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# Development of Community, Capabilities, and Understanding through Unmanned Aircraft-Based Atmospheric Research

## The LAPSE-RATE Campaign

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**ABSTRACT:** Because unmanned aircraft systems (UAS) offer new perspectives on the atmosphere, their use in atmospheric science is expanding rapidly. In support of this growth, the International Society for Atmospheric Research Using Remotely-Piloted Aircraft (ISARRA) has been developed and has convened annual meetings and "flight weeks." The 2018 flight week, dubbed the Lower Atmospheric Profiling Studies at Elevation–A Remotely-Piloted Aircraft Team Experiment (LAPSE-RATE), involved a 1-week deployment to Colorado's San Luis Valley. Between 14 and 20 July 2018 over 100 students, scientists, engineers, pilots, and outreach coordinators conducted an intensive field operation using unmanned aircraft and ground-based assets to develop datasets, community, and capabilities. In addition to a coordinated "Community Day" which offered a chance for groups to share their aircraft and science with the San Luis Valley community, LAPSE-RATE participants conducted nearly 1,300 research flights totaling over 250 flight hours. The measurements collected have been used to advance capabilities (instrumentation, platforms, sampling techniques, and modeling tools), conduct a detailed system intercomparison study, develop new collaborations, and foster community support for the use of UAS in atmospheric science.

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The use of unmanned aircraft systems (UAS) to make measurements of the atmosphere and its interactions with the surface has become increasingly popular. The use of these systems to capture in situ and remotely sensed observations has introduced new perspectives to the field of atmospheric science. The relative ease of deployment of these systems has advanced frequent, detailed profiling of the atmosphere (e.g., Lawrence and Balsley 2013). At the same time, the relatively slow flight speed of some fixed-wing platforms has increased the spatial resolution at which critical variables can be sampled (Hemingway and Frazier 2018). Additionally, the ability offered by rotary wing and hybrid UAS to hover and profile vertically has opened new opportunities for vertical profiling of the atmosphere from areas where only limited space is available for launch and recovery (e.g., McGonigle et al. 2008; Brady et al. 2016; Hemingway et al. 2017; Wildmann et al. 2017).

Many atmospheric science UAS campaigns have focused on data collection in the planetary boundary layer (PBL) (e.g., Reuder et al. 2012; Bonin et al. 2013; Lothon et al. 2014; Altstädter et al. 2015), because the ability to deploy UAS in a targeted manner to understand localized processes of interest enables answering questions related to the subsynoptic–spatiotemporal scales of PBL features. Together, fixed- and rotary-wing UAS offer high-resolution observations beyond what is captured using operational meteorological observing networks (Hemingway et al. 2017). Beyond the PBL, UAS have been deployed to study the atmosphere and its interactions with other components of the Earth system over a variety of regions, covering both lower latitudes (e.g., Corrigan et al. 2006; Ramanathan et al. 2007; van den Kroonenberg et al. 2008; Houston et al. 2012) and higher latitudes (e.g., Curry et al. 2004; Cassano et al. 2010; Knuth and Cassano 2014; de Boer et al. 2018; Kral et al. 2018). In addition to the flexible deployment options offered by these systems, the lower cost of UAS and lack of human passengers allows these systems to be deployed to collect observations where existing sensor technologies cannot regularly do so, including around supercells (e.g., Elston et al. 2011), in hurricanes (e.g., Cione et al. 2016) and over the Arctic Ocean (e.g., Curry et al. 2004).

In recognition of this rise in popularity, the European Union funded a COST (Cooperation in Science and Technology) Action to foster development of a community around UAS-based pursuits in 2008. From this action grew the International Society for Atmospheric Research Using Remotely-Piloted Aircraft (ISARRA). ISARRA has held annual meetings every year since 2012, with four meetings having occurred in Europe (2013, 2014, 2016, 2017) and two in the United States (2015, 2018). The 2018 meeting was hosted by a joint committee of representatives from the University of Colorado, the National Center for Atmospheric Research, and the National Oceanic and Atmospheric Administration, with the conference being in Boulder, Colorado, between 9 and 12 July 2018 (de Boer et al. 2019).

Since 2012, several ISARRA conferences have featured coordinated flight activities to allow participants to demonstrate and evaluate their aircraft, sensors, and other items related to the scientific deployment of UAS. The 2018 conference aimed to provide participants with a field experience that highlighting Colorado-specific science topics and leverage ongoing work within the state of Colorado to foster community relations surrounding the use of UAS. Based on these desires, the conference organizers planned for a week-long flight period, named Lower Atmospheric Profiling Studies at Elevation–A Remotely Piloted Aircraft Team Experiment (LAPSE-RATE) in the San Luis Valley (SLV) of south-central Colorado immediately following the ISARRA conference (14–21 July 2018). The SLV is a high-altitude depositional basin located in south-central Colorado with an average elevation of 2,336 m above sea level. The valley stretches approximately 200 km north–south and 120 km east–west and is bounded on the east by the Sangre de Cristo Mountains and on the west by the San Juan Mountains. The central valley is primarily flat, and land cover comprises mostly agriculture and shrub/scrublands. Irrigated agriculture is possible due to groundwater and streams fed by snow from the surrounding mountain ranges. The Great Sand Dunes National Park and Preserve lies along the eastern side of the valley, bringing some tourism to the area.

While previous flight periods were largely centered around platform intercomparison and demonstration, LAPSE-RATE set out to accomplish this while additionally organizing data collection to target specific science themes, including:

- *The morning boundary layer transition*: Given the "high and dry" nature of the SLV, a lack of water vapor in the overlying atmosphere results in very efficient nighttime cooling and daytime solar heating. Therefore, the diurnal cycle in temperature can be substantial, making for large swings between stable and convective boundary layers. Sampling this transition required distributed profiling of the lower (0–400 m) atmosphere, with measurement sites distributed geographically across different surface types and across different parts of the valley.
- *Deep convection initiation*: Thunderstorms routinely form over the mountains surrounding the SLV. However, on some days these storms advect into or form over the central valley as well. The initiation and maintenance of storms within the central valley could be impacted by local sources of potential energy and/or coherent circulations tied to surface type gradients. Sampling these events entailed distributing teams throughout the northern portion of the valley to make detailed measurements of the thermodynamic state and its evolution with time across a variety of spatial gradients in the valley to attempt to assess whether the surface plays a role in the development and evolution of storms over the valley itself.
- *Aerosol properties*: A variety of aerosol sources make the SLV an interesting area to study aerosol properties. Sources of particles include agriculture, the Great Sand Dunes National Park, wildfires, biogenic emissions, and advection. Routine profiling of the lower atmosphere allowed teams operating aerosol samplers to document particle sizes and concentrations under a variety of boundary layer and synoptic wind regimes.
- *Valley drainage flows*: While the SLV itself is very broad and of substantial scale (see Fig. 1), several smaller valleys feed into it. Based on numerical simulations and reports from valley crop dusters, we suspected that clear nights could result in distinct density currents from

these smaller valleys into the main SLV. Focused sampling within the Saguache Valley and its outflow area enabled measuring the evolution of these density currents and mapping its outflow into the SLV.

- *Atmospheric turbulence profiling*: Understanding atmospheric turbulence in the lower atmosphere is key to development of numerical models. Further, turbulence can undermine the performance of communication systems due to its impact signal integrity. Teams deployed a variety of measurement platforms to characterize the diurnal cycle of turbulence intensity in the "high desert" environment of SLV to provide a unique dataset on variability within the valley, terrain effects, and the impact of low water vapor amounts on turbulence generation.

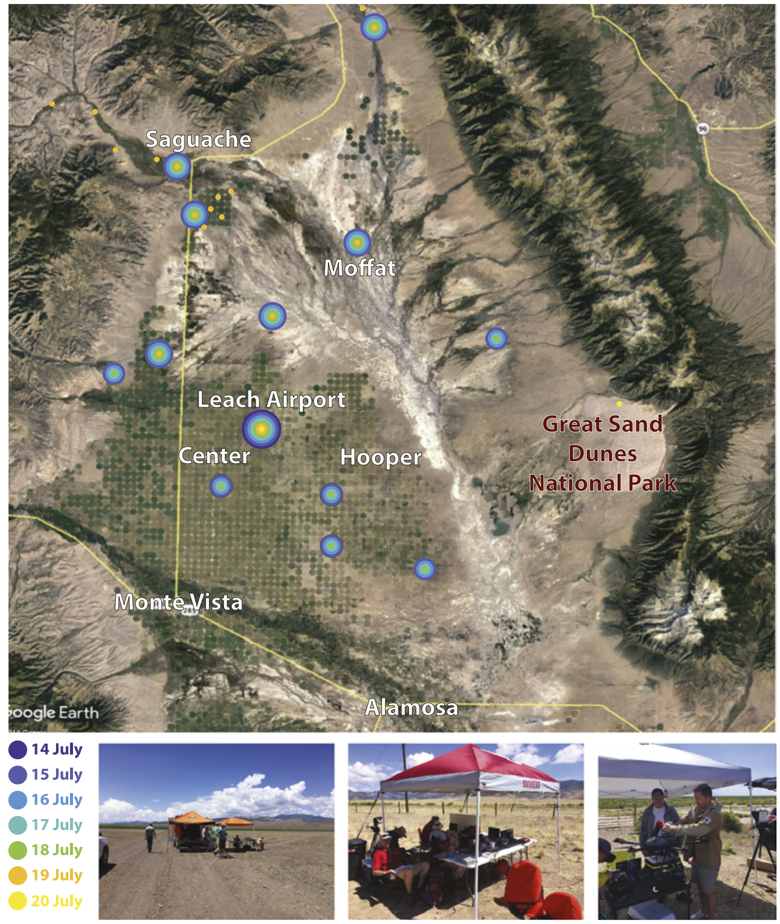


Fig. 1. (top) Map of operational sites overlaid on a satellite map (map courtesy of Google). Colors indicate the date of flights at a given location, while the size of the dot indicates the total number of days sampled at that location. (bottom) Photographs provide examples of the field camps for different teams (left to right: OSU, OU, and FMI/Kansas State).

## Campaign overview

In total, 10 flight teams deployed 34 different aircraft over the course of the flight week (Table 1 provides an overview of platforms). Together, these aircraft sampled altitudes between the surface and 914 m above ground level (AGL). There were 1,287 flights completed totaling 262.4 flight hours, with most flights occurring over 5 flight days. In addition to the unmanned aircraft deployed, the team also integrated sampling using a variety of surface-based instrumentation. One of the surface-based sensing systems deployed was the University of Oklahoma Collaborative Lower Atmospheric Profiling System (CLAMPS; Wagner et al. 2019). In addition to a surface meteorological station, CLAMPS includes a scanning Doppler wind lidar, an Atmospheric Emitted Radiance Interferometer (AERI), and a microwave radiometer (MWR). For LAPSE-RATE, CLAMPS also included a ground station for rawinsonde releases. During LAPSE-RATE, CLAMPS was deployed at the Moffat school and collected continuous wind, temperature, and humidity profiles for the entire campaign. The CLAMPS team also released and monitored a total of 21 rawinsondes at the Moffat School. The CLAMPS AERI and MWR data for LAPSE-RATE were jointly processed using the AERI Optimal Estimation retrieval algorithm (AERIoe; Turner and Löhnert 2014; Turner and Blumberg 2018) to retrieve temperature and water vapor profiles with a temporal resolution of 10 min. Every 5 min, the CLAMPS Doppler lidar conducted a 24-point plan position indicator (PPI) scan at 70° elevation followed by six-point PPI scan at 45° elevation (the latter was primarily used for quick real-time estimates of the wind environment). Wind profiles were retrieved from the 70° PPI scans using the velocity–azimuth display (VAD) technique.

In addition to CLAMPS, the University of Colorado deployed two Doppler lidar systems to take continuous measurements of the low-level winds at Saguache airport and at the Moffat

Table 1. A summary of LAPSE-RATE aircraft, including information on platform type and measured quantities.

| Aircraft | Operator | Description | Measurements |
|---|---|---|---|
| S1 | Black Swift Technologies (BST), University of Colorado Boulder (CU) | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| S2 | BST/NOAA | 3-m fixed wing | $T$, RH, $p$, 3D winds, surface IR temperature, aerosol concentration |
| Intense Eye V2 | EngeniousMicro LLC | Quadcopter | $T$, RH, $p$, 3D winds, solar irradiance, differential temperature |
| PRKL1 | Finnish Meteorological Institute (FMI) | Hexacopter | $T$, RH, $p$, total aerosol concentration, coarse mode concentration |
| PRKL2 | FMI | Hexacopter | $T$, RH, $p$, $CO_2$, water vapor |
| M600P | Kansas State University (KSU) | Quadcopter | $T$, RH, $p$, aerosol concentration (132–3648 nm) |
| Solo (8) | Oklahoma State University (OSU) | Quadcopter | $T$, RH, $p$ |
| Phantom | OSU | Quadcopter | $T$, RH, $p$ |
| M600P_1 | OSU | Hexacopter | $T$, RH, $p$, 3D winds, $CO_2$ |
| M600P_2 | OSU | Hexacopter | $T$, RH, $p$, 2D winds |
| Anaconda | OSU | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| MARIA | OSU | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| Albatross | OSU | 3-m fixed wing | $T$, RH, $p$, 3D winds, turbulence |
| AR Wing 900 | OSU | 1-m fixed wing | $T$, RH, $p$ |
| DataHawk2 | University of Colorado Boulder (CU) | 1-m fixed wing | $T$, RH, $p$, 3D winds, IR surface/sky temperature |
| TTwistor | CU | 3-m fixed wing | $T$, RH, $p$, 3D winds |
| Mistral | CU | 4-m fixed wing | $T$, RH, $p$, 3D winds |
| Talon | CU | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| BLUECAT 5B | University of Kentucky (U.K.) | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| BLUECAT 5C | U.K. | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| BLUECAT 5D | U.K. | 2-m fixed wing | $T$, RH, $p$, 3D winds |
| S1000 | U.K. | Octocopter | $T$, RH, $p$, 3D winds |
| M600P | U.K. | Hexacopter | $T$, RH, $p$ |
| Solo | U.K. | Quadcopter | $T$, RH, $p$, 3D winds |
| Solo | U.K. | Quadcopter | $T$, RH, $p$, $CO_2$, $O_3$, $NO_2$, CO, $NH_3$, VOCs, $CH_4$ |
| M600P_1 | University of Nebraska–Lincoln (UNL) | Hexacopter | $T$, RH, $p$ |
| M600P_2 | UNL | Hexacopter | $T$, RH, $p$ |
| CopterSonde2 | University of Oklahoma (OU) | Quadcopter | $T$, RH, $p$, 2D winds |
| Inspire 2 | Virginia Tech (VTech) | Quadcopter | $T$, 2D winds |

School (see Fig. 1). These Leosphere WindCUBE v1 Doppler lidar systems use the Doppler beam swinging method for quantifying wind speed, wind direction, and turbulence dissipation rate (Bodini et al. 2018) from 40 to 220 m above the surface using four beams approximately 30° from vertical (Rhodes and Lundquist 2013; Lundquist et al. 2015).

Beyond these systems, a variety of instrumented vehicles were deployed, including mobile mesonet vehicles from the University of Nebraska–Lincoln and the NOAA National Severe Storms Laboratory. These systems have forward-mounted instrument suites capable of measuring temperature, moisture, pressure, and winds while either stationary or in motion. Both the CLAMPS and the NOAA mobile mesonet were used to launch multiple radiosondes daily. The University of Colorado also provided the recently developed Mobile UAS Research Collaboratory (MURC) to serve as a central base of operations in the field, mainly at Leach Airport. The MURC is an instrumented van designed to operate independently to support UAS operations and provide near-surface meteorological information for scientific use and real-time decision making. The MURC is additionally equipped with two workstations and two servers to support routine computing tasks and intensive data processing and storage. The MURC's meteorological instrumentation, including pressure, temperature, and humidity sensors, a 3D sonic anemometer, and cup and vane anemometer for redundancy and pilot information, sit atop an extendable 15-m mast. The mast also has instrumentation to measure position, orientation, and movement and a large communications suite that increases the range of the UHF/VHF vehicle-to-vehicle radios.

To conduct the horizontal and vertical sampling required to shed light on the scientific phenomena mentioned above, the LAPSE-RATE team developed a series of distributed sampling plans to capture information on these different topics. These plans were developed daily the evening before the sampling was to be conducted by assessing likely weather conditions using operational forecast models, guidance from the National Weather Service office in Pueblo Colorado, data from an experimental real-time version of the Weather Research and Forecasting (WRF) Model run at large-eddy-permitting resolution (described in more detail below), and input from participating team leads. Resulting operations spanned the scientific objectives listed above and distributed teams throughout the valley as depicted in Fig. 1. To the extent possible, an attempt was made to allow for continuity in sampling at given sites (e.g., Moffat School, Leach, and Saguache Airports) to support model verification and process studies.

Weather during LAPSE-RATE was generally good for both flight operations and for studying the specific phenomena of interest. Lower-atmospheric (0–5 km) temperatures from radiosondes launched at Leach Airfield during the week are presented in Fig. 2a, along with MURC observations of 15-m temperature (*T*), relative humidity (RH), and wind speed (Wspd) and direction (Wdir) (Figs. 2b,c). Weather was generally consistent under two synoptic regimes. On 14 and 15 July, a cold front was situated to the north of the San Luis Valley, resulting in

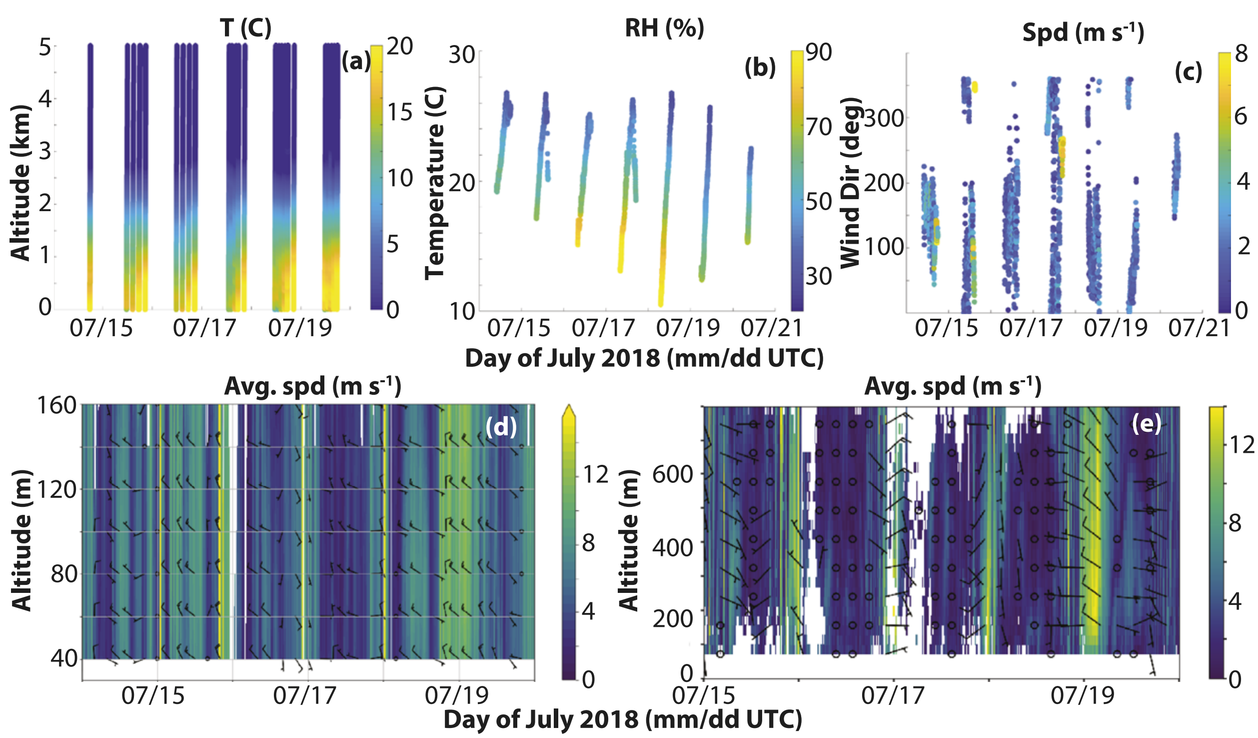


**Fig. 2. An overview of the meteorological conditions observed during the LAPSE-RATE campaign. Included are temperature data from radiosondes and (a)–(c) surface temperature, humidity, and wind speed and direction (from MURC) from Leach Airport, as well as lower-atmospheric wind conditions (d) from the CU Doppler lidar stationed at Saguache and (e) from the CLAMPS system deployed at Moffat.**

the advection of monsoonal moisture from the Pacific. This resulted in the development of widespread afternoon thunderstorms over surrounding mountains, with some storms advecting over the valley and producing heavy precipitation and gusty winds. Beginning 17 July, a region of high pressure established over Colorado, resulting in reduced storm activity, though afternoon storms over the mountains surrounding the San Luis Valley persisted. The Leach radiosondes and MURC data show a consistent lower atmosphere featuring a strong (15°–20°C) diurnal cycle in temperature, with early morning temperatures around 10°–12°C and afternoon temperatures exceeding 27°C. In general, winds throughout LAPSE-RATE were light and variable, with higher wind speeds associated with afternoon convective events and morning cold-air drainage from smaller valleys. The lower atmosphere was generally stable in the early morning and quickly transitioned to a well-mixed convective boundary layer throughout the morning.

The first day of LAPSE-RATE (Saturday, 14 July) included a "Community Day" (more details below) and time to conduct intercomparison flights near the MURC vehicle. Teams took turns completing predetermined flight patterns in the vicinity of the MURC, with the MURC acting as a reference measurement. The following two days (15–16 July, conditions were appropriate to support the development of convective storms and therefore the decision was made to dedicate these two days to sampling of the initiation of deep convection. Platforms sampled in a distributed manner between 0900 and 1500 local time in order to capture the development of convective structure and evaluate the variability of such structure over a variety of surfaces, including dry desert areas, irrigated farmland, dried river beds, and nearby valley environments. This sampling additionally included making measurements on the lower portions of both east- and west-facing slopes, where solar insolation would differ more dramatically over the course of the day than over the level valley floor. Tuesday, 17 July, was designated as a day for participating groups to conduct research flights to collect measurements aligned with the scientific objectives of the projects that supported their participation in the campaign. Many of the groups took the opportunity to assess new capabilities and to complete additional intercomparison activities. Many of these flights were conducted on a schedule conducive to evaluating the evolution of the lower atmosphere over the morning hours. To continue such sampling, 18 July was specifically deemed a morning boundary layer transition day, with all teams strategically distributed throughout the valley, again covering a variety of surface types, to conduct regular profiling of the lower atmosphere. These profiles occurred between 0700 and 1300 local time, and while a slightly earlier start might have been advantageous, the forecast called for early morning fog so the decision was made to start a bit later. The final coordinated flight day of LAPSE-RATE was conducted on Thursday, 19 July, and teams were redistributed to focus attention on the two smaller valleys feeding into the northern end of the large SLV to collect measurements of cold-air drainage from nighttime cooling in these areas. To capture the valley flow and its reversal, sampling occurred between 0530 and 1100 local time. For this final mission, the surface-based assets were also shuffled a bit, with the mobile mesonet vehicles driving east–west and north–south transects over the northern part of the San Luis Valley, and the MURC moving to the north of the Leach airfield to capture more of the outflow.

## Development of community

The coordination of such a large field activity required extensive planning in order to develop flight permissions, property access, lodging, sampling strategies, integration of ground-based observing assets, equipment preparation, and more. Therefore, the ultimate level of success of this campaign rested on the group's ability to effectively interface with each other and with supporting entities. Such coordination was supported by a variety of different activities, including the preexistence of the ISARRA community, active funded research projects, and ongoing work by UAS Colorado, a local nonprofit entity committed to promoting and improving UAS-based aerospace activities in the state of Colorado, to develop the San Luis Valley as a UAS-friendly environment.

Leveraging these activities, LAPSE-RATE coordination began in earnest with an in-person meeting at the 2018 American Meteorological Society Annual Meeting in Austin, Texas. This meeting included representatives from most of the participating teams, as well as community and government organizations such as NCAR and NOAA. This meeting laid the initial groundwork for campaign planning, kicking off regular teleconferences between the participating teams for campaign coordination. These discussions sparked coordination with the Federal Aviation Administration, local county governments, landowners, local educational organizations, relevant National Weather Service local forecast offices, and others. They also fueled the completion of precampaign numerical simulations and analyses of historical radar and surface meteorological observations to help optimize sampling strategies related to the mutually determined scientific objectives.

In addition to the precampaign coordination meetings, a small team of participants conducted a precampaign scouting trip to the SLV in May 2018. This trip lead to several important decisions, including limiting the sampling area to the northern half of the valley, the general layout for field operations based on availability of sampling sites and land access, leveraging the Alamosa County Emergency Operations Center for daily weather briefings and setting Alamosa as a central operating hub due to the availability of lodging and infrastructure for campaign participants. Ultimately, the planning leading up to the campaign extended and strengthened the collaborative nature of the U.S. and international communities leveraging unmanned aircraft for atmospheric science.

Integral to the success of both the planning discussions and the scouting trip was the early integration of early-career researchers. Various early-career researchers were directly involved with the campaign planning and execution, and often carried much of the load of communicating between planning meetings. Additionally, graduate and undergraduate students were heavily involved with the execution of the campaign and subsequent preparation of the datasets. Finally, several high school students were integrated into reporting on the campaign in local and social media. This extended participation was supported broadly by the U.S. National Science Foundation and U.S. Department of Energy, who both provided funding to help support the travel for these participants. In total 65 students and postdocs, including 25 female and minority participants, were involved with the planning, execution, and postcampaign analysis of LAPSE-RATE. Such broad involvement buoys the advancement of a sense of community across this interdisciplinary field of research for generations to come.

Another central goal of the LAPSE-RATE effort was to inform and provide access for the local San Luis Valley community. To support this outreach, most of the first day of the campaign consisted of a Community Day. Organized by education and outreach teams from participating institutions, this event included up-close access to the aircraft to be deployed during the rest of the week and the people who would be operating them (Fig. 3). Additionally, there were brief presentations and a discussion panel featuring panelists from participating universities and government entities. These events offered the community an opportunity to ask direct questions about what parameters were being measured and how the use of UAS to measure these parameters benefits understanding of processes important to the local community (e.g., precipitation for agriculture, local wind events). Also, the Community Day allowed local property owners to meet with many of the pilots before flight operations commenced. To offer an in-person look at flight activities, some of the research teams leveraged this time to conduct system flight tests and other flights to compare their sensing system with ground-based assets. The event was attended by around 100 community members spanning all age

**Fig. 3. Photos from the LAPSE-RATE Community Day, including (clockwise from top left) Upward Bound students getting an up-close look at aircraft; panelists talking about UAS, work in atmospheric science and answering community questions; a young meteorologist in the making; and LAPSE-RATE participants from most participating institutions and their aircraft.**

groups, including young children, Upward Bound participants from local high schools, local ranchers, interested community members, and government officials.

## Development of capabilities and understanding

The data collected during LAPSE-RATE have spurred a variety of studies and have helped to demonstrate and expand the capabilities of participating teams. Detailed scientific investigations are underway. For example, data collected during LAPSE-RATE supported work to measure and predict Lagrangian coherent structures with UAS (Nolan et al. 2018). This research demonstrated the value of synthesizing observational data from UAS, ground-based sensors, and model output to detect and predict the transport of airborne chemical or biological agents, or other transported materials. Additionally, a new housing for temperature and humidity sensors on University of Nebraska multirotor UAS was tested during the LAPSE-RATE campaign (Islam et al. 2019). This housing was designed to shield sensors from insolation, external (conductive) heat sources, and precipitation (artificial wet-bulbing) while maintaining sufficient sensor aspiration and minimizing turbulence in the aspirating flow. Similarly, publications are being developed on instruments and platforms that were evaluated during LAPSE-RATE. Specific examples include work conducted to improve wind estimates from the CopterSonde system deployed by the University of Oklahoma and its sampling "scoop" of the CopterSonde (Greene et al. 2018, 2019).

The near-MURC flights offered an opportunity to assess the how the different platforms deployed during ISARRA [details on this intercomparison can be found in Barbieri et al. (2019)] can be intercompared. This work identified some important differences among sensors from different manufacturers and the placement of those sensors on the UASs (e.g., precautions taken to properly shade and ventilate sensors from solar heating). To our knowledge, these LAPSE-RATE activities represent the most extensive UAS atmospheric measurement intercomparison effort to date. Additional intercomparisons were completed between UAS platforms measuring similar quantities to one another, and between UAS and other deployed resources such as the CLAMPS and radiosondes (e.g., Fig. 4).

Beyond the efforts discussed above, the campaign offered an opportunity for teams to expand their capabilities by providing a field campaign setting in which to test new techniques

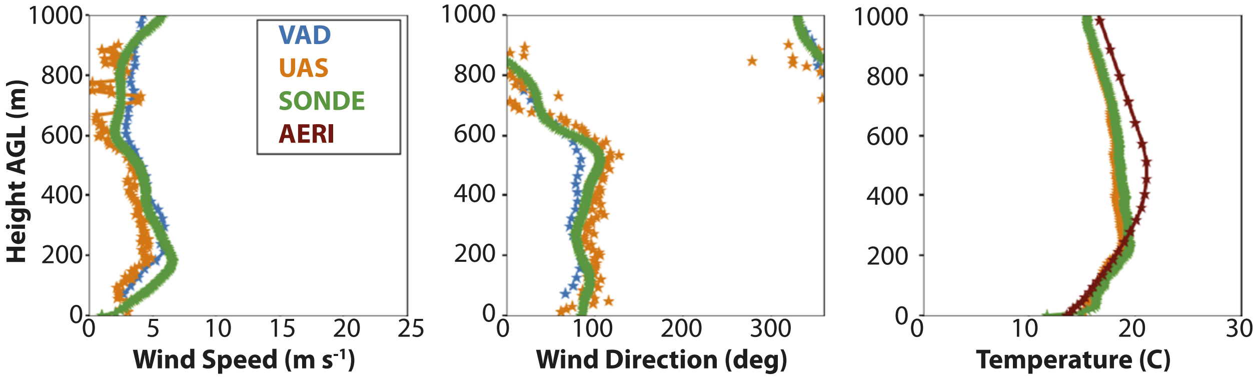


**Fig. 4. A comparison of CLAMPS-based remote sensing, UAS, and radiosonde profiles of (left) wind speed, (center) wind direction, and (right) temperature. These comparisons were completed at Moffat school on 19 July.**

and technologies. Several groups field-deployed new platforms and sensors for the first time during LAPSE-RATE. For platforms this christening included the first field deployment of the MURC by the University of Colorado, the first field-deployment of several aircraft including Kentucky's S-1000, the CU Mistral, and the EngeniousMicro LLC IntenseEye V2. For sensors, this included the NOAA–University of Colorado MiniFlux and NOAA NightFox payloads, several airborne sonic anemometers mounted on rotorcraft, the University of Nebraska's thermodynamic payload (Islam et al. 2019), and differential temperature sensors deployed by EngeniousMicro LLC. Similarly, teams gained experience with new flight patterns and capabilities. For example, while some groups (e.g., University of Colorado) had significant experience operating aircraft in the "follow me" mode, where the pilot and spotting team are in a moving vehicle and the aircraft is operating in a mode where it stays within close range of that vehicle (see Fig. 5), other groups were conducting initial flights in this mode

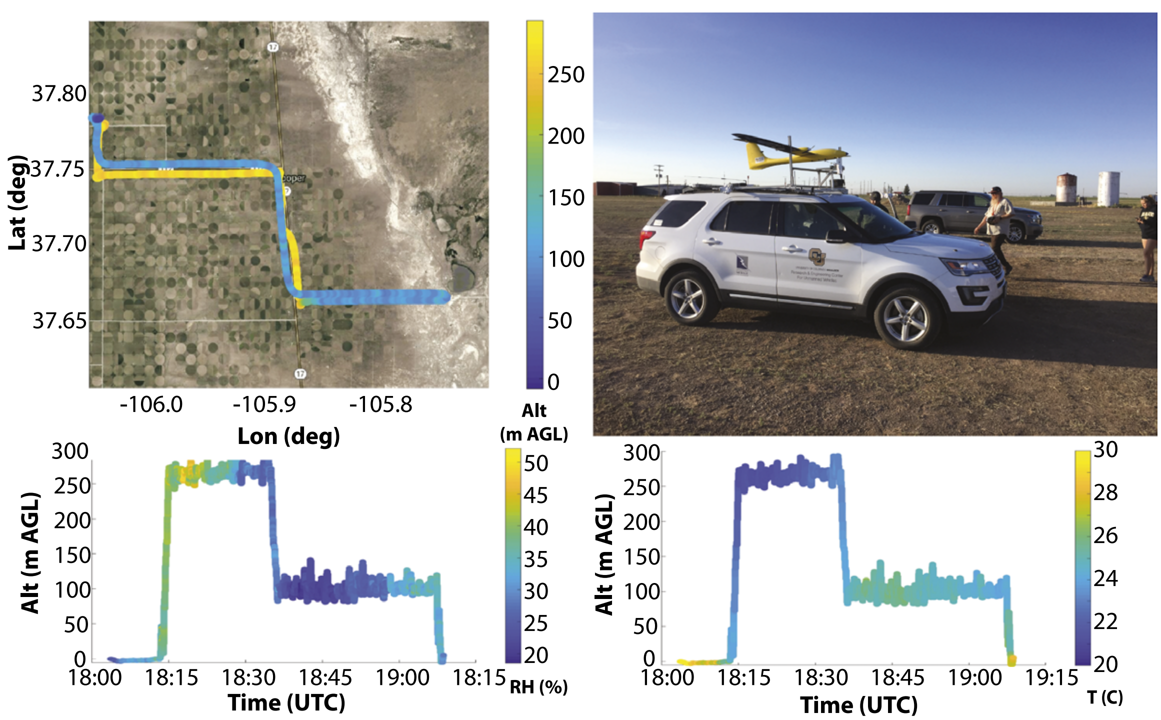


**Fig. 5. An example "follow me" flight from LAPSE-RATE. (top left) Track of the aircraft and ground vehicle, with color representing the aircraft altitude. (bottom) Time–height cross sections from this flight, with color representing measured (left) relative humidity and (right) temperature. (top right) University of Colorado team preparing for a "follow me" flight, with the aircraft on the roof-mounted launcher prior to takeoff.**

(University of Kentucky). The Oklahoma State University program worked to advance their swarm capabilities during LAPSE-RATE, having multiple platforms in the air simultaneously to measure identical quantities in close proximity, and the University of Oklahoma furthered their "extended mesonet" capabilities, with copter systems profiling autonomously (with pilot supervision) at regular intervals from a fixed location. Finally, the Virginia Tech team conducted multiplatform flights to attempt to triangulate wind vectors around Leach Airport (e.g., Nolan et al. 2018).

The campaign produced several nice examples of how these platforms are well equipped to observe interesting phenomena. For example, the Finnish Meteorological Institute's PRKL1 platform was equipped with a particle measurement module including two condensational particle counters (TSI Corp CPC, model 3007, ~0.01 to >1.0 $\mu$m). Each CPC was calibrated to a different cutoff diameter ($D_{50}$ = 7 and 14 nm, respectively) to allow observation of new particle formation (NPF) events. During LAPSE-RATE, two different NPF events were observed (16 and 18 July). Figure 6 (left) shows the measured total aerosol number concentration between 2,300 and 3,000 m MSL for the two size cutoffs, with early measurements showing comparable concentrations from the two sensors that slowly increased during the late morning, eventually featuring a significant concentration of particles between 7 and 14 nm associated with NPF from increased solar activity and sufficient gaseous precursors. On 18 July, the increased small particle concentration was clearly seen at altitude (>3,000 m MSL), indicating NPF associated with particles aloft, with these elevated concentrations of particles between 7 and 14 nm decreasing over the course of the day due to ongoing particle growth (Fig. 6, right). Additional aerosol measurements such as these, in conjunction with observations from the other platforms on thermodynamic state and ground-based radar systems could help to understand aerosol–cloud interactions in convective systems.

Another interesting phenomenon targeted during the campaign was the diurnal cold-air drainage from smaller valleys that feed into the SLV. Nighttime cooling results in density currents that flow down valley and then intersect in the larger valley. Once solar heating has initiated convection, updrafts form on the valley walls, resulting in a reversal of the flow to one that has an up-valley direction. To measure these processes, we distributed teams across the northernmost portions of the San Luis Valley, with a primary focus on the Saguache Valley. Figure 7 shows an example of measurements of this flow collected on 19 July 2018. These measurements were obtained by two separate aircraft operation flights within a few miles of one another—the University of Colorado TTwistor aircraft conducted circular flights with periodic altitude changes, while the University of Kentucky BLUECAT5 conducted racetrack flights across the valley, scanning a smaller range of altitudes (Fig. 7, left). An evaluation of

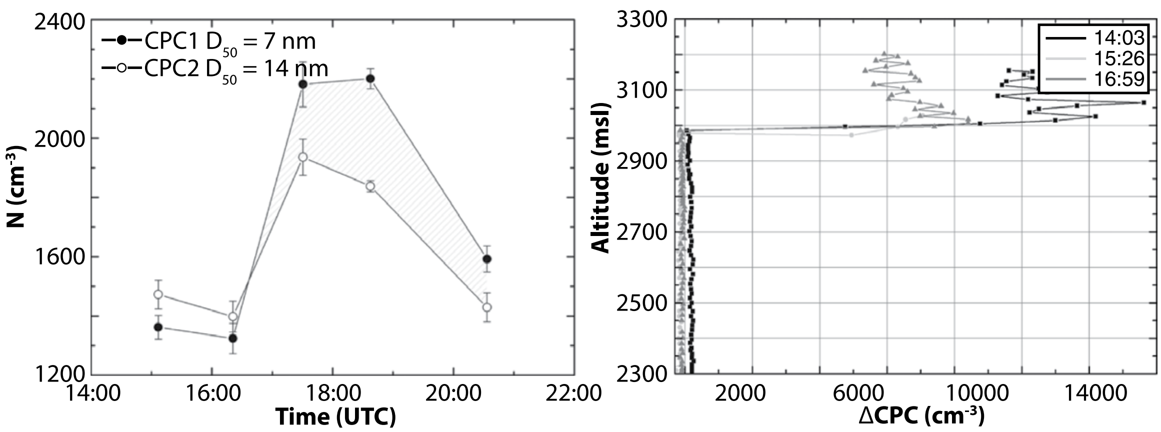


**Fig. 6. Measurements from the FMI CPCs indicating new particle formation events. (left) Temporal evolution of particle concentrations from CPCs with 7- and 14-nm size cutoffs. (right) Vertical variability of the difference between the concentrations measured by these CPCs as a function of time.**

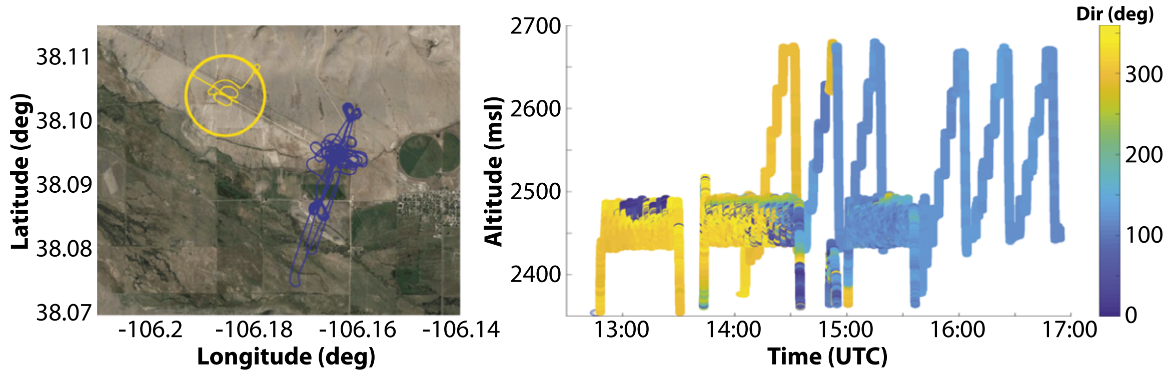


**Fig. 7. Measurements from flights conducted by the University of Colorado TTwistor and University of Kentucky BLUECAT5 aircraft on 19 July to evaluate cold-air drainage from the San Luis Valley. (left) Locations of the flights (yellow points are the University of Colorado aircraft; blue points are the University of Kentucky aircraft). (right) Time–height cross section of the measured wind directions from both aircraft (the stair-step patterns are the CU TTwistor).**

the wind shows that initially winds were from the west-northwest at all altitudes. However, around 0815–0830 local time (1415–1430 UTC), a rapid transition occurs, with a reversal of flow first detected by the BLUECAT5, and slightly later by the TTwistor. Some vertical structure exists, with the TTwistor finding a last remaining pocket of down-valley flow at the top of its pattern around 0850 local time (1450 UTC). After this time, all winds have transitioned to an up-valley regime (east-southeast). Combining routine profiling flights with extended transect flights offer a unique opportunity to provide detailed perspectives on the extent of finescale flows such as this one that are not easily achieved using other platforms.

Finally, in addition to measurement capabilities, the LAPSE-RATE campaign demonstrated a high-resolution numerical model for predicting finescale weather features in support of small UAS operations. NCAR's real-time version of the WRF Large Eddy Simulation (WRF-LES) model was configured to run in real time on the Cheyenne supercomputer at NCAR (CISL 2017). The WRF-LES forecast system (Muñoz-Esparza and Kosović 2018), features meso-to-microscale coupling with 100-m grid spacing on its inner-most domain to produce large-eddy permitting forecasts that respond to meso- and synoptic-scale flows (e.g., terrain-induced circulations in the San Luis Valley). This system was recently adapted to support small UAS operations. Adaptations include development of a new workflow to produce small-UAS centric output (e.g., turbulence intensity, low-level winds, ceiling, visibility, simulated reflectivity) and optimizing the system configuration for improved performance over the San Luis Valley. During LAPSE-RATE, the system was run twice daily to support next-day and day-of mission planning.

Data collected using the UAS deployed during LAPSE-RATE are currently being used to evaluate and improve the model and perform data assimilation experiments. A comparison between WRF-LES forecast of 10-m winds and observations made by the Automated Weather Observing System (AWOS) at Saguache Airport is shown in Fig. 8. The real-time WRF-LES was able to capture the abrupt flow reversal observed around 0830 local time (1430 UTC); however, the 10-m winds associated with the simulated drainage flow were too strong and the timing of the simulated reversal was approximately 30 min later than observed. These two forecast errors, while seemingly small, could be critical for small UAS flight planning. Current efforts are focused on understanding the source of these errors, with early indications pointing at least in part to the forcing data derived from the National Centers for Environmental Prediction (NCEP) High-Resolution Rapid Refresh (HRRR; Benjamin et al. 2016) model. The wide distribution of UAS observing locations and frequent flights offer a unique dataset for evaluating the performance of these modeling tools that could not be easily achieved using point measurements as discussed in Glasheen et al. (2020).

In addition to evaluating model performance, several experiments are being completed to understand the impacts of assimilating UAS-collected data into the outer domain of the NCAR forecast system. Preliminary results obtained using a Newtonian relaxation assimilation scheme are shown in Fig. 8. Here, assimilation of UAS data collected during flights performed in two upstream locations in Saguache canyon notably improves predictions of 10-m wind speed and direction at the Saguache Municipal Airport that were caused by the finescale density current associated with morning down-valley flow regimes. The bias in the modeled 10-m wind speed is reduced with its modeled evolution more closely matching the ebb and flow observed, with an overall reduction in RMSE of roughly 25%. While these initial results are encouraging, studies are underway to more fully assess the value of UAS data assimilation using more sophisticated DA approaches such as 3DVAR, ensemble Kalman filtering (EnKF), and hybrid techniques. The coordinated nature of the UAS flights and efforts to intercompare these measurements and understand uncertainties offer both a comprehensive dataset that can be used in a data assimilation mode as well as verification data that can be left out of the assimilation and used to evaluate its impact.

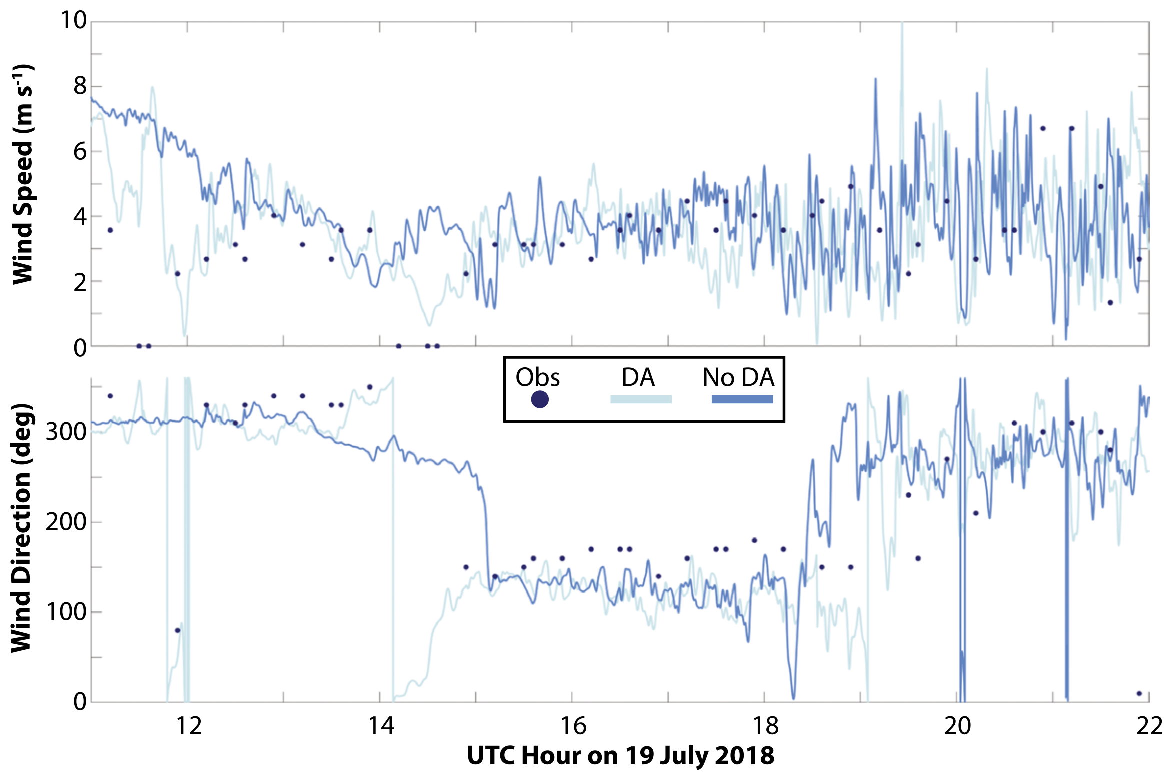


**Fig. 8. (top) Wind speed and (bottom) wind direction as simulated by WRF for the morning drainage flow at Saguache airport on 19 July 2018. Included are simulation results (lines) and observations from surface instrumentation at the Saguache airport (dots). Simulation results are shown for experiments with (DA) and without (No DA) assimilation of data from UAS operating nearby.**

## Looking ahead

All of the datasets collected are being processed and prepared for public consumption. To support a high level of documentation, campaign organizers have worked to develop a special issue in *Earth System Science Data*. This issue will include institutional articles documenting the measurements obtained during LAPSE-RATE, including detailed information on sensors, platforms, deployment locations, challenges and problems, measurement uncertainty, and dataset availability. Additionally, this special issue can offer documentation on the numerical simulations completed as well as the ancillary datasets collected (e.g., radiosondes, mobile mesonets, towers). Such an integrated issue was not only deemed to be important from the perspective of thoroughly documenting the collected datasets, but also sets a positive example for the UAS-centric atmospheric science community to encourage the future development of similar articles when new datasets are obtained.

In addition to the thousands of flight hours completed safely within the national airspace, perhaps among the greatest successes to be counted among those coming from the ISARRA community is the development of new collaborative relationships between participants. This community-building includes continuation and expansion of collaborations between institutes conducting flight operations to address specific scientific questions, extend capabilities, or foster engineering advancement of UAS. It also includes cooperation and discourse between industry and the research community to foster instrument and platform development and help to improve existing products. Finally, it includes collaboration between observational teams and modeling teams working to improve weather forecasts for the general public as well as weather forecasts specifically tailored to support current and future operation of UAS in the national airspace, as is being contemplated by a host of large companies who have significant delivery needs, search and rescue groups, and others.

The 2019 ISARRA conference was held in Lugo, Spain, between 16 and 19 July 2019, and an associated flight week took place between 22 and 24 July. The 2020 conference is scheduled to be held in October 2020 at the Andoya Rocket Range (Norway), but it is not yet clear whether a flight week will take place. While flight weeks are not a required component of the annual ISARRA conference, the LAPSE-RATE campaign provides a nice example and blueprint for successful future campaigns, and demonstrates the power of bringing teams with common goals together.

## Summary

The ISARRA conducted the 1-week, UAS-based field campaign LAPSE-RATE in the San Luis Valley of Colorado during the summer of 2018. During this campaign, an international group of participants conducted a series of flights to observe the lower atmosphere and better understand the capabilities of their aircraft. In total, over 100 participants completed nearly 1,300 flights. Planning, outreach activities, and coordinated sampling resulted in the development of numerous new collaborations, while data collected have been used to evaluate and improve aircraft and sensors, develop modeling capabilities, and understand atmospheric phenomena. Future iterations of ISARRA flight weeks will help to expand the atmospheric science community leveraging these platforms in their research, and further demonstrate the value that UAS-based measurements have for advancing our understanding of the atmosphere.

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## Appendix: List of abbreviations

| | |
|---|---|
| AERI | Atmospheric Emitted Radiance Interferometer |
| AERIoe | AERI Optimal Estimation retrieval |
| AGL | Above ground level |
| AWOS | Automated Weather Observing System |
| CISL | NCAR Computational and Information Systems Laboratory |
| CLAMPS | Collaborative Lower Atmospheric Profiling System |
| COST | European Cooperation in Science and Technology |
| CPC | Condensation particle counter |
| DA | Data assimilation |
| EnKF | Ensemble Kalman filter |
| HRRR | High Resolution Rapid Refresh model |
| ISARRA | International Society for Atmospheric Research Using Remotely-Piloted Aircraft |
| LAPSE-RATE | Lower Atmospheric Profiling Studies at Elevation–A Remotely-Piloted Aircraft Team Experiment |
| LES | Large-eddy simulation |
| MSL | Mean sea level |
| MURC | University of Colorado Mobile UAS Research Collaboratory |
| MWR | Microwave radiometer |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Centers for Environmental Prediction |
| NOAA | National Oceanic and Atmospheric Administration |
| NPF | New particle formation |
| PBL | Planetary boundary layer |
| PPI | Plan position indicator |
| RMSE | Root-mean-square error |
| SLV | San Luis Valley, Colorado |
| UAS | Unmanned aircraft system |
| UHF | Ultrahigh frequency |
| UTC | Coordinated Universal Time |
| VAD | Velocity–azimuth display |
| VHF | Very high frequency |
| WRF | Weather Research and Forecasting Model |

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