulted in very detailed 4-D characterizations of meteorology, aerosol and trace gas measurements and processes that affect air quality, air quality forecasts and their relationship to remote sensing. The AERONET DRAGON networks established for these campaigns represent the most detailed AERONET spatial characterizations to date.

2.5.1 Maryland (Greater Baltimore)-July 2011

This campaign selected a highly urbanized and industrial region of the Mid-Atlantic that is subjected to high summertime humidity and periodic pollution buildup. The studied region was approximately 125 km long following the I-95 corridor from the Washington Beltway north to the MD/Delaware state line and about 40 km wide encompassing Baltimore, agricultural fields, suburbs and the Chesapeake Bay. Forty-three AERONET sites were established one month prior to the campaign and continued monitoring for approximately one month after. The meteorology was classic mid-Atlantic for July with daytime temperatures approaching 39°C on the hottest days, high humidity with daytime dew points sometimes reaching 25°C , plus nearly stagnant conditions with southerly flow resulting in AODs exceeding 1.0 at 500 nm on some days and showing considerable diurnal and day-to-day dynamics. Two cold frontal passages advected the pollution away from the region (AOD as low as 0.1 @ 500nm), with subsequent gradual buildup over a period of days. The Angstrom exponent (440-870 nm) during this period was typically greater than 1.5, indicating fine mode dominated aerosols as one would expect in this region/season. Munchak et al. (2013) utilized DRAGON Maryland AERONET data to assess the impact of urban surface reflectance variations on the biases in satellite retrieved AOD from the MODIS Dark Target algorithm. They also determined the new 3 km resolution MODIS retrievals could detect AOD gradients better and make retrievals closer to clouds than the standard 10 km MODIS product.

2.5.2 San Joaquin Valley, California (Bakersfield to Fresno)-Mid January to Mid February 2013

The San Joaquin Valley occupies the southern half of California's Central Valley which is bounded by the convergence of the high Sierra Nevada range to the east and series of coastal mountain chains to the west. The valley is flat with intensive irrigated agriculture. The region is notable for the air quality challenges to its 3 million inhabitants, freeway corridors, and intensive agriculture including ammonia emissions and fugitive dust that contributes to particularly strong air pollution in January and February. The planetary boundary layer (PBL) is typically shallow at ~1 km or less and adiabatically stable owing to strong radiational cooling at night resulting in frequent and persistent fog events. This combined with various agricultural, fossil fuel, petrochemical and largely undocumented biomass burning emissions throughout the valley creates a complex environment for aerosol and reactive gas processes that were observed from January 20 to February 15, 2013 by DISCOVER-AQ. A DRAGON deployment of 17 AERONET stations from Fresno in the north to Bakersfield 175 km to the south, and to the east from Porterville at the foothills of the Sierra Nevada to Huron 75 Km to the West. Porterville at the time of the campaign was heavily affected by pollutant build up from airflow blockage by the mountains to the east. Optical depths at 500 nm at Porterville showed extreme episodic and diurnal range of AOD owing to local emissions, hygroscopic growth from high relative humidity in fog and the variable PBL height. Measured AOD values at 500 nm ranged from 1.2 during stagnation conditions and post fog events to 0.1 after the valley was ventilated from passage of a cold front.

2.5.3 Houston, Texas (Greater Houston/Galveston)-August 2013

Houston is a massively sprawling city with a downtown center approximately 30 km north of Galveston and the Gulf of Mexico. A dense petrochemical industry borders the ship channel that bisects southern Houston with numerous sources of gases and aerosols complemented by automobile emissions and other industry. Climatology showed that air quality is poorest during August thus like the Maryland campaign, it afforded the best opportunity to understand the processes relating emissions and air quality issues to remote sensing. The aircraft tracks largely were square racetrack circuits with six intensive vertical profiles over ground-based supersites. Seventeen DRAGON AERONET sites were used to characterize the column aerosol properties for three months (July-September) that allowed a large range of aerosol conditions of mostly fine mode aerosols with AOD ranging from ~0.1 to 0.7 @ 500nm. On August 23-25 a Saharan dust intrusion moved into the region, lowering the Angstrom Exponent to 0.8. The region during August was characterized by high humidity and significant afternoon cloud development.

2.5.4 Colorado -July 2014

The northeastern plains of the front range of the Rockies formed the backdrop for the last DISCOVER-AQ campaign conducted in July 2014. The airborne and ground-based measurement campaign track ranged from diverse landscapes and aerosol sources from central Denver to suburban Fort Collins 130 km N and 50 km to rural Greeley feedlots to the East, south 30 km to Platteville dominated by irrigated crops and intense fossil fuel exploration and extraction and return to Denver metropolitan area 40 km to the SE. High temperatures and intense solar radiation characterized July 2014. Aerosol optical depths averaged 0.2 at 500 nm and day-to-day variations were typically small however several days of fine mode aerosol events elevated the AOD to ~0.4.

2.6 DRAGON-NE Asia--Korea, Japan

Northeast Asia faces arguably the most severe air quality issues on the planet owing to the very high population density coupled with high levels of industrialization and additionally downwind of major dust source regions. These contribute to significant trans-boundary aerosol transport compounded by emissions from several megacities in the region. Given the AERONET limitations for retrievals with low uncertainty (AOD >0.4 at 440 nm) for complex refractive index retrieval products, NE Asia routinely experiences aerosol loading that exceeds those limitations on most days, thus investigations of the spatial and temporal variations of single scattering albedo in addition to AOD are possible. The following two campaigns called DRAGON-Korea and DRAGON-Japan operated from March to June 2012. The NE Asia DRAGON campaigns did not have a significant airborne component, thus the emphasis was on assessing the spatial and temporal variations of aerosol optical properties. Numerous opportunities occurred for satellite and model validation under a variety of aerosol gradients.

2.6.1 DRAGON-KOREA

Seoul was the focus for half of the 22 AERONET surface stations deployed from March to June 2012 including 5 permanent sites in South Korea with long-term records. Seoul is a mega-city of 25 million (metropolitan region) spread across a landscape of the Han River plains, hills and low elevation forested mountains. Industry and fossil fuel power generation contribute emissions to a significant pollution aerosol loading in addition to aerosol advected from China. South Korea in general is a landscape that is challenging for satellite retrievals of AOD due to significant variation in background surface reflectance and varied topography (~70% mountainous, mostly forested) and variability in aerosol properties (fine and coarse). A decision was made to expand the network in spring 2012 to a regional or meso-scale network to further assess the impact of transported aerosols from across the Yellow Sea and from Seoul with sites on the west coast, interior plus eastern and southern sites. AOD at 500 nm from regional sites had daily values ranging from ~0.2 to 1.5 while sites in Seoul varied from ~0.5 to 2.1 during episodic aerosol events.

2.6.2 DRAGON-JAPAN

Osaka, Japan was the focus of an eight AERONET site DRAGON campaign, coincident in time with the DRAGON-KOREA campaign from March through June, 2012. Osaka is a mega-city of very dense urban development that is bounded by low mountains on three sides and Osaka Bay to the south (see paper Sano et al., 2016, this issue). Industry and transportation emissions are sources for the dominant background aerosol loading and as in Seoul , episodic coarse mode dust and transported fine mode industrial aerosols were observed during the four-month intensive measurement period. Owing to two nearby mountain sites, boundary layer assessments were possible, also facilitated by a mobile handheld sun photometer.

A second DRAGON network of six AERONET and 1 SKYNET sites on the small (326 km^2) rural western island of Fukue captured the dynamics of transported fine mode aerosol properties while an airborne campaign measured in-situ gas chemistry from these events (Hatakeyama et al., 2014). Historically many researchers have used Fukue Island to identify long-range transported aerosols (Takami et al., 2013). Sano investigated AOD at the site in 2003 (Sano, 2004). Measurements showed periodic high AOD days that might be contributed by transported anthropogenic aerosols and Asian dust events from the continent. Part of the DRAGON-Fukue network was maintained until 2013.

2.7 Studies of Emissions and Atmospheric Composition, Clouds, and Climate Coupling by Regional Surveys (SEAC^{4}RS)

The SEAC^{4}RS mission (Toon et al., 2016) was a combined airborne and ground-based effort to assess aerosols and trace gas chemistry processes. The objective necessarily required knowledge of surface and boundary layer meteorology to assess sources of aerosols and trace gasses. The airborne implementation was changed from SE Asia (maritime continent) to the southeast US regional assessment of aerosol and trace gas chemistry processes in 2013, after permission to utilize airfields in SE Asia was not granted. This change of locations represented a major challenge and a significant scaling up from a meso-scale to a regional scale ground-based aerosol network. It also provided an opportunity to overlap with the Houston DISCOVER-AQ DRAGON network (12 sites in ~60 x 60 km) with a regional scale SEAC4RS network of (30 sites in ~1000 X 2000 km). Both networks operated at full density from August through October 2013. About 50% of the SEACR4RS sites remain in operation as of 2017 to provide long-term context of the program. Toon et al. (2016) provides a detailed overview of the SEAC4RS program results. The NASA DC-8 with in situ aerosol sampling instrumentation and the 4STAR airborne sun photometer provided regional and continental scale transects that have been compared to the ground-based measurements (Reid et al, 2017).

Additionally another airborne and ground based field campaign was occurring during this time period called Southeast Nexus (SENEX; Warneke et al., 2016) that emphasized volatile organic compounds (VOC) and aerosol precursors. This campaign was focused on Alabama, Georgia and N. Florida. The regional network by its size captures the range of aerosol properties one would expect over the Southeast US including transported dust from West Africa, biogenic aerosols created from VOCs, fossil fuel emissions, coastal maritime aerosols and biomass burning transported from fires in the Western US.

2.8 KORUS-AQ

Similar to the DISCOVER-AQ campaigns, a focused airborne campaign called KORUS-AQ was conducted across South Korea from May 1 to June 12th 2016 by National Institute of Environmental Research (NIER) and NASA. In situ and remote sensing resources were on board three aircraft flying from near surface to ~28,000 ft. profiling the atmosphere in three dimensions for up to 8 hours on approximately 20 days. This campaign was heavily supported by a DRAGON mesoscale network of 21 advanced AERONET Cimel photometers most with solar and lunar AOD retrievals as well as the experimental hybrid sky scans designed to allow retrieval of aerosol radiometric and microphysical optical properties throughout the day. AERONET results for the lunar AOD and retrievals from hybrid scans are undergoing evaluation at this writing. It is noteworthy that two over water oceanographic platforms provided aerosol and normalized water leaving radiances over two sites in the Yellow Sea during this time in support of ocean color investigations. Additionally two ships had Microtops sun photometers that were calibrated at GSFC to be consistent with AERONET reference instruments. Furthermore, supporting the KORUS-AQ campaign there was a High Spectral Resolution Lidar (HSRL) onboard the DC-8 and ground-based lidars as well as several contributing SKYNET PREDE sun-sky scanning spectral radiometers.

In addition, a regional scale campaign of ground-based remote sensing and in-situ measurements upwind and downwind of S. Korea was conducted during this period. This included the Institute of Remote Sensing and Digital Earth SONET network, AERONET and China Aerosol Remote Sensing NETwork (CARSNET, Che et al., 2009, 2015) Cimel Sun-sky radiometer networks in NE China that contributed twenty stations focused eastward from Beijing, and south to Shanghai. In collaboration with Institute of Remote Sensing and Digital Earth of the Chinese Academy of Sciences and the University of Maryland an airborne in situ aircraft based study of chemical composition of the atmosphere was also conducted during this period.

Coincidentally an enhanced network of eight AERONET sites was distributed across Japan from Fukuoka in the south to Sapporo in the north. This network augments the extensive SKYNET network of sun-sky radiometers in Japan that provides similar aerosol observations as AERONET, but also collocated lidar profiling and in some supersite locations in situ particle observations. Since there is overlap at some of the AERONET and SKYNET sites in S. Korea and Japan a unique and comprehensive comparison is planned between the networks.

The greater KORUS campaigns extensively sampled fine mode aerosols from locally and regionally transported industrial and urban sources, biomass burning from Siberian fires and regionally transported coarse mode dominated dust that strongly affected all countries on May 5, 2016 and to a lesser extent on several other days during the campaign. All aerosol types except the Siberian biomass burning aerosols were also sampled during research aircraft flight days. The opportunity to assess accuracies and limitations of multiple satellite and AERONET retrievals plus aerosol model forecasts for a variety of aerosol types, cloud and humidity conditions is expected to increase our understanding of the processes that govern air quality issues in NE Asia.

2.9 ObseRvations of Aerosols above Clouds and their intEractionS (ORACLES)

The NASA venture class suborbital program, (ORACLES) is an ongoing airborne campaign focused on biomass burning aerosol emissions from south central Africa transported over the south Atlantic to assess the aerosol cloud interaction over the persistent stratocumulus deck from August through September 2016 and planned for repeats in 2017 and 2018 (Zuidema et al., 2016). Approximately 15 AERONET sites from Mozambique, Zambia, Angola, Namibia, S. Africa, St. Helena and Ascension Island are providing regional context of aerosol properties from source to receptor sites for the campaign. Additionally a tightly focused DRAGON network (7 sites in 20 x 30 km grid) was set up on the central Namibian coast to assess the impact of aerosols on coastal fog and quantify any influence fog may play in the aerosol size distribution in this arid region.

Table 3 DRAGON campaign summaries; D=dust, FF=fossil fuel, B=biogenic BB=biomass burning, M=maritime. Because of time period of measurement, number and location of instruments and variable aerosol types transported by synoptic scale meteorology, AOD and particularly SSA averages are approximate. Most campaigns are referenced at: https://aeronet.gsfc.nasa.gov/new_web/campaigns.html where DRAGON data sets are also available with detailed point of contact (POC) information.

Campaign	Date	Locat'n Lat/Lon	AERONET sites	Aerosol source	~AOD$_{440}$ Range	~SSA$_{440}$	POC
UAE[2]	Aug-Sep 2004	UAE 24° x 54°	16	D, FF	0.1 – 0.8	0.93	Reid/Holben
CATZ	Jun-Aug 2007	USA 39° x -76°	24	M, B, FF	0.1-0.8	0.96	Holben/ AERONET
TIGERZ	May-Jun 2008	India 26° x 80°	8	D, BB	0.3-1.2	0.88	Holben/ Tripathi
7-SEAS:							
PENANG	Jul-Sept 2012	Malaysia 5° x 100°	8	FF	0.3-2.0	0.96	Holben/Lim
Singapore	Aug-Sep 2012	Singapore 1° x 104°	6	FF	0.2-1.5	0.94	Holben/ Salinas
DISCOVER-AQ							Crawford
Maryland	Jun-Aug 2011	USA 39° x -77°	43	FF, B	0.1-0.8	0.98	Holben/ AERONET
San Joaquin	Jan-Feb 2013	USA 37° x -120°	16	FF	0.1-1.3	NA	Holben/ AERONET
Houston	Sep 2013	USA 30° x -95°	18	FF	0.1-0.3	0.NA	Holben/ AERONET
Colorado	Jul 2014	USA 40° x -105°	13	FF, BB	0.1-0.3	NA	Holben/ AERONET
D-KOREA	Mar-May 2012	S. Korea 36°x 127°	22	FF, D	0.1-1.3	0.98	J.Kim/ Holben
D-JAPAN	Mar-May 2012	S. Japan	15	FF, M, D	0.1-1.3	0.98	Sano/ Holben
SEAC4RS	Aug-Sep 2013	SEUS 33° x -87°	24	FF, B, BB, M	0.1-0.7	0.95	Toon/ Holben
Korus-AQ							Crawford
Korea	May 2016	S. Korea	22	D, FF, M	0.2-1.0	0.91	J.Kim/ Holben
Japan	May 2016	Japan 35°x 135°	7	FF, D	0.1-0.8	0.94	Sano/Holben
China	May 2016	China 40° x116°	11	FF, D	0.1-1.2	0.89	Z. Li/Che

ORACLES	Aug-Sep 2016	Namibia -22° x 14°	7	FF, D, BB, M	0.1-0.5	0.84	Holben/ Knox

3.0 Summary of the special issue contributions

Three important research areas have come from the DRAGON campaigns: 1) In situ and remote sensing aerosol properties comparisons; 2) aerosol process studies; and 3) satellite and model validation studies. The first DRAGON-like campaigns focused in part on in situ versus remote sensing comparisons of aerosol optical, radiative and microphysical properties. Although some of the associated publications both pre- and post- date this issue they do merit a brief discussion. Schafer et al. (2014) showed an average difference of ~0.01 between in situ SSA from aircraft profiles compared to AERONET based retrievals for the DISCOVER-AQ MD DRAGON data set in July 2011. Sawamura et al., (2014) used the diversity of airborne and ground-based aerosol observations including the DRAGON measurements as a reference to intercompare project observations to HSRL radiative and microphysical properties. They found better agreement within the specified uncertainties using the remote sensing techniques compared to the airborne in situ observations. AERONET DRAGON Schafer et al. (2017 in preparation) has made comparisons of in situ measured size distributions from the multiple DISCOVER-AQ airborne profiles to the DRAGON AERONET sun photometer retrievals. Comparisons of rehydrated in situ measurements integrated vertically to the ambient retrieved remote sensing observations showed relatively good quantitative agreement based on approximately 40 flights coincident in time and space with the ground-based measurements. Sawamura et al.. (2017) used DRAGON AERONET (California and Houston) to evaluate HSRL-2 and airborne in situ AOD measurements.

Process studies have also broadened the research horizon possible from these data sets some of which appear in this special issue. For example Eck et al. (2014) used the DISCOVER-AQ Maryland DRAGON network observations to study the effect of non-precipitating cumulus clouds on AOD in adjacent regions on a horizontal scale of a few km. They found that on some days Angstrom exponent and size distribution were relatively constant while AOD was significantly enhanced (sometimes doubling in less than 1 hour) near moderately sized cumulus clouds. These results were corroborated by airborne lidar and airborne in situ measurements. This has potential implications for the need for better understanding of small-scale high temporal variations of aerosol-cloud processes and potential particle formation in clouds.

Much of the research activity with the DRAGON campaigns focused on air quality relating remote sensing parameters to surface PM 10. Seo et al. (2015) analyzed the DRAGON-Korea 2012 database testing various linear models that include boundary height and effective radius to surface PM 10 measurements in the vicinity of Seoul for the winter, spring and also long-term measurements. They found the best relationship in the winter owing to well-mixed aerosol layers while poorest relationships occurred during the spring when long-range aerosol transport stratified the aerosol profile.

The DRAGON-Asia campaigns were used to broadly describe trans-boundary advection of aerosols as a DRAGON scale network in Osaka was imbedded in a regional scale network over southern Japan (Sano et al., 2016). This analysis showed that during episodic long-range trans-boundary transport that aerosol loading was highest in the west of Japan but highly variable in space and time both for fine and coarse mode aerosol events. The long-range trans-boundary aerosols during this period were shown to follow the NCEP derived 700 to 850 mb wind vectors. Sano et al. (2016) investigated the variability of AOD under clean and polluted days in Osaka using DRAGON network measurements. They also detailed aerosol transportation over the city using high spatial and temporal resolution measurements by DRAGON-Osaka. Owing to two nearby mountain sites, boundary layer assessments were possible facilitated by nearby DRAGON-Osaka and AERONET stations. The DRAGON-Fukue instruments did not capture the intense March 10-11 fine mode event due to cloud contamination. However, the authors successfully measured the event by judiciously timed handheld Microtops-II sun photometer observations (Nakata et al, 2016). The value of AOD at 440 nm was over 2. Takami et al. (2013), reported the particle composition less than 1 µm diameter by Aerodyne's aerosol mass spectrometer and that the most abundant components were SO_4^{2-}, NH_4^+, and OC during the event (Kaneyasu et al., 2014).

Tan et al. (2015) investigated the ability to use surface based measurements to predict AOD in the cloudy tropics of Penang Malaysia where data gaps can be frequent and persistent. His predictive model had an r^2 of 0.68 compared to actual measurements of AOD from the DRAGON network.

By far the largest application of the DRAGON data sets has been in validation of satellite data. Most synoptic scale validation teams assume a spatial uniformity about a ground-based control point often citing the Anderson et al (2003) nominal scale length of 100 km. Frequently queries are made about the spatial representation of AERONET sites for which there is no simple answer due to proximity to aerosol sources, plus local and synoptic meteorology. The DRAGON campaigns have provided a better understanding for some specific circumstances that provide for better assessment of the spatial resolution of various satellite products and also high and low resolution model assessments. Prior to this issue, Munchak et al. (2013), noted the new collection 6 MODIS 3-km AOD product could potentially assess local aerosol gradients missed by the standard 10-km resolution product. They used the MD DISCOVER-AQ airborne HRSL lidar and MD-DRAGON data sets to assess the fidelity of the 3-km AOD product finding improvement over the coarse resolution product but some variability added due to the complexity of urban cover-types. Kim et al. (2016) used the DRAGON- NE Asia networks to refine the single scattering input to a single channel AOD retrieval model used with the GEO COMS Meteorological Imager (MI). They note that the surface based inputs from DRAGON significantly improved the model to predict AOD, thereby reducing previous over-estimates.

The Ozone Monitoring Instrument (OMI) on board Aqua has been a pioneering instrument to retrieve SSA and AOD from space in the UV. Jeong et al. (2015) have used the DRAGON NE-Asia data set in an optimal–estimation procedure that provides error estimates while simultaneously retrieving inversion products. This method was shown to compare better to the ground-based measurements than the OMI operational retrieval. From this validation the authors identified the parameters that most affected the AOD and SSA retrieval accuracy.

In a comprehensive comparison of the high temporal resolution Geostationary Ocean Color Imager (GOCI) and polar orbiting VIIRS and MODIS instruments, Xiao et al. (2016) using DRAGON NE-Asia and additional AERONET observations in 2013, that encompassed a broad range of conditions from low to high aerosol loading. Their analysis suggests that the satellite products do a better job of tracking aerosol variability on a day-to-day basis than tracking the high-resolution spatial variability.

Choi et al. (2016) used the DRAGON NE-Asia data sets to evaluate the GOCI AOD retrievals using the improvements to the GOCI Yonsei Aerosol Retrieval (YAER) algorithm. The algorithm makes retrievals over the Yellow Sea that often have Case II waters (highly turbid from sediment) as well as the highly variable S. Korean landmass reflectances during periods with highly variable aerosol types and concentrations. GOCI YAER AOD correlated very well with AERONET but showed lower skill with Angstrom exponent, fine mode fraction and SSA.

Garay et al. (2016) have assessed the current 17.6 km resolution AOD products against a multiple diverse DRAGON data sets collected around the world. They found that 75% of the data fell within 0.05 of the AERONET surface based measurements. They document the development and assessment of a prototype version of a high resolution (4.4 km) retrieval products compared against the same DRAGON data sets.

4 Conclusions

The DRAGON campaigns afford the opportunity to observe and assess aerosols under a variety of aerosol types and meteorological conditions. Sixteen multi-month mesoscale DRAGON campaigns were conducted and described that measured and/or retrieved intensive and extensive aerosol properties at high spatial and temporal resolution. The results shown in these studies challenge the long held assumptions of large-scale aerosol spatial uniformity as too simplistic and provided data for improvement of accuracies of higher resolution satellite and model retrievals as well as afford a deeper understanding of aerosol process studies. From the DRAGON campaigns, we now know that in situ and ground-based remote sensing of SSA have differences averaging ~0.01 in the mid Atlantic US, rapid aerosol-cloud interactions occur and can be detected with high resolution remote sensing at scales of a few kilometers, and finer resolution satellite products can capture the mesoscale spatial variability of aerosol although also showing that modifications to both satellite and model algorithms and assumptions may be necessary in order to achieve the required accuracy of these finer resolutions.

The unique opportunities for validation of high spatial resolution satellite aerosol retrievals and assessment of regional model estimates of aerosol optical, radiative and microphysical properties are only beginning to be examined. The DISCOVER-AQ and KORUS-AQ campaigns in concert with in situ surface and airborne measurements provide for detailed comparison and assessment against remotely sensed aerosol properties and further results are expected. The papers presented in this issue demonstrate the variety of research opportunities and sets the stage for new applications such as nighttime lunar meso-scale AOD assessments from the most recent KORUS-AQ and ORACLES campaigns and also for future DRAGON networks.

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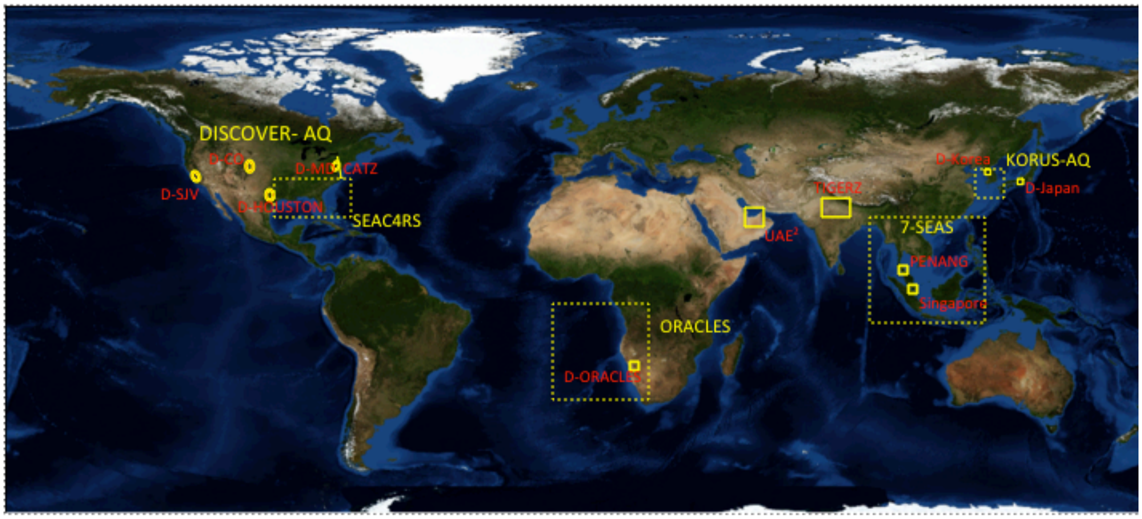

Figure 1, The distribution of DRAGON campaigns conducted from 2004 to 2016 are framed in yellow with red labels. Yellow labels indicate larger campaigns with dashed frames that included DRAGON networks.