The interactions of updrafts and cold pools can play a pivotal role in determining convective storm characteristics. Convective updrafts are driven by latent heating, buoyancy, and vertical pressure gradients, and their velocities range from 5–10 m s\(^{-1}\) in tropical maritime convection to 50–70 m s\(^{-1}\) in midlatitude supercells.

Cold pools, on the other hand, are formed through latent cooling due to evaporation and/or melting and are a surface manifestation of storm downdrafts. They range in depth from 100–200 m to nearly 5 km, and in horizontal extent from a few kilometers...
to hundreds of kilometers. Their mean temperature deficits range from as little as 1 K to more than 11 K. New convective updrafts can be initiated by cold pools and cold pool collisions. Cold pools also impact the orientation of the updraft, the concentration of near-surface rotation, and convective organization, all of which feed back to updraft intensity and longevity through their location relative to the parent storm updraft. The strength of the cold pool is impacted by the microphysical processes and organization of the parent storm, which, in turn, are a function of the storm updraft, completing the feedback loop.

Accurately simulating convective storms requires adequate representation of updrafts and cold pools. This has been problematic due to, for example, insufficient grid resolution, which affects cold pool generation, propagation, frequency, and intensity, as well as insufficient observations with which to evaluate models. Past field campaigns have successfully used radars to measure deep convective updrafts, but additional observations using different observational platforms under a variety of environmental conditions are still necessary.

The Colorado State University Convective Cloud Outflows and Updrafts Experiment (CLOUD-Ex) builds on previous

Some of the storm types and storm features observed during CLOUD-Ex. (a) A counterclockwise rotating left-moving supercell (8 Jun 2017); (b) one of the towers of three vertically stacked drones (indicated by black arrows) located under a convective anvil (5 Jun 2017); (c) a strong outflow boundary under a precipitating anvil (25 May 2017); and (d) weak rotation on the ground in association with the supercell observed on 25 May 2017.
studies through the use of novel techniques. 

C³LOUD-Ex had three specific objectives:

1. to obtain high spatial (on the order of 100 m through 1 km) and temporal (seconds) resolution measurements of cold pool and gust front characteristics, at and above the surface, both parallel and perpendicular to the gust front;
2. to obtain observations of updraft velocities using multiple radar and radiosonde platforms; and
3. to evaluate and enhance the representation of updraft and cold pool processes through model–observation comparisons of high-resolution C³LOUD-Ex case-study simulations.

C³LOUD-Ex was conducted during 11–20 July 2016 and 1 May to 12 June 2017 over north-eastern Colorado, southeastern Wyoming, and south-western Nebraska, areas where deep convective storm systems are frequently observed during spring and early summer. Sixteen cold
pool and seven supercell updraft case studies were successfully obtained during CLOUD-Ex. Instrumented drones, portable radiosondes, WSR-88D and CSU-CHILL radar, portable surface stations, and a portable disdrometer comprised the instrumentation used in the field.

**Cold-pool measurement strategy**

After deciding which cold pool to sample, three CLOUD-Ex teams drove ahead of the advancing gust front and set up a Flying Curtain, a novel measurement strategy that allows for horizontal and vertical cold pool measurements to be made both parallel and perpendicular to the gust front. The Flying Curtain remains stationary relative to the ground, while the cold pool moves along with the gust front through the horizontally oriented Flying Curtain. Three surface observation points were set up in a line (roughly south to north in most cases) at the base of the curtain. An anchor point (ANCHR) was established at the south end of the line and the 2nd and 3rd points were located 100 m (100M) and 1 km (1KM) away from the ANCHR, respectively. At each of the three points a surface station and two vertically stacked drones, one at 20-m and the other at 120-m AGL, were deployed. Radiosondes were simultaneously launched at the ANCHR and the 1KM fixed locations (shallow deployment). Occasionally, a storm system of interest fell within the region, for which we received an FAA altitude waiver [allowing us to fly the drones up to 1,200 ft (~366 m)], and two vertical towers of three drones located at 20-m, 120-m, and 350-m AGL were located at the ANCHR and 100M points (deep deployment).

**Updraft measurement strategy**

In CLOUD-Ex, radiosondes were used to specifically target the vertical velocities and thermodynamic characteristics of convective updrafts. Targeting updrafts with radiosondes was challenging, and the radiosondes did not always ascend directly through the primary updraft, especially due to the high cloud bases encountered during the field campaign. Various other regions of the storms were therefore also
The C3LOUD-Ex Flying Curtain allows for horizontal and vertical cold pool measurements to be made both parallel and perpendicular to the gust front. The cold pool is indicated by the blue shading, and the location of the Flying Curtain with the red line. Time 1 represents the earliest time, while Time 3 is the latest time. It is important to note that the Flying Curtain remains stationary relative to the ground, and that the cold pool moves through it from left to right.

Forecasting approach

At long lead times, synoptic data were obtained from operationally available global models. Mesoscale models [in particular, High Resolution Rapid Refresh (HRRR) and NCAR Ensemble models] were used at 2- to 3-day lead times to identify the location of moisture, instability, lift, and shear, and to help assess the potential for convection to survive moving off higher terrain. Model output was supplemented by the GOES-16 5-min CONUS and 1-min mesoscale sectors preliminary, nonoperational data, including the three-channel water vapor and split-window difference products, and visible and IR imagery. Environmental soundings were launched en route to selected deployment locations to assess the validity of the HRRR initialization and other model guidance, as well as the strength of the capping inversion and amount of midtropospheric moisture, both often poorly resolved by the forecast models. Once convection initiated, forecasting shifted to nowcasting to help identify the most favorable locations for the cold pool and updraft measurement strategies using the C3LOUD-Ex radar network and satellite imagery.

C3LOUD-Ex updrafts

In situ observations of seven supercell updrafts were successfully obtained using radiosondes, where the updraft vertical velocities were calculated using a 12-s centered-in-time derivative of the radiosonde GPS position and time measurements. The maximum radiosonde updraft velocity directly measured throughout the field campaign was $36.2 \pm 2.6$ m s$^{-1}$, but when adjusted for instances where the balloon popped, the maximum updraft velocity measured was $49.9$ m s$^{-1}$. However, there was large variability in the updraft observations. The updraft measurements obtained during C3LOUD-Ex can be thought of as a lower bound on the updraft velocity estimates because of the uncertainties, such as balloon icing, that cannot be easily accounted for, and because the radiosondes frequently did not ascend through the strongest regions of the rotating updrafts.

C3LOUD-Ex cold pools

Overview of cold-pool characteristics

The 16 cold pools observed during C3LOUD-Ex had a wide range of temperature perturbations,
understand cold-pool processes, (2) assess the spatial and temporal variability of cold pool characteristics both perpendicular and parallel to the gust front, and (3) provide observational evidence to assess several hypotheses advanced in two recent cold pool modeling studies.

maximum temperature-perturbation magnitudes (relative to the pre–cold pool soundings) range from −8 K to close to 0 K, and cold pool depths range from 200 to 2,300 m, where cold pool depth is defined as the lowest altitude at which the temperature perturbation ≥ 0 K. A cold pool observed on 17 May 2017 demonstrated the strength of using the combined CLOUD-Ex datasets to: (1) better

understand cold-pool processes, (2) assess the spatial and temporal variability of cold pool characteristics both perpendicular and parallel to the gust front, and (3) provide observational evidence to assess several hypotheses advanced in two recent cold pool modeling studies.
The cold pool in this case was produced by a convective storm that developed along the Cheyenne Ridge, southeast of Cheyenne, WY. The cold pool propagated southward toward the CSU-CHILL radar, where it was observed near Pierce, CO, under clear-sky conditions. The Flying Curtain was set up parallel to the gust front of the advancing cold pool. All three shallow deployment positions (ANCHR, 100M, and 1KM) were oriented east–west, where ANCHR was farthest west. In total, data from four pairs of sounding launches, six drones, three surface stations, and the CSU-CHILL radar were obtained.

The gust propagated through the Flying Curtain between 2000 and 2030 UTC (2:00 and 2:30 PM LT). Wind velocities to the north of the gust front reached approximately 10 m s\(^{-1}\). RHI scans through the cold pool depicted a classic density current structure including a deeper head and shallower tail region and cold pool depths of 1–1.5 km throughout the sampling time period.

Four pairs of soundings were launched simultaneously from the ANCHR and 1KM points at ~20-min time intervals. The (PRE) soundings were launched at 1936 UTC, before the gust front passage. The CP1 soundings (2001 UTC) were released after a shift in the surface wind direction at the surface stations, while the CP2 soundings (2023 UTC) were launched after the wind speeds had increased and the gust front had passed the Flying Curtain. Finally, the CP3 soundings (2042 UTC) were released behind the gust front, well within the propagating cold pool.

Following a wind shift, a warming in the temperature profile was first observed with the passage of the gust front, consistent with observations in previous studies, and is thought to be due to the lifting of near-surface warm air upward and along the gust front. The warming was followed by a decrease in temperature as the body of the cold pool passed through the Flying Curtain. A significant time lag was found in the drop of the temperature at the surface compared with those at ~100 m above the surface. Based on prior simulations of other similar cold pools, we hypothesized that the time lag is likely due to enhanced surface sensible heat fluxes within the gust front and to surface frictional effects. Finally, analysis of the observations collected at the ANCHR, 100M, and 1KM points suggests that cold pool temperatures vary on spatial scales of 100 m and 1 km, while the surface wind speeds vary on the order of 1 km. The relative humidity appears to be relatively constant over scales of both 100 m and 1 km. However, this finding is for one cold pool only; other C\textsuperscript{3}LOUD-Ex cold pools are being examined to assess the robustness of this finding. If robust, this will have
significant implications for the vertical and horizontal model grid spacings necessary to resolve cold pool processes.

Conclusions

The analyses of the CLOUD-Ex observations reported here have several implications for enhancing the numerical modeling of deep convective storms:

1) The depth of CLOUD-Ex cold pools ranged from 200 to 2,300 m. It is therefore important to ensure that vertical grid resolutions are sufficiently high across this depth if we are to accurately represent the range in cold pool depths and processes within NWP and research models. Horizontal grid resolutions also need to be carefully considered if the spatial variations in cold pool properties both parallel and perpendicular to the gust front (observations of which are greatly facilitated by the Flying Curtain strategy) are to be properly simulated. The preliminary analysis conducted here suggests that temperature variability on scales of ~100 m is the most restrictive of the requirements, although additional assessments are needed to determine the robustness of this result.

2) The cold pool results shown here clearly demonstrate the strength of using high spatial and temporal resolution datasets, together with high-resolution modeling studies, to better understand those processes active in the vertical, and along and perpendicular to the gust front. In this way we can better predict the impacts of cold pools on deep convective storms, and hence their intensity, initiation, propagation, and longevity.

3) Several past studies have shown that updraft velocities of simulated deep convective storms may be significantly greater than corresponding dual-Doppler estimates. In CLOUD-Ex, radiosonde estimates were at times higher than corresponding dual-Doppler estimates, highlighting the great strength in using updraft velocity estimates obtained from both radiosondes and radars when evaluating simulated updraft velocities.
BAMS: What would you like readers to learn from this article?

Sue van den Heever (Colorado State University): I would like readers to understand their properties and to ultimately quantify storm processes. BAMS: What surprised you the most about the work you document in this article?

SvdH: I was also amazed that the UAVs within the Flying Curtain can withstand cold pool outflow winds of about 50 mph before being advected downwind.

Sean Freeman (Colorado State University): I want readers to know our novel Flying Curtain drone deployment strategy observed that cold pools vary on spatial scales of 100 m to 1 km. This result implies that numerical models hoping to capture cold pool processes must be operated at a grid spacing capable of resolving those features.

BAMS: How did you become interested in the topic of this article?

SvdH: Prior modeling studies, including our own, have suggested that simulated cold pools are highly heterogeneous and that updraft velocities are often overpredicted. Our goal was to obtain extensive observations of storm updrafts and cold pools to better evaluate high-resolution simulations of deep convective storms.

SF: So much is still unknown about convective storms, but cold pools and updrafts especially require many more observations to fully understand their properties and to ultimately quantify storm processes.

BAMS: What was the biggest challenge you encountered while doing this work?

SvdH: The biggest challenge to me was to work out the best way to use the UAVs in the field to make scientifically meaningful measurements of cold pool heterogeneity. Developing the Flying Curtain, in which a wall of spatially and temporally coherent multi-instrument observations of cold pools were made, provided an unprecedented dataset of cold pool heterogeneity.

Leah Grant (Colorado State University): It was surprising how difficult it actually was to successfully launch radiosondes into the core of updrafts during CLOUD-Ex. It was easiest with supercell storms because they have strong inflow and large updrafts, but we still had a lot of misses and launches that entered the updraft periphery well above cloud base. Some of the most successful launches that entered the updraft cores were launched within the cold pools. The launches we attempted into nonsupercell storms were nearly all misses. Looking back, the deep boundary layer and high cloud bases characteristic of the High Plains in eastern Colorado and southeastern Wyoming certainly contributed to this challenge.

BAMS: How will you follow up?

LG: The Flying Curtain strategy has paved the way for exciting new research with multirotor drones. We have an upcoming field campaign planned in 2022 and 2023 called BACS (Bioaerosols And Convective Storms) in the eastern plains of Colorado. The goal of this NSF-sponsored research is to understand the exchange of biological aerosols like pollen, fungi, and bacteria between the surface and atmosphere; how cold pools influence this exchange and loft bioaerosols above the near-surface layer; and cold pool impacts on the ingestion of bioaerosols by convective storms, where the bioaerosols can then impact the formation of cloud and ice particles. Multirotor drones and radiosonde launches will be used to obtain vertical profiles of thermodynamic, wind, and aerosol information in pre- and post-cold pool conditions. We are excited to learn what new findings about cold pool transport of bioaerosols we will discover in this campaign.
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