DISCOVER-AQ has been implemented as a series of four field studies in recognition of the differences in factors controlling air quality that exist between various locations and seasons. The Baltimore–Washington study in July 2011 was intended to focus on a region strongly affected by both upwind and local emissions, with ozone (O\textsubscript{3}) events influenced by a mixture of sources, including power generation, transportation, and biogenic hydrocarbons.

Flights over California’s San Joaquin Valley in January–February 2013 focused on observing how wintertime shallow boundary layer conditions and weak ventilation allow pollutants to accumulate near the surface as emissions from agriculture, livestock, wood burning, and transportation contribute to unhealthy levels of particulate matter (PM).

Houston, TX (September 2013), offered the opportunity to observe a complex environment due to both the unique and concentrated emissions associated with the petrochemical industry and coastal meteorology that can alternately alleviate or exacerbate poor air quality.

A final deployment plan to Denver, CO (July–August 2014), focused on a region of complex mountain flows and a mixture of emissions from urban activity, agriculture, and oil and gas exploration.

These differences present unique challenges to both air quality models and satellite remote sensing.
Comparisons of data for PM$_{2.5}$ and O$_3$ from multiple DISCOVER-AQ study locations are presented here to highlight both the promise and the challenge of using satellite measurements to diagnose surface air quality.

**Aerosol Optical Depth and PM$_{2.5}$**

The first comparison examines relationships between in-situ PM$_{2.5}$ and remotely-sensed column aerosol optical depth (AOD) observed during summer in the Baltimore–Washington study and winter in the southern San Joaquin Valley. Hourly PM$_{2.5}$ data come from Beta Attenuation Monitors (BAMs) used by the Maryland Department of Environment in Beltsville, MD, and the San Joaquin Valley Air Pollution Control District in Bakersfield, CA.

Column AOD observations available during daylight hours at 15-min resolution are associated with co-located AERONET sunphotometers. For each location, an extended period of increasing PM$_{2.5}$ was selected for comparison. In both cases, surface PM$_{2.5}$ and column AOD show corresponding increases, however, the relative magnitudes of surface PM$_{2.5}$ versus AOD are vastly different. Notice, for instance, that AOD for Beltsville is divided by a factor of four in Figure 1. These differences can be attributed to several factors. The first and likely most important factor is the depth over which PM$_{2.5}$ is distributed. During the summer-time period over Maryland, aircraft observations of aerosol scattering revealed that the layer of particle pollution typically reached from the surface up to 2 km. Conversely, during wintertime in California’s Central Valley, the aircraft observed particle pollution to be consistently confined to the lowest 600 m above the ground, enabling very high surface PM$_{2.5}$ to be associated with modest values of AOD. Along with deeper mixing in the summer, warmer and wetter conditions contribute to higher AOD, as particles take on water, increasing in size, and scattering light more effectively.

A third factor is the difference in the composition of particle pollution in these two regions. Over Maryland, inorganic composition was dominated by sulfate in contrast to California where contributions from dust, smoke, and organic nitrates resulted in differences in particle optical properties (scattering vs. absorption), water uptake, and size distributions that impact aerosol scattering.
DISCOVER-AQ observations are providing a critical testbed for evaluating the use of satellites to observe air quality.

A Comparison of O₃ Episodes in Baltimore and Houston

Figure 2 offers a comparison of two O₃ episodes, one from the Baltimore–Washington study and the other as observed during flights over Houston, TX. For each case, O₃ profiles observed by the P-3B are shown for the day prior and the day of the episode. Profiles are colored to differentiate the three passes (morning, midday, and afternoon) over each of the monitoring sites.

While these examples are not presented as either representative or typical, they provide useful information on the challenges to remote-sensing of O₃ in the lower atmosphere by satellites. For context, these observations will be discussed in terms of the expected capabilities for future geostationary observations by the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument expected to be operational before the end of this decade. TEMPO is expected to be sensitive to O₃ changes of 10 parts per billion by volume (ppbv) in the lower troposphere.

Focusing first on the day-to-day difference in O₃, the average O₃ difference over Maryland from July 27–28 in the lowest kilometer was 30 ppbv; however, this number reduces to only 14 ppbv when considering the lowest 3 km. The presence of a stratospherically influenced layer just above the boundary layer on July 27 reduces the change in the O₃ column, effectively masking the increase in near-surface O₃. For Houston, the change in average O₃ from September 24–25 is 30 ppbv (40 ppbv below 1 km). Both of these differences would be visible to TEMPO, however, the need to understand the role of vertical structure is apparent, particularly in the Maryland case.

While day-to-day differences are important, the promise of hourly observations from TEMPO will revolutionize the application of satellite observations to air quality. From Figure 2, the in-situ profiles show clear evidence of temporal changes in O₃ related to photochemical production, even on the cleaner days. For the Maryland observations, the clean day shows more evidence for local O₃ production than the following episode day, which demonstrates numerous plumes, raising questions regarding the role of transport versus local chemical production that are beyond the scope of this article. For both days in Maryland, average O₃ changes across the day fall below the 10 ppbv sensitivity threshold for all sites. In stark contrast, large O₃ production rates are evident over Houston for both days. On the cleaner day, six of the eight profile sites experienced average O₃ increases of more than 10 ppbv and three sites saw changes in excess of 20 ppbv. This increased to seven sites on the day of the O₃ episode with three of the sites experiencing average O₃ increases of more than 30 ppbv.

For the Houston observations, spatial variability in O₃ is equally important. Figure 3 shows the time series for surface O₃ at 42 sites across the Houston area for the same period as shown in Figure 2. Data for these sites are colored based on their maximum 8-hr average O₃ over the two-day period. These time series demonstrate both an overall change in the regional O₃ level (see higher baseline values on September 25) and much greater spatial variability due to local O₃ production rates across the region.
The highest O₃ production rates were in proximity to emission sources associated with Houston’s ship channel (see map). Higher nitrogen oxides (NOₓ) emissions in this area are suggested in the time series data on September 24 with O₃ at sites colored in red trending below many of the orange and yellow sites and all but one red site showing O₃ to be fully titrated at night. These emissions along with favorable meteorological conditions on September 25 enabled much greater O₃ production in the ship channel area. When considered along with the profile data in Figure 2, these differences should be large enough to diagnose the spatial pattern of surface ozone increase across the region by the TEMPO satellite.

Summary

DISCOVER-AQ observations are providing a critical testbed for evaluating the use of satellites to observe air quality. By collecting observations with high temporal and spatial resolution across a range of clean and polluted conditions, as well as different seasons and locations, the relevant gradients in criteria pollutants and their remotely-sensed analogs are being defined and the value of additional information (e.g., boundary layer depth, humidity, aerosol hygroscopicity and composition, ozonesonde profiles) is being assessed. This information will help prioritize investments in additional ground observations most likely to improve the connection between satellites and regulatory monitoring networks.

Figure 3. Surface O₃ across the Houston area on September 24–25, 2013.

Notes: The time series on the left shows O₃ at 5-min resolution for 42 sites; time series for each site is colored by the maximum 8-hr average value (yellow = below 75 ppbv; orange = 75–100 ppbv; red = above 100 ppbv); site locations are shown on the map to the right and are similarly colored.