This article considers the measurements of nitrogen dioxide collected during the DISCOVER-AQ series of air quality field campaigns.
The final deployment in the DISCOVER-AQ series of air quality field campaigns focused on the Northern Front Range of Colorado, including the Denver Metropolitan Area in July and August 2014. The overarching goal of these campaigns was to improve the interpretation of satellite observations for diagnosing near-surface air quality conditions. This called for observations to be combined from multiple perspectives that included ground-based, as well as airborne in situ and remote sensing measurements. These observations were collected to demonstrate how future geostationary satellites could provide information of direct benefit to agencies responsible for monitoring and regulating air quality. This article focuses specifically on measurements of nitrogen dioxide, a short-lived pollutant with a distribution that is closely aligned with emissions from fossil fuel combustion sources. Better knowledge of nitrogen dioxide distributions on regional scales is critical to understanding the photochemical production of ozone in nonattainment areas as well as production of other secondary reactive nitrogen species such as nitric acid and peroxyacyl nitrates (PAN), which are related to issues of nitrogen deposition and long-range transport, respectively.

The sampling domain covered approximately 75 miles along the Front Range from Fort Collins in the north to Chatfield Park just south of Denver and reached roughly 30 miles east of the Rocky Mountain foothills to Greeley and Platteville located northeast of Denver (see Figure 1a). Working closely with the Colorado Department of Public Health and Environment (CDPHE), sites within the state’s monitoring network were chosen for focused sampling on the ground and by overflying aircraft. CDPHE has an extensive network for monitoring ozone, but nitrogen dioxide monitoring is limited.

To address this gap during the field study, the area was saturated with nitrogen dioxide measurements that included both in situ and remote sensing instruments operating on the ground and in the air. EPA researchers equipped six ground sites with research-grade instruments for in situ measurements of nitrogen dioxide. In addition to this augmentation by EPA, NASA installed Pandora spectrometers at a dozen ground sites to remotely sense the total abundance of nitrogen dioxide in the overhead atmospheric column by direct-sun observations throughout the day.

To complement these ground-based instruments, several aircraft flew overhead. One aircraft, NASA’s P-3B, provided in situ information on the vertical distribution of nitrogen dioxide in the lower atmosphere by conducting spiral soundings over the ground sites throughout the day. Another aircraft, NASA’s HU-25C flew high overhead carrying the Geo-TASO

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**Figure 1:** a) A map of the DISCOVER-AQ Colorado measurement domain with morning and afternoon observations of NO\textsubscript{2} by Geo-TASO overlaid in panels b) and c), respectively. The white line depicts the sampling path of the P-3B that was flown repeatedly across the domain over 15 flight days. The spiral soundings over key ground sites show up as circles. Panel d) shows the latitudinal distribution of NO\textsubscript{2} from all P-3B flight data collected below 1 km above ground level. Data were binned and averaged over 0.01 x 0.01 deg. Symbol size varies from east to west with larger symbols indicating measurements taken farther west in proximity to the mountains. (Note: Geo-TASO observations in panels b and c of the NO\textsubscript{2} abundance beneath the aircraft are expressed in units of column density, which is the total number of molecules per unit area observed by the instrument).
Nitrogen Dioxide Observations during DISCOVER-AQ by Crawford et al.

...instrument capable of detecting the nitrogen dioxide column abundance from beneath the aircraft down to the surface.

While this article will focus on the observations listed above, additional nitrogen dioxide measurements were collected from other partnering research aircraft (NCAR C-130 and NASA B200), ground sites, and mobile labs. The discussion below demonstrates how each of these perspectives offer a unique and important piece of information regarding the distribution of nitrogen dioxide across the Front Range.

Figure 1 (panels b and c) provides a sample of the type of information that future geostationary satellites will provide each hour over the entire continental United States, wherever skies are clear. Looking down from high altitude onboard the HU-25C, the Geo-TASO instrument was used to map the distribution of nitrogen dioxide across the region during the morning and afternoon of August 2, 2014.

While the view is dominated by the large nitrogen dioxide enhancement northeast of central Denver, there are clear differences between morning and afternoon. In the morning, the main enhancement is more concentrated and lesser enhancements are observed to the northeast, suggesting possible transport along the Platte River valley and up towards Greeley. In the afternoon, the distribution is more diffuse and there is evidence of transport towards the mountains in the direction of Golden. While a detailed explanation for these distributions are beyond the scope of this article, they are consistent with the general morning and afternoon atmospheric circulation in the Denver area.

The view of the regional nitrogen dioxide distribution from Geo-TASO represents conditions for a single day. To evaluate its representativeness, Geo-TASO data are compared to average conditions observed from the NASA P-3B, which sampled the region on 15 flight days during the study. The white line on panels b and c in Figure 1 shows the flight route which...
was flown two to three times per day. Circles indicate locations where spiral soundings were collected over ground sites.

All data collected in the lowest kilometer were spatially binned and averaged at 0.01 x 0.01 deg resolution and plotted in panel d of Figure 1. The data are plotted by their latitude to enable direct comparison with the distributions in panels b and c. To indicate the longitude of the P-3B observations in panel d, symbols sizes are varied, with smaller symbols indicating observations farther to the east. The P-3B and Geo-TASO data agree in several important respects. The most obvious is the large and persistent enhancement of nitrogen dioxide just north of central Denver. The nitrogen dioxide baseline is also higher in the southern portion of the domain. A more subtle observation is that to the north, P-3B nitrogen dioxide is more abundant over the eastern portion of the domain, consistent with the morning enhancements in the Geo-TASO observations.

To complement the spatial remote sensing from the air, Pandora spectrometers provided continuous observations of the total nitrogen dioxide column abundance over ground sites. This enabled a comparison of nitrogen dioxide measurements at the surface from ground monitors with column abundances equivalent to what would be seen by a satellite. In Figure 2, surface and column measurements are compared for three ground sites. The LaCasa and I-25 sites are both located in Denver just south of the largest enhancements in nitrogen dioxide observed by Geo-TASO. Both sites show similar behavior in the diurnal trend of nitrogen dioxide column abundance. The Golden site is located closer to the mountains due west of Denver. It exhibits a similar trend with only about half the total nitrogen dioxide abundance in the early morning. By late afternoon, nitrogen dioxide column has increased to about 70 percent of the values in Denver, consistent with the behavior of afternoon observations of Geo-TASO shown in Figure 1c.

When looking at the surface monitor observations in Figure 2, a very different pattern emerges. During the morning, in particular, nitrogen dioxide decreases at the surface while column abundances increase. This is most striking at LaCasa where surface nitrogen dioxide decreases by nearly a factor of two while column abundance increases by a factor of two. This suggests that vigorous mixing and boundary layer

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**Figure 3:** Changes in the vertical distribution of NO₂ throughout the day as observed by the NASA P-3B over the LaCasa site located in Denver. Data were collected from spiral soundings over the site over 15 flight days. Data were segregated into three periods: Morning (0930–1030), Midday (1100–1320), and Afternoon (1400–1630).
growth is diluting surface nitrogen dioxide during a period when total emissions are continuing to accumulate. Evidence for this is provided in Figure 3 showing how the average profile of nitrogen dioxide changes above the LaCasa site depending on the time of the spiral soundings of the P-3B. While the soundings do not occur often enough to fully resolve the diurnal cycle in column abundance, the data demonstrate that vertical mixing causes dramatic changes in the lower atmospheric distribution of nitrogen dioxide throughout the day. It is important to understand these mixing effects alongside the photochemical factors contributing to the diurnal behavior of nitrogen dioxide.

**Conclusion**

Through the examples presented above, a picture emerges for the essential role of geostationary satellite observations in future monitoring and regulation of air quality. Satellites can provide the broad spatial coverage and total column abundances needed to complement surface observations that are spatially limited but key for assessing exposure. Interpreting differences in the variability of surface and column measurements will also provide critical information on vertical mixing, which affects the exposure to primary pollutants, as well as the rates of ozone and particulate matter formation. This information will be critical to model assessments of air quality and improvement strategies.

By contrast, the density of ground-based Pandora observations and airborne sampling used in DISCOVER-AQ cannot be sustained. Rather, these represent vital validation tools that will need to be used in a targeted fashion to ensure that ground-based and satellite observations are connected and able to provide a more complete picture of air quality than is possible with either alone. This vision of an integrated air quality observing system will be fulfilled by NASA’s launch of a satellite instrument called TEMPO (Tropospheric Emissions: Monitoring of Pollution) later this decade. DISCOVER-AQ observations such as those described here are playing an important part in the preparation to take immediate advantage of TEMPO observations as soon as possible after launch. em

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