BAMS Article

A Storm Safari in Subtropical South America

Proyecto RELAMPAGO

SPECIAL RELAMPAGO-CACTI COLLECTION

Stephen W. Nesbitt, Paola V. Salio, Eldo Ávila, Phillip Bitzer, Lawrence Carey, V. Chandrasekar, Wiebke Deierling, Francina Dominguez, Maria Eugenia Dillon, C. Marcelo Garcia, David Gochis, Steven Goodman, Deanna A. Hence, Karen A. Kosiba, Matthew R. Kumjian, Timothy Lang, Lorena Medina Luna, James Marquis, Robert Marshall, Lynn A. McMurdie, Ernani de Lima Nascimento, Kristen L. Rasmussen, Rita Roberts, Angela K. Rowe, Juan José Ruiz, Eliah F.M.T. São Sabbas, A. Celeste Saulo, Russ S. Schumacher, Yanina Garcia Skabar, Luiz Augusto Toledo Machado, Robert J. Trapp, Adam C. Varble, James Wilson, Joshua Wurman, Edward J. Zipser, Ivan Arias, Hernán Bechis, and Maxwell A. Grover

ABSTRACT: This article provides an overview of the experimental design, execution, education and public outreach, data collection, and initial scientific results from the Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations (RELAMPAGO) field campaign. RELAMPAGO was a major field campaign conducted in the Córdoba and Mendoza provinces in Argentina and western Rio Grande do Sul State in Brazil in 2018–19 that involved more than 200 scientists and students from the United States, Argentina, and Brazil. This campaign was motivated by the physical processes and societal impacts of deep convection that frequently initiates in this region, often along the complex terrain of the Sierras de Córdoba and Andes, and often grows rapidly upscale into dangerous storms that impact society. Observed storms during the experiment produced copious hail, intense flash flooding, extreme lightning flash rates, and other unusual lightning phenomena, but few tornadoes. The five distinct scientific foci of RELAMPAGO—convection initiation, severe weather, upscale growth, hydrometeorology, and lightning and electrification—are described, as are the deployment strategies to observe physical processes relevant to these foci. The campaign's international cooperation, forecasting efforts, and mission planning strategies enabled a successful data collection effort. In addition, the legacy of RELAMPAGO in South America, including extensive multinational education, public outreach, and social media data gathering associated with the campaign, is summarized.

KEYWORDS: Deep convection; Education; Hydrometeorology; Lightning; Severe storms; South America;

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Corresponding author: Stephen W. Nesbitt, snesbitt@illinois.edu
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AFFILIATIONS: Nesbitt, Dominguez, Hence, Trapp, and Grover—Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois; **Salio, Ruiz, and Bechis**—Centro de Investigaciones del Mar y la Atmósfera, CONICET-UBA, and Departamento de Ciencias de la Atmósfera y los Océanos, Universidad de Buenos Aires, UMI-IFAECI, CNRS-CONICET-UBA, Buenos Aires, Argentina; **Ávila**—Facultad de Matemática, Astronomía, Física y Computación, Universidad Nacional de Córdoba, and Instituto de Física Enrique Gaviola, CONICET, Córdoba, Argentina; **Bitzer and Carey**—Department of Atmospheric and Earth Science, The University of Alabama in Huntsville, Huntsville, Alabama; **Chandrasekar, Rasmussen, Schumacher, and Arias**—Colorado State University, Fort Collins, Colorado; **Deierling**—Smead Aerospace Engineering Sciences, University of Colorado Boulder, and National Center for Atmospheric Research, Boulder, Colorado; **Dillon, Saulo, and Garcia Skabar**—Servicio Meteorológico Nacional, and Comité Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina; **Garcia**—Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba, Córdoba, Argentina; **Gochis, Medina Luna, Roberts, and Wilson**—National Center for Atmospheric Research, Boulder, Colorado; **Goodman**—Thunderbolt Global Analytics, Huntsville, Alabama; **Kosiba and Wurman**—Center for Severe Weather Research, Boulder, Colorado; **Kumjian**—Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, Pennsylvania; **Lang**—NASA Marshall Space Flight Center Huntsville, Alabama; **Marquis and Varble**—Atmospheric Sciences and Global Change Division Pacific Northwest National Laboratory, Richland, Washington; **Marshall**—Smead Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, Colorado; McMurdie—Department of Atmospheric Sciences, University of Washington, Seattle, Washington; **Nascimento**—Universidade Federal de Santa Maria, Santa Maria, Brazil; **Rowe**—Department of Atmospheric and Oceanic Sciences, University of Wisconsin–Madison, Madison, Wisconsin; **São Sabbas and Toledo Machado**—Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil; **Zipser**—University of Utah, Salt Lake City, Utah

The United States is infamous for its hazardous convective storms that produce high-impact weather (HIW), including tornadoes, hail, strong winds, lightning, heavy precipitation, and flooding, and cause significant loss of life and property. The hazardous storms are also important components of the regional climate over much of the eastern two-thirds of the United States. Past field campaigns, observational studies, and model experiments have produced knowledge that is the foundation of current forecast capabilities of hazardous-weather-producing storms in the United States. Much of this knowledge was gained from storms studied over the U.S. Great Plains region (e.g., Rasmussen et al. 1994; Davis et al. 2004; Wurman et al. 2012; Geerts et al. 2017).

Studies of Great Plains severe thunderstorms link their occurrence and hazards to abundant lower-tropospheric moisture, steep midtropospheric lapse rates, and strong tropospheric vertical wind shear (e.g., Doswell et al. 1996). The specific presence of tornadoes is additionally linked to strong lower-tropospheric vertical wind shear (e.g., Thompson et al. 2012). In contrast to the United States, where these ingredients and resultant storms have been extensively studied, in other regions of the world, severe weather and its ingredients may or may not follow the “template” of storms in the United States. While severe convective storms in Europe have garnered recent study (e.g., Groenemeijer et al. 2017), the recognition of other intense, organized convective hotspots enabled by spaceborne radar—including southeast South America (SESA), central Africa, and the Indian subcontinent (Nesbitt et al. 2006; Zipser et al. 2006; Houze et al. 2015)—have not been accompanied by extensive in situ and surface-based remote sensing studies of convective storm evolution and life cycle similar to those conducted in the United States and Europe.

Severe weather is reported in many satellite-identified global convective hotspots (Bang and Cecil 2019), However, differently configured meteorological services and inconsistent severe weather databases outside the United States make the use of event reports challenging in comparing among various regions of the world. Even in the United States, forecasting and nowcasting severe convection remains challenging (e.g., Herman et al. 2018; Brooks and Correia 2018), and there is significant uncertainty in predicting how the frequency and nature of convective storms may change in the future (National Academy of Sciences, Engineering, and Medicine 2016). With a goal of improving the understanding of global severe convective storms, we are motivated by the following questions: To what extent do the meteorological and geographical ingredients for severe convective storms in intense convective hotspots, often patterned after storms in North America, translate across the globe? Are the hazards associated with archetypical storms and their environments (i.e., supercells, mesoscale convective systems, multicell storms), and conceptual models of storm life cycle and life cycle transitions and their associated hazard probabilities, generated from U.S. storms consistent across global regions? How do proxies for severe storm frequency from satellites and large-scale models compare with detailed observations in severe storms, particularly in regions where the physical processes producing severe weather may differ?

The answers to these questions ultimately impact our ability to monitor and predict severe convective hazards globally on both weather and climate time scales, as well as using statistical techniques that relate storm environments to hazards (e.g., Trapp et al. 2007). We postulate that the answers to these questions through intensive field observations and modeling efforts of the global convective hotspots can help to provide the answers to these and other questions that currently limit predictability of severe storms both globally and over the United States by revealing new insights into the physical processes in convective storms, as well as anticipate changes in global convective hazard frequency and intensity under potential future climate change scenarios.

SESA has unique meteorological conditions and geography compared with the U.S. Great Plains that results in a high spatial density of convective storms in a variety of storm modes that form in the lee of unique continental-scale and mesoscale topography (Rasmussen and Houze 2016; Mulholland et al. 2018). SESA also has a relatively long convective season (austral spring through autumn; Zipser et al. 2006; Rasmussen and Houze 2011) and terrain-focused convective initiation regions (Cancelada et al. 2020), making it an ideal natural laboratory to study the initiation and evolution of deep convection, the role of complex terrain in modulating convective processes, and attendant HIW using fixed and mobile observatories. Motivated by the scientific questions identified above, along with further scientific rationale described below, the Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations (RELAMPAGO) field campaign was conducted to study the HIW producing storms in this region.

An intense convection hotspot. RELAMPAGO observed the unique environmental and storm processes in central Argentina, where the convective systems, according to satellite-based analysis, contain superlative convective structures by many measures. Satellite-based tracking of mesoscale convective systems (MCSs) formed near the Andes, and the Sierras de Córdoba (SDC), a prominent mesoscale mountain range located roughly 700 km to the east of the Andes, have revealed their extreme size and propagation to regions as far away as Bolivia and coastal Brazil (Velasco and Fritsch 1987; Durkee et al. 2009; Vidal 2014). In SESA, MCSs contribute 90% or more of the annual rainfall and contain extremely deep and wide convective cores (Nesbitt et al. 2006; Houze et al. 2015; Rasmussen et al. 2016), which make this region prone to extreme rainfall and flash and riverine flooding (Hamada et al. 2015). The most vertically extensive radar echo observed by satellite precipitation radar (Zipser et al. 2006) occurred in central Argentina, and the region features the highest frequency of low microwave brightness temperatures as a proxy for hail frequency (Cecil and Blankenship 2012; Bang and Cecil 2019) as well as the highest lightning flash counts per storm (Cecil et al. 2005; Zipser et al. 2006).

The NOAA *GOES-16* Geostationary Lightning Mapper observed the most extensive (>700 km, 31 October 2018) and longest-duration (16.73 s, 4 March 2019) World Meteorological Organization–record lightning flashes in Argentina (Petersen et al. 2020). Satellite and ground-based radar observations indicate that the storm modes in the region near the SDC can produce supercells quickly after orogenic convection initiation (CI), which can grow upscale into MCSs much more rapidly than in the U.S. Great Plains (Mulholland et al. 2018). In contrast to the United States, a large number of SESA convective systems appear to backbuild (e.g., Schumacher 2015; Peters and Schumacher 2015) with respect to the mid- and upper-level flow, with new updrafts developing on the upstream (west) side of the storm (Anabor et al. 2008, 2009; Rasmussen et al. 2014).

The region near the SDC commonly experiences severe hail (Mezher et al. 2012; Matsudo and Salio 2011; Rasmussen et al. 2014), with hailstones even reaching gargantuan sizes (Kumjian et al. 2020). Farther west, near the Andes, is the Mendoza region, which is infamous for its frequency of damaging hailstorms; 8% of days between 15 October and 31 March between 2000 and 2003 observed hail > 2 cm (Rosenfeld et al. 2006). Tornadoes are also observed in central Argentina, but the regions of observed maximum tornado frequency are located well east of the SDC, and tornadoes are rarely observed near the SDC or Andes (Altinger de Schwarzkopf and Rosso 1982; Brooks and Doswell 2001; Rasmussen et al. 2014) despite the presence of supercell thunderstorms (Mulholland et al. 2018; Trapp et al. 2020).

Synoptic-scale ingredients. Midlatitude synoptic disturbances in the Southern Hemisphere subtropical jet, and attendant jet streaks, are greatly deformed when they encounter the massive Andes Mountains. The subtropical jet, located near 30°S latitude throughout much of the year, provides for strong deep-layer vertical wind shear and cold-air advection aloft, resulting in steep midlevel lapse rates (Ribeiro and Bosart 2018). Jet streak–Andes interactions can modulate the low-level flow downstream over Argentina (Shapiro 1981; Rasmussen and Houze 2016).

The South American low-level jet (SALLJ) facilitates tropical–extratropical exchange in South America, transporting moisture from the Amazon to the La Plata basin and increasing potential instability (Vera et al. 2006). Between 60% and 70% of precipitation over SESA comes from moisture of terrestrial origin that is predominantly transported by the SALLJ (van der Ent et al. 2010; Martinez and Dominguez 2014), with moisture transport peaking in austral spring months. The poleward penetration of the SALLJ into SESA (Nicolini et al. 2002) is strongly associated with baroclinic disturbances entering the region from the west (Salio et al. 2002; Marengo et al. 2004; Nicolini and Saulo 2006; Salio et al. 2007; Rasmussen and Houze 2016). This poleward penetration often coincides with the deepening of a lee trough called the northern Argentinean low (NAL; Seluchi et al. 2003; Saulo et al. 2004, 2007). The NAL enhances the local pressure gradient force, leading to poleward SALLJ penetration near the Andes, with a wind speed maxima (up to 25 m s^{-1}) at 1–1.5-km altitudes as far south as 35°S (Nicolini and Saulo 2006), typically maximizing at night (Nicolini and García Skabar 2011).

The enhancement of the SALLJ and NAL with an upper-level disturbance often increases potential instability, deep (0–8-km) vertical wind shear, and low-level wind veering, providing an environment favorable for organized convection (Salio et al. 2007; Borque et al. 2010; Rasmussen and Houze 2016; Mulholland et al. 2018). Terrain, cold fronts, stationary fronts, and outflow boundaries from preexisting convective systems that impinge on the SALLJ can serve as a mechanism for CI. However, the mechanisms of CI and initial survival, and the upscale growth of convective systems as they move away from their initiation location, often observed near terrain, are not well characterized in SESA or globally (Banta and Schaaf 1987; Wilson and Mueller 1993; Coniglio et al. 2006).

RELAMPAGO research themes. Within the framework of the above science questions and the unique geoclimatic setting of SESA, RELAMPAGO, together with its sister project, the Department of Energy–funded Clouds, Aerosols, Complex Terrain Interactions (CACTI) campaign [see accompanying article by Varble et al. (2021)], took an integrated and expansive observational approach to document processes relevant to on the following research themes:

- *Convective initiation*: Determine relevant environmental processes that lead to the initiation of deep convection over and near complex terrain and contrast the mechanisms near the SDC and Andes.
- *Severe convective storms*: Observe processes by which hail, strong winds, and tornadoes are generated in environments close to the Andes and SDC, two regions that offer key meteorological and physical–geographical contrasts to severe storm environments in the United States.
- *Upscale growth of convection*: Identify kinematic, thermodynamic, microphysical processes by which deep convection intensifies and grows upscale in the immediate vicinity of complex terrain features, including those that produce extremely tall and/or broad convective systems, and contrast these mechanisms near and apart from topography.
- *Lightning*: Observe lightning, transient luminous events (TLEs), and high energy emissions from thunderstorms (HEETs); determine their characteristics across the spectrum of convective systems in/near the SDC and Andes; and relate those characteristics to processes in deep convective systems.
- *Hydrometeorology*: Characterize the relationship between land surface fluxes, atmospheric processes, and surface/subsurface hydrologic response in the Carcarañá basin (a subbasin of the La Plata basin that includes the SDC eastern slopes), with a focus on extremes.

RELAMPAGO observations

RELAMPAGO (summarized in Table 1) deployed a combination of fixed and mobile assets that leveraged the operational observing networks and focused on locations where convective processes of interest were likely found based on climatological studies. Extending the analysis of Zipser et al. (2006), TRMM observed precipitation radar (PR) echo tops in the 99.9999th percentile are shown in Fig. 1a, indicating the high observed frequency of extremely tall convective cores in the study region. Our operations regions (Fig. 1b) focused on the regions near and to the east of the SDC mountain crest in Córdoba Province (referred to as the Córdoba domain) and the Andes west of San Rafael, Mendoza Province (referred to as the Mendoza domain). An operations center established by the National Center for Atmospheric Research Earth Observing Laboratory (NCAR EOL) in Villa Carlos Paz, in the Córdoba domain, provided a location that enabled the preparation of weather forecasts and coordinated deployment of mobile teams (see related sidebars to

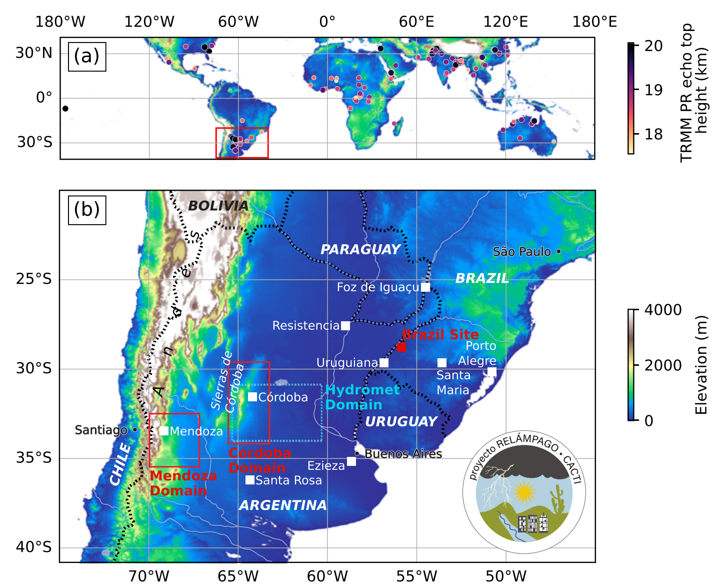

Fig. 1. (a) TRMM Precipitation Radar (PR) December 1998–September 2013 observed echo-top heights in the 99.9999th percentile (following Zipser et al. 2006). (b) A zoomed-in view of the region in the red box in (a) showing RELAMPAGO mobile observation domains (red boxes; see Fig. 6), the Brazil site (red square), operational sounding sites (white squares), and hydrometeorology observation domain (cyan dashed box; see Fig. 4). Terrain elevation (m MSL) is shaded in each figure.

learn more about these key elements of RELAMPAGO) to the SDC foothills or nearby plains, or to the Mendoza domain. The CACTI primary site was located in the Sierras de Córdoba near Villa Yacanto, which, along with terrain-focused CACTI aircraft operations, anchored several RELAMPAGO deployments. A fixed site operated by Brazil was located near Sao Borja, Rio Grande do Sul, Brazil, and observed convective systems 800 km to the northeast near the Parana River.

RELAMPAGO consisted of three stages of deployment (Fig. 2). During an extended observing period (EOP), which extended from 5 June 2018 to 30 April 2019, a network

Table 1. RELAMPAGO in a nutshell. Shaded are aspects related to RELAMPAGO's design (green), data collection (blue), and broader impacts (purple).

6 years planning the field campaign; 3 site surveys before the campaign; more than 10,000 km toured to determine possible deployment sites.
234 scientists, technicians, and students at the Operational Center from 6 countries (the United States, Argentina, Brazil, Australia, Spain, and the United Kingdom)
94 graduate and undergraduate students from the United States (51), Argentina (34), Brazil (5), Australia (2), Spain (1), and the United Kingdom (1) participated in the field campaign
16 universities and research centers collaborating for RELAMPAGO organization and deployment from 3 countries (United States, Argentina, and Brazil)
2 forecast dry runs before the campaign; 89 forecast briefings during the campaign; 3 mesoscale forecast models and one 60-member model ensemble ran over the RELAMPAGO domain
5 research themes: convective initiation, severe convective weather, upscale growth of convection, lightning, and hydrometeorology
47 IOP days directed from the operations center at Villa Carlos Paz
19 missions: 3 DOWs, 1 COW, 3 mesonets, 12 Pods, 3 disdrometers, 6 sounding operating units driven more than 30,000 km; 3 operational and 1 fixed sounding station with additional observations per request from the RELAMPAGO team
1,192 fixed and mobile soundings
3 ground-based C-band radars operating over the RELAMPAGO Córdoba sector
1,010 h of *GOES-16* Mesoscale Domain Sector observations during EOP and IOP
>49 million raindrops measured by RELAMPAGO disdrometers
2,285 impacts on RELAMPAGO deployed hailpads
2 storms reaching more than 18 km in altitude; more than 45,000 GOES overshooting tops during EOP
2.9 million lightning flashes observed with a lightning mapping array over 163 days
3 river basins observed and runoff-rating curves determined
21 TB of mobile radar data collected
1 open house at Córdoba, 2 open houses in collaboration with CACTI, 15 visits at schools and community centers; more than 5,000 people were interacted with; innumerable people stopped at instrumentation on the roads during RELAMPAGO deployments
5,500 followers at the @RELAMPAGO2018 Twitter account; 690 severe weather reports received using the @RelampagoEdu Twitter account; 3 citizen crowdsourcing projects, dissemination of ~10,000 hail rulers
19 institutions and local government agencies hosting instruments, 25 families hosting instruments at their own homes or farms

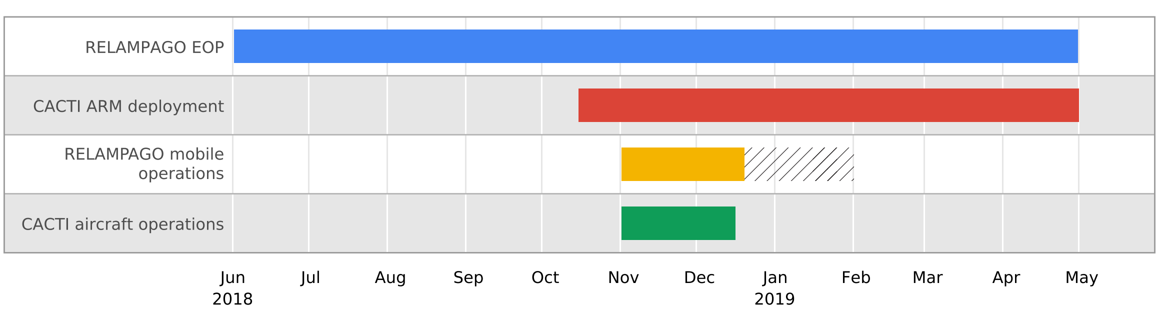

Fig. 2. Timeline of RELAMPAGO–CACTI deployments.

of 30 hydrometeorological stations was operated across the Rio Carcaraná basin (see the "Hydrometeorological observations" section for more details). The period of mobile operations in RELAMPAGO was from 1 November to 17 December 2018, during which targeted observations were directed from the RELAMPAGO operations center at Villa Carlos Paz. The Colorado State University (CSU) C-band dual-polarization radar and enhanced soundings at Córdoba operated until 31 January 2019 and captured observations of several additional storm events.

The observational assets in RELAMPAGO were complemented by operational sounding sites at Córdoba, Mendoza, Santa Rosa, Resistencia, Ezeiza, Uruguaiana, Santa Maria, Porto Alegre, and Foz do Iguaçu, which launched at least twice-daily soundings at 0000 and 1200 UTC throughout the campaign. Operational radars in the region included the C-band INVAP S.E. RMA-320 dual-polarization Doppler radar operating at Córdoba (RMA1), and two S-band non-Doppler radars operated by Mendoza Province. Mesonet data and rain gauge data cataloged during RELAMPAGO included sites contributed by agricultural, livestock, and water agencies as well as the private sector in Argentina, southern Brazil, and Uruguay.

During the RELAMPAGO operations, fixed and mobile platforms were used to collect observations of the thermodynamic and kinematic environment, storm structures, lightning, precipitation, and land surface states and fluxes. Some of these observations were continuous, while others targeted phenomena during the campaign based on RELAMPAGO forecast operations (see "RELAMPAGO forecast operations" sidebar). Many of these instruments are depicted in Fig. 3.

Hydrometeorological observations. The hydrometeorological EOP began on 1 June 2018, five months before the intensive observing period (IOP), and ended on 30 April 2019. The EOP consisted of a network of fifteen 10-m towers from NCAR's Earth Observing Laboratory (EOL) (yellow markers in Fig. 4), which included seven eddy covariance (EC) towers. In addition, we installed fifteen 2-m towers from NCAR's Research Application Laboratory (RAL) (magenta markers in Fig. 4). These towers, installed throughout a broad region encompassing the SDC and adjacent eastern plains, collected basic hydrometeorological measurements (temperature, humidity, precipitation, soil moisture, etc.), and drop size distributions (in addition to a NASA-deployed disdrometer site in Córdoba), whereas the EC towers

RELAMPAGO forecast operations

Forecasting the initiation, location, convective mode, timing, and propagation of deep convection was critical to the success of RELAMPAGO. A team of forecasters from SMN and graduate students from U.S. and Argentine universities were assembled to support science team decisions regarding mobile asset deployment. Forecast briefings were given twice a day at 1200 and 2100 UTC at the operations center, with an additional 1830 UTC briefing providing guidance specifically tailored for G-1 operations. On any given day, there were three forecasters on duty, including two SMN personnel providing local knowledge and expertise. An individual forecaster was available during each mission to monitor current weather and provide nowcasting guidance. Numerical model guidance was critical to assess location and intensity of potential deep convection. To this end, University of Illinois (UI), CSU, Universidad de Buenos Aires (UBA), and SMN provided convection-permitting regional and global variable resolution runs over the RELAMPAGO region to supplement global numerical guidance. SMN and Centro de Investigaciones del Mar y la Atmósfera (UBA) implemented a mesoscale ensemble-based data assimilation and forecast system on NCAR's Cheyenne supercomputer, which fostered the operational implementation of this system at SMN.

Since briefings used for operational decision-making, the forecasters had to work rapidly and depend on each other to evaluate and effectively communicate the current weather situation to the team. Forecasting successful CI was particularly difficult as the convection-permitting models often produced false alarms. In addition, predictability of severe and upscale-growth events more than 36 h in advance was sometimes poor, which affected some deployments, and even a missed upscale-growth event in Córdoba while the mobile teams were in Mendoza (IOP9b). Fortunately, the experimental design and cooperation with CACTI allowed for observations in the two regions simultaneously. The forecasting team was truly a cultural exchange experience. The stressful work allowed people of diverse backgrounds to work closely together for several days, creating a truly integrated team. Group photos of the forecast teams are shown in Fig. ES1 in the online supplemental material.

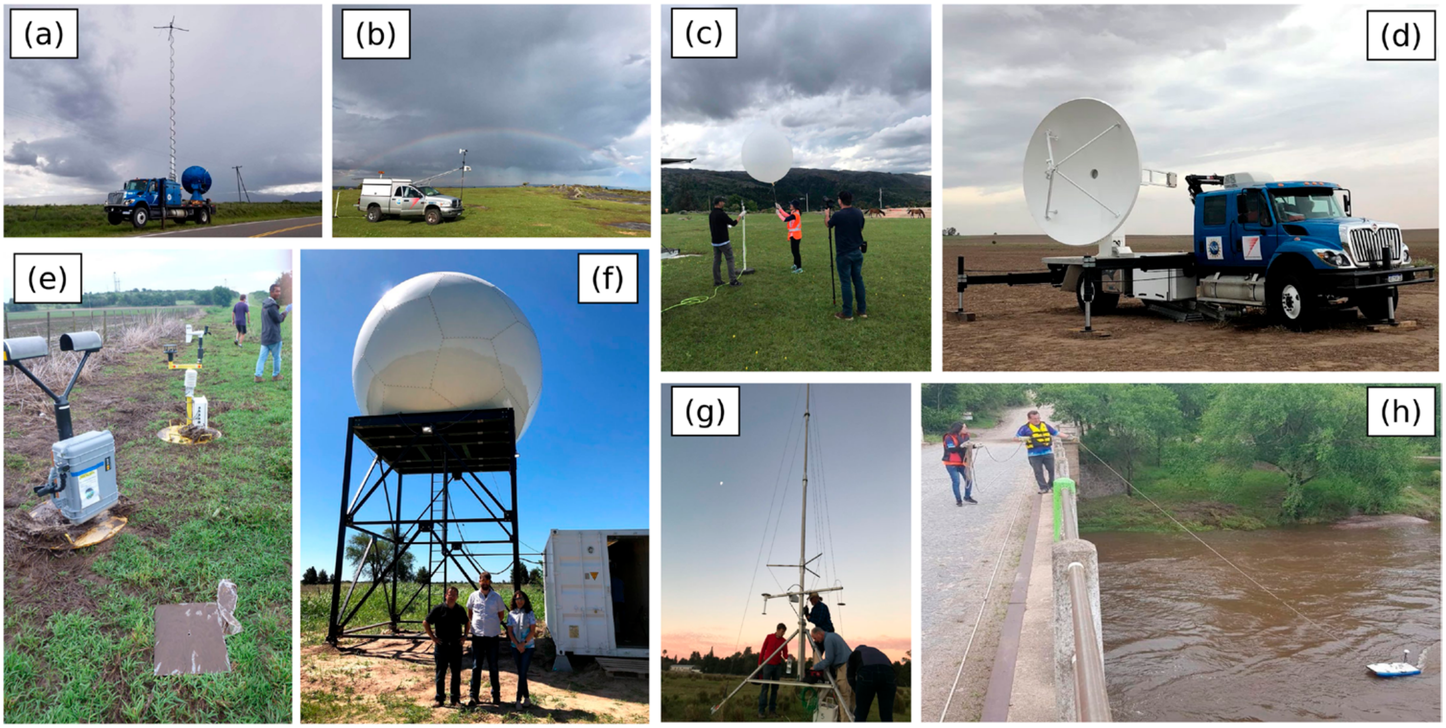

Fig. 3. Photos of selected RELAMPAGO instrumentation: (a) CSWR DOW7 near the SDC, (b) CSWR Scout 2 mesonet vehicle, (c) mobile radiosonde team, (d) COW, (e) Pod and disdrometer, (f) CSU C-band radar, (g) NCAR EOL Integrated Surface Flux System (ISFS) tower installation, and (h) acoustic Doppler current profiler.

measured turbulent energy, moisture, and momentum fluxes. The EOP was conducted to understand how land surface heterogeneity impacts the initiation and growth of convection on hydrologically relevant time scales, and how precipitation is partitioned into subsurface infiltration, runoff, and evapotranspiration.

During the RELAMPAGO operations, the Hydrometeorology ("Hydromet") team performed streamflow observations along the headwater rivers of the SDC (Fig. 4). Two months prior to the start of mobile operations, eight stream-level sensors were deployed (cyan stars in Fig. 4) and gathered cross-section information. Performing streamflow observations associated with convective events is difficult because of the uncertainty in forecasting the intensity and location of the events, as well as the fast hydrological response of the basins.

Teams were deployed to measure streamflow with acoustic Doppler current profilers and with digital cameras to perform large-scale particle image velocimetry (LSPIV) measurements along the selected river cross sections. LSPIV, a nonintrusive flow velocimetry technique, quantified streamflow during flash flood events. During RELAMPAGO, the team performed a total of 10 observational campaigns, including several extreme hydrometeorological events on 5, 11–12, and 27 November 2018. Due to the abundance of events, we were able to construct the stage-discharge curves for the upper basin for the Santa Rosa, Quillinzo, and La Cruz sites.

Soundings and mobile in situ observations. Balloon-borne soundings from fixed and mobile platforms provided an unprecedented view of the environments supporting the initiation, organization, and maintenance of convection in RELAMPAGO. When including data from operational sounding sites and the DOE-ARM site, 2,712 soundings were collected during the RELAMPAGO–CACTI EOP. Of these, 1,557 were collected during the RELAMPAGO campaign (28 October to 18 December 2018), and 574 of these were launched from vehicles that were highly mobile, positioned in targeted locations for each IOP, sometimes redeployed within an IOP. The Servicio Meteorológico Nacional (SMN) provided 532 soundings at Villa Maria

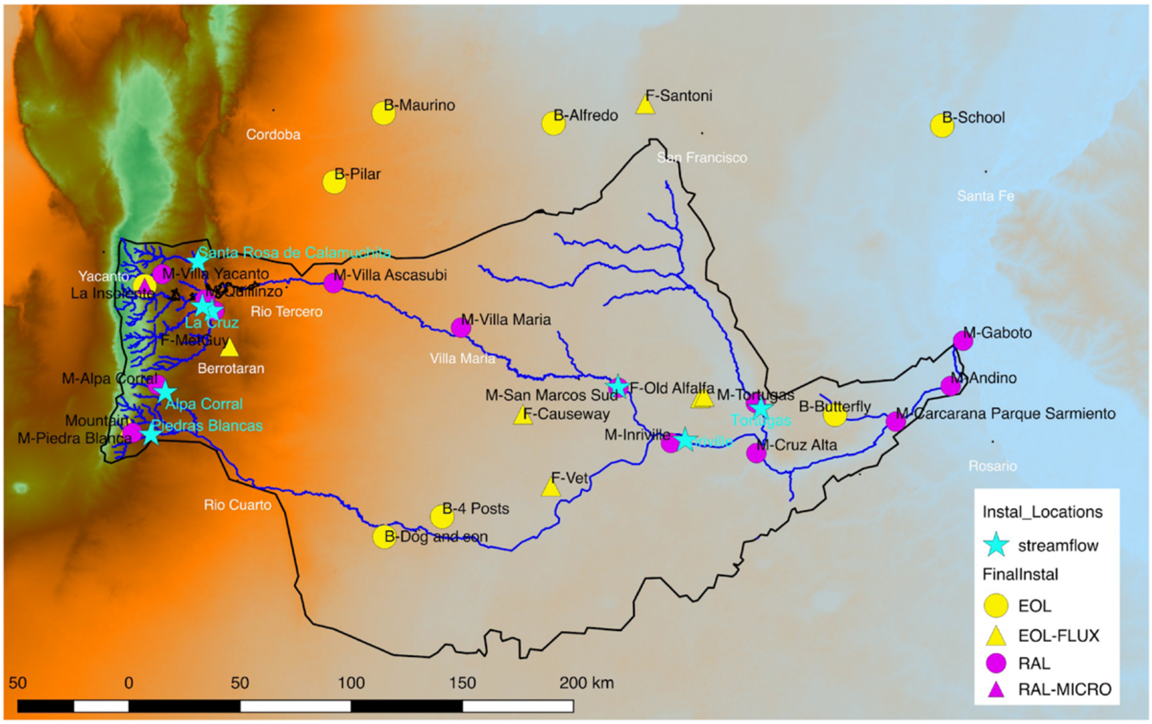

Fig. 4. RELAMPAGO streamflow measurements (cyan stars), NCAR EOL towers (yellow) including the EC towers (triangles), and RAL towers (magenta) including the microradars (triangles). The black outline is the Carcarañá River basin, and shading indicates topography.

del Río Seco and supplemental soundings at Córdoba, Mendoza, and Resistencia (these soundings were uploaded to the Global Telecommunications System). The Center for Severe Weather Research (CSWR) deployed three mobile mesonet trucks, measuring wind, temperature, and relative humidity, mounted far forward of the vehicle slipstream at 4 m AGL. CSWR also deployed fifteen 1-m portable weather stations or “Pods” to targeted locations, measuring temperature, relative humidity, wind velocity, and pressure. The mesonet vehicles typically deployed the Pods to observe transects on available paved roads to measure spatiotemporal variations in storm inflow and outflow.

Schumacher et al. (2021) describes RELAMPAGO sounding operations. Figure 5 shows a time series of equivalent potential temperature, and u and v wind components from Córdoba including supplemental RELAMPAGO soundings, as well as the timing of RELAMPAGO missions. Periods of enhanced vertical wind shear, enhanced northerly low-level flow associated with the SALLJ, and low-level potential instability coincided with several IOPs, but not all where deep convection was observed. In all, the bulk of RELAMPAGO sounding observations reflect conditions generally unfavorable for deep moist convection, but several soundings had precipitable water exceeding 50 mm and mixed-layer CAPE exceeding 3,000 J kg^{-1}. The 0–6-km bulk wind difference was routinely 15–25 m s^{-1}, with some soundings having >40 m s^{-1}; these shear magnitudes supported highly organized convective structures (e.g., Markowski and Richardson 2010; Trapp 2013). However, some mobile soundings during the campaign demonstrated near-storm convective environments comparable to those documented in the more densely observed central United States. This large collection of soundings will enable in-depth investigation of the convective environments characteristic of Argentina and facilitate novel comparisons with other regions of the world.

Radars. The CSWR deployed three mobile X-band Doppler on Wheels (DOW) radars (Wurman et al. 1997, 2021) to facilitate targeted observations of the preconvective environment, storm structures, and boundary layer structures such as gust fronts and other mesoscale boundaries. DOW6 and DOW7 are dual-polarization, dual-frequency Doppler radars. DOW8 was configured as a high-power single-polarization system for enhanced clear-air sensitivity.

The three DOWs often were deployed to obtain dual-Doppler or, in some instances, multi-Doppler coverage of phenomena. Extensive and multiple in-country site surveys were conducted prior to the start of the campaign to identify suitable sites for deployments. The RELAMPAGO sounding, radar, and Pod deployment locations for all missions are shown in Fig. 6.

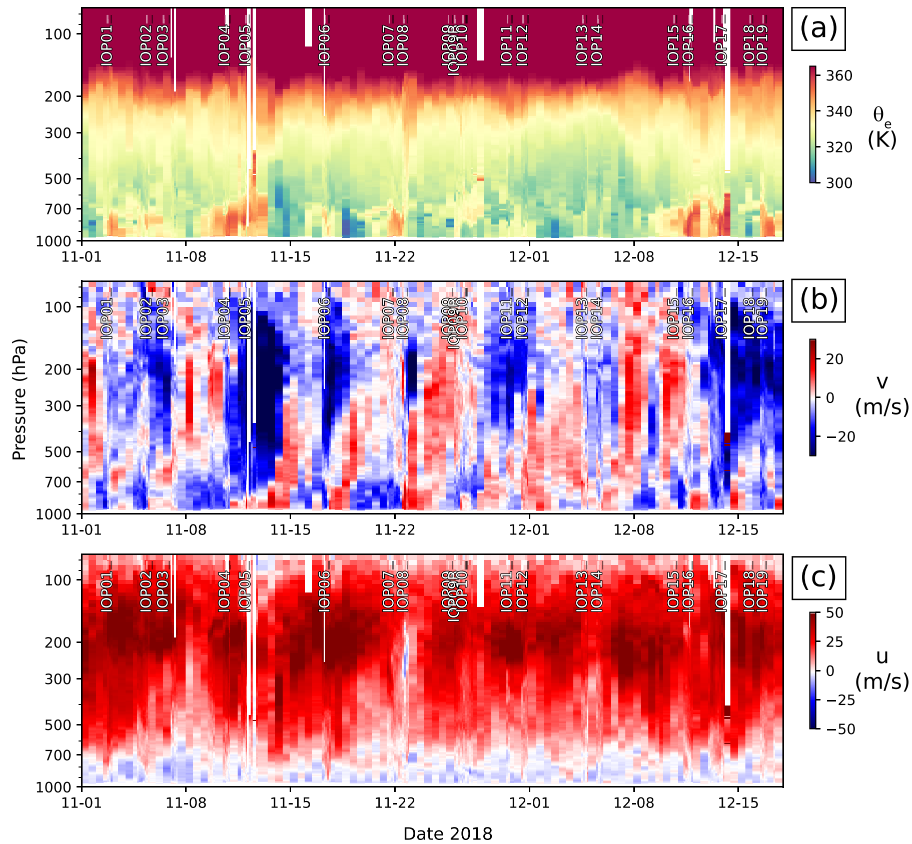

Fig. 5. Sounding-derived time series of (a) equivalent potential temperature (K), (b) meridional wind (m s^{-1}), and (c) zonal wind (m s^{-1}) from the NCAR 5-hPa interpolated sounding dataset from Córdoba during the RELAMPAGO IOP. RELAMPAGO mission timing is noted in each panel.

To facilitate broader coverage over the Córdoba domain by longer-wavelength radars, CSWR and CSU each provided, deployed, and operated C-band radars. The CSU C-band radar was operated near Lozada, Córdoba, for the period 10 November 2018–31 January 2019. The CSU C-band radar was operated in mixed surveillance and range height indicator (RHI) mode; during IOPs the scan strategy was manually adjusted depending on IOP objectives. The CSU C-band documented several tall convective structures (Fig. 7a), including 10 days with 18-dB*Z* echo tops > 16 km MSL, and a storm observed on 25 January 2019 that contained echo tops near 20 km MSL. An example from the tallest storm observed by the CSU C-band is shown in Figs. 7b–e, with differential reflectivity and specific differential phase columns (e.g., Kumjian et al. 2014), strong C-band attenuation and differential attenuation (e.g., Rauber and Nesbitt 2018), and a >10-km-wide slabular updraft structure apparent in Doppler velocity.

The CSWR deployable C-band radar (the "COW") is a custom built dual-pol, dual-frequency system, and was completed approximately a week before it was shipped to Argentina for RELAMPAGO. CSWR deployed the radar to near Monte Ralo, Córdoba, from 11 November to 14 December 2018. The COW is deployable, with approximately a few hours of setup/teardown time, but for logistical reasons the COW remained in the same location for the duration of the project. Surveillance scan strategies varied depending on the IOP objective. In total, the CSWR radars collected 351 h of data during RELAMPAGO (see "Mobile operations in RELAMPAGO" sidebar).

Deployable hail pads. The Pennsylvania State University (PSU) deployed hail pads during selected RELAMPAGO IOPs. The hail pads were similar to those used by the CoCoRaHS efforts in the United States (Cifelli et al. 2005), deployed in the path of an approaching storm. The hail pads were retrieved and analyzed after storm passage and collected observations during IOP4, IOP9, IOP10, IOP14, and IOP17, and often featured large numbers of impacts by small (<1 cm) hailstones. The PSU team also made poststorm surveys, taking manual measurements of hail sizes with digital calipers. Drone aerial photogrammetry was used during IOP10, in which size estimates for nearly 1.6×10^4 hailstones were obtained (Soderholm et al. 2020). These compared favorably to the manual measurements and featured some hail up to 4 cm in maximum dimension. These data will be used for validation of numerical modeling of hail sizes (e.g., Kumjian and Lombardo 2020), and the multifrequency DOW radar data that have shown promise for use in sizing hail (Kumjian et al. 2018).

Lightning. RELAMPAGO lightning instrumentation, deployed to document the extreme lightning flash rates and storm electrification processes in thunderstorms in SESA (Fig. 8, Table 2), included 10 electric field change meters, the Córdoba Argentina Marx Meter Array (CAMMA; Zhu et al. 2020) deployed by the University of Alabama in Huntsville, an 11-station Lightning Mapping Array (LMA) deployed by Marshall Space Flight Center (Lang et al. 2020), eight electric field mills (EFMs; Antunes de Sa et al. 2020), and four VLF/LF magnetic field receivers, termed Low Frequency Autonomous Magnetic Field Sensors (LFAMS), both deployed by the University of Colorado Boulder. The Universidad Nacional de Córdoba deployed a particle charge sensor. Brazilian National Institute for Space Research installed three transient luminous events (TLE) and two video cameras with low-light-level 30 frames per second (fps) imaging, and one high energy emissions from thunderstorms (HEET) station, with one neutron detector, extending the Transient Luminous Event and Thunderstorm High Energy Emission Collaborative (LEONA) Network (São Sabbas et al. 2017). The LFAMS network extended the lightning detection coverage over the Mendoza region. The LEONA-HEET station was installed at UNC, to detect possible neutron background enhancements and bursts. To have an unobstructed view toward the upper-atmosphere/near-Earth space region above the RELAMPAGO storms, the three LEONA TLE stations were installed ~250–400 km from Córdoba.

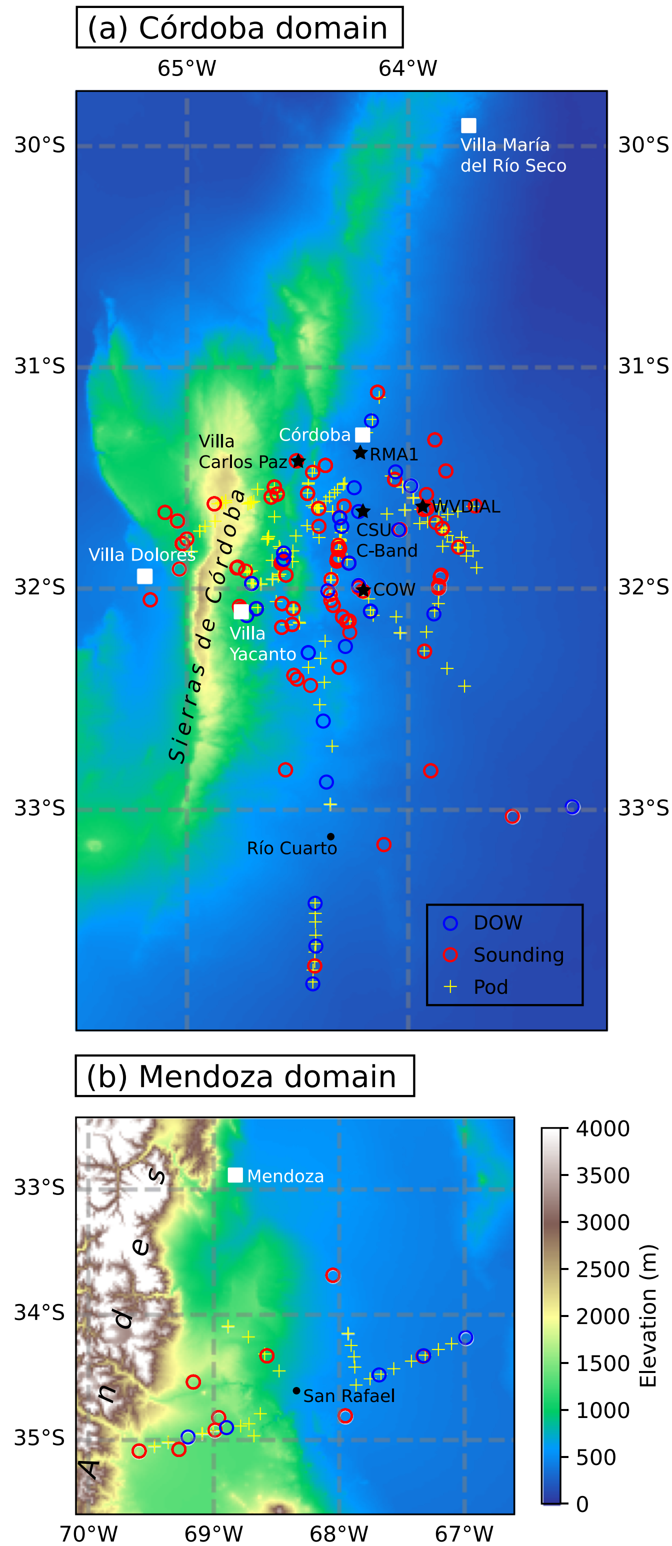

Fig. 6. Maps showing fixed sounding assets (white squares); radars and the operations center (black stars); and DOW, sounding, and Pod deployment locations for the (a) Córdoba and (b) Mendoza domains.

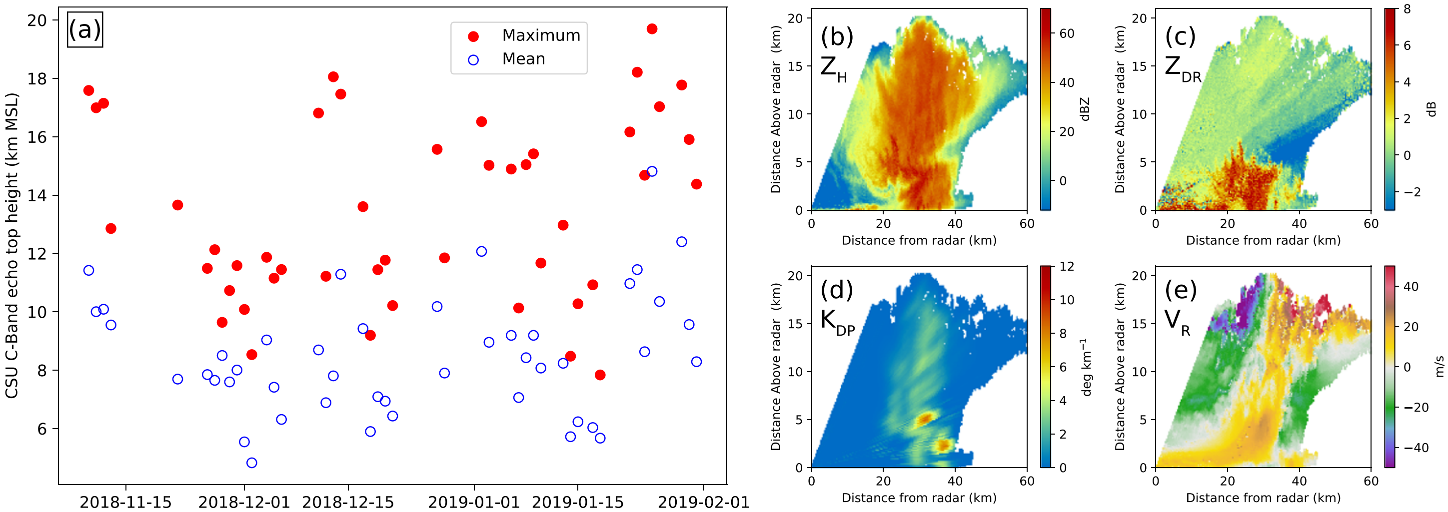

Fig. 7. (a) Daily 18-dB*Z* echo-top height statistics (MSL) from the CSU C-band radar: daily mean echo top (blue symbols) and maximum echo top (red symbols). From a range–height indicator scan at 2034 UTC 25 Jan 2019 at 257° azimuth: (b) radar reflectivity, (c) differential reflectivity, (d) specific differential phase, and (e) radial velocity.

NCAR WV-DIAL. A water vapor differential absorption lidar (WV-DIAL; Spuler et al. 2015; Weckwerth et al. 2016), a compact, field-deployable, micro-pulse differential absorption lidar was deployed at Pilar, Córdoba, during IOP. The WV-DIAL provides continuous monitoring of water vapor in the lower troposphere at 150-m range resolution and 1–5-min temporal resolution from 300 m to 4 km AGL in daytime operation with greater range at night. The instrument provided continuous monitoring of lower-tropospheric humidity, cloud-base height, and aerosol information east of the SDC.

GOES-16. NOAA's Geostationary Operational Environmental Satellite (GOES-East) located at 75.2°W collected 1,010 h of 1-min rapid-scan mesoscale domain sector (MDS) imagery during the period 1 November 2018–21 April 2019 in support of RELAMPAGO. For most of the RELAMPAGO missions, the Advanced Baseline Imager (ABI) collected imagery at the 1-min cadence for all 16 spectral bands in the visible (at 500-m resolution) through infrared (at 2-km resolution) wavelengths (Schmit et al. 2017, 2018; Goodman et al. 2019). This was the largest volume of research data collected to date since the launch of the satellite in November 2016. The MDS center point for its 1,000 km × 1,000 km regional coverage was requested based upon the prior day forecast for possible severe convection within the experiment

Mobile operations in RELAMPAGO

CSWR provided 3 DOW radars, the COW, 3 mesonets, 12 pods, and 5 sounding systems for the RELAMPAGO project. Three further sounding systems were fielded by universities, two by UI and one by CSU. In total, mobile vehicles drove ~50,000 km throughout the duration of the project. CSWR had an additional 17 participants from multiple outside institutions, including ASI students, constituting a diverse multicultural group (Fig. S2). These participants were core to CSWR operations, having mission-critical roles in the preparation and deployment of assets. Each vehicle, and the operations center, had a Spanish-speaking participant to help with logistics and informal outreach during IOPs.

After the daily weather briefing (~12–15 h before departure time), the mission scientist would communicate with the mobile operations coordinator (MOC) and provide a preliminary Google Earth diagram of asset deployment locations. The MOC would refine the deployment locations and distribute the mission asset summary and instrument specific locations to each mobile team. One to two hours prior to departure, the MOC would hold a briefing for the mobile teams and ensure instruments and teams were ready for the mission. After the teams left, the MOC moved to the operations center to provide an interface between mobile assets and the mission scientist, allowing the mission scientist to focus primarily on the evolving event in real time and not the specific deployment and/or instrument details. Communication with the mobile teams was primarily done through WhatsApp, and there were multiple WhatsApp channels focusing on general and specific mission issues. The MOC monitored and set reasonable crew duty days that satisfied the mission objectives.

domain. Concurrent with the 1-min multispectral imagery, the GOES-East Geostationary Lightning Mapper (GLM) collected continuous total lightning (in-cloud and cloud-to-ground) event, stroke, and flash data throughout the day and night with 2-ms temporal resolution and 8-km spatial resolution (Rudlosky et al. 2018). The rapid evolution of GOES-identified

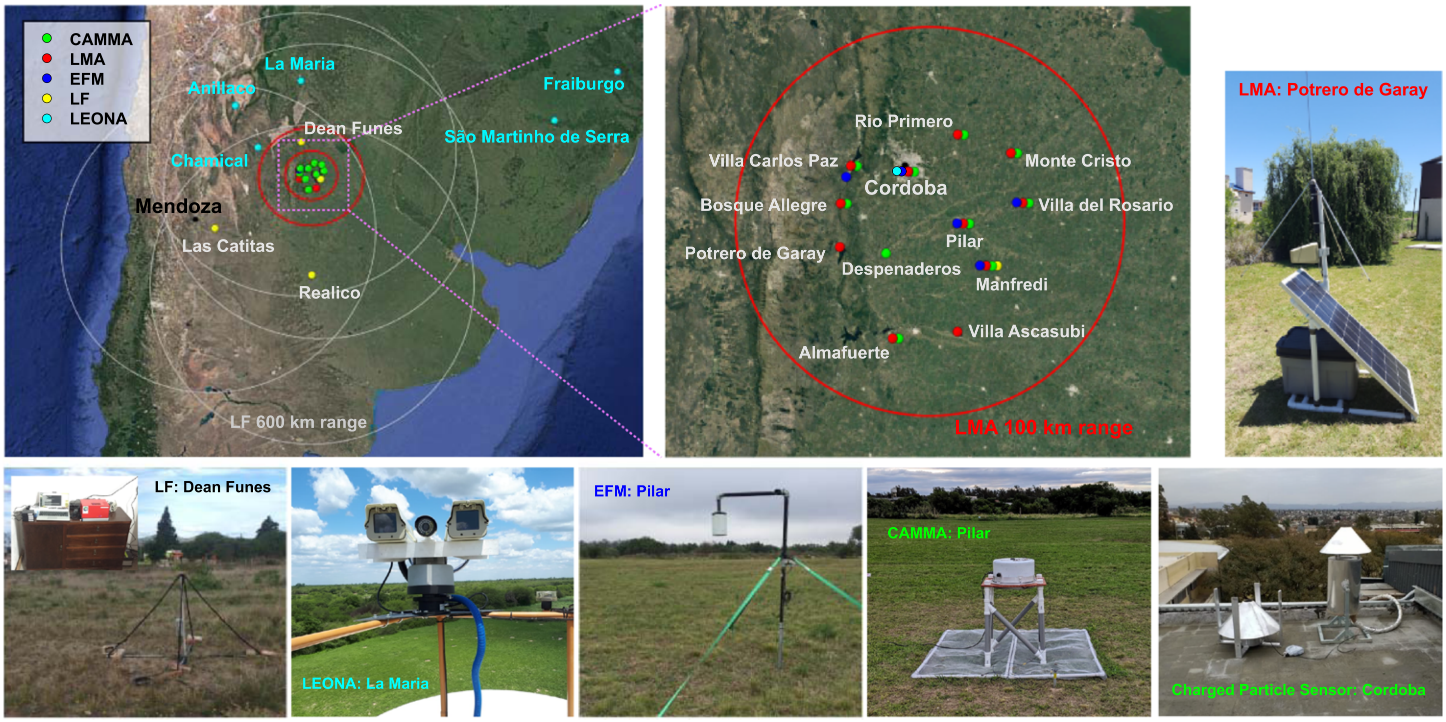

Fig. 8. Maps of the lightning and Effects of Electrical Activity Related to Convective System (FAIRIES) instrumentation that operated during RELAMPAGO and photographs of selected instruments.

Table 2. Lightning-related instrumentation deployed during RELAMPAGO.

Instrumentation and measured quantity	Detection frequency regime/energy range	Temporal resolution	Data products	Purpose
NASA LMA: Radio emissions from lightning	60–66 MHz (11 stations)	~1 μs	Sources, flashes	GLM validation, total lightning activity, areal extent, and propagation
UAH CAMMA: VLF/MF electric field change	Slow: 1 Hz–57 kHz	Slow: ~1 μs	L0 (L1): raw (QC'ed) waveform	Slow: charge retrieval, continuing current, flash energy
	Fast: 1.6 kHz–2.5 MHz	Fast: ~100 ns	L2: sources	Fast: lightning mapping, peak current, flash type
CU LFAMS: Radio emissions from lightning	1–400 kHz	1 μs	Raw QC'ed waveform as well as stroke time, location, and peak current	Lightning flash rates and geolocation over larger domain covering the Mendoza region
INPE LEONA network				
Transient luminous events (TLEs)	30-fps low-light-level video cameras	~16.7 ms	TLE occurrence, type, duration, and location	TLE detection and characterization
Atmospheric neutrons	16.7-Hz–1-kHz thermal (~0.025 eV) neutron detector	Fast: 1 ms Slow: 1 min	Neutron count, enhancement/ burst occurrence, and duration	Thunderstorm/lightning excited neutron emission measurement
CU EFM: Vertical electric field	DC to 100 Hz	1 ms	Electric field amplitude and polarity	Electric field of storms overhead
UNC particle charge sensor (PCS): Induced charge and raindrop fall velocity			Sign and magnitude of the charge and size of raindrops	

overshooting tops, radar, and spaceborne and ground-based lightning structure in a severe hailstorm during RELAMPAGO is examined in Borque et al. (2020).

Brazilian RELAMPAGO component. An observation site near São Borja in far western Rio Grande do Sul state (RS), near the Argentine border (instrumentation listed in Table 3) was coordinated by the Instituto Nacional de Pesquisas Espaciais (INPE) and the Universidade de São Paulo, with the collaboration of the Universidade Federal de Santa Maria. The main goal of this site was to observe mature or decaying stages of convective systems that initiated in north-central Argentina, to observe locally initiated storms.

Table 3. Instruments at the Brazil site in São Borja.

Measurement	Sensors
Radars	Gematronik X-band radar
Surface meteorology	4 micronet stations measuring temperature, dewpoint temperature, atmospheric pressure, wind speed and direction, accumulated rainfall
Precipitation	Parsivel2 disdrometer Joss–Waldvogel disdrometer Tipping-bucket rain gauge
Electrification	4 electric field mills
Total column water vapor	2 GPS systems
Upper-air soundings	Launched daily at 1800 UTC and sequentially during storm events
Hail	Hail pads

During RELAMPAGO at São Borja, five intense convective episodes were observed (Table 4). For most of these cases, data from a single-polarization S-band radar, X-band dual-polarization radar RHIs with high temporal resolution, *GOES-16* rapid scans, and successive launches of radiosondes were collected, in addition to the data collected from the network of surface instruments.

Interactions with CACTI. The DOE ARM-funded CACTI field campaign [see companion article by Varble et al. (2021)] was planned and operated in coordination with RELAMPAGO to maximize the benefits of each campaign. The CACTI primary observing site near Villa Yacanto in the SDC 20 km east of the mountain ridgeline and the secondary sounding site near Villa Dolores on the plains immediately west of the SDC were frequently used as part of the RELAMPAGO radar, sounding, and surface meteorology networks. The Gulfstream-1 (G-1) aircraft also performed 22 flights during RELAMPAGO. Flight plans and operations depended on forecasting support and real-time flight guidance provided by RELAMPAGO investigators, SMN staff, and graduate students. Nine flights overlapped with RELAMPAGO mobile missions, in which sounding launches and aircraft flight legs were carefully coordinated.

Table 4. Storms sampled by the RELAMPAGO-Brazil observational site in Sao Borja, Rio Grande do Sul, Brazil.

Date	Type of event
13 Nov 2018	Intense QLCS with bowing segment
17 Nov 2018	Large MCS causing local flash floods
27 Nov 2018	Supercell producing a downburst
12 Dec 2018	Gust front associated with a nocturnal QLCS
14 Dec 2018	Intense nocturnal storms

RELAMPAGO IOPs

A list of the IOPs during the RELAMPAGO is given in Table 5. More information and imagery are available at the NCAR EOL Field Catalog page (http://catalog.eol.ucar.edu/relampago). Each mission was designed to address lighting and hydrometeorology objectives

Table 5. RELAMPAGO IOPs. IOPs are classified by their primary objective resulting in eight convective initiation (CI; green) IOPs, six upscale-growth (UG; blue) IOPs, five severe weather (SW; orange) IOPs, and one unclassified IOP.

IOP	Date	Primary mission type	CSWR radars	Radar scan mode	No. of soundings	No. of Pods	Mesonet data
1	2 Nov	CI	DOW 6, 7, 8	CI	10	10	Y
2	5 Nov	UG	DOW 7, 8	UG	12	7	Y
3	6 Nov	CI	DOW 7, 8	CI	21	9	Y
4	10 Nov	SW	DOW 6, 7, 8	CI/SW	27	11	Y
5	12 Nov	UG	DOW 6, 7, 8	UG	40	9	Y
6	17 Nov	No classification	—	—	28	0	N
7	21 Nov	CI	DOW 6, 7, 8, C-band	CI	30	11	Y
8	22 Nov	SW	DOW 6, 7, 8, C-band	CI/S	23	12	Y
9a	25 Nov	SW	DOW 6, 7, 8	SW	22	12	Y
9b	26 Nov	UG	C-band	UG	0	0	N
10	26 Nov	CI	DOW 7, 8	CI/SW	28	12	Y
11	29 Nov	CI	DOW 7, 8 C-band	CI/SW	30	12	Y
12	30 Nov	UG	DOW 7, 8 C-band	CI/UG	42	8	Y
13	4 Dec	CI	DOW 6, 7, 8, C-band	CI/SW	33	12	Y
14	5 Dec	UG	DOW 6, 7, 8, C-band	CI/UG	35	9	Y
15	10 Dec	SW	DOW 6, 7, 8	CI	6	9	Y
16	11 Dec	SW	DOW 6, 7, 8, C-band	CI	14	9	Y
17	13 Dec	UG	DOW 7, 8 C-band	CI/UG	27	6	Y
18	16 Dec	CI	DOW 7, 8	CI	21	12	Y
19	17 Dec	CI	DOW7	CI	24	10	Y

in addition to its primary objectives, and sometimes handoffs (i.e., changes in sampling strategies) from one objective to another occurred during missions.

Convection initiation. CI IOPs emphasized observation of the mesoscale environments surrounding forecasted regions of deep convection leading up to the initial onset of radar precipitation echoes, making heavy use of the radiosonde resources available for the project to sample the evolution and heterogeneity of CAPE, CIN, and LFC relative to local topographic features, and the radars to identify early stage convective cell locations. There were seven IOPs dedicated to characterizing environments associated with CI. Five of these were focused near fixed assets in the SDC near Villa Yacanto to maximize observing of forecasted topographic initiation. One mission occurred on the plains east of the SDC, and another occurred in Mendoza province along the Andes foothills. A variety of convective outcomes were observed during CI-focused IOPs: (i) 3 days with CI and sustained growth and intensification, (ii) 4 days with CI of short-lived, relatively weak precipitation, and (iii) 2 days in which little to no precipitation was detected at the ground despite forecasts from model forecasts of significant precipitation following CI.

Deployment of RELAMPAGO instrumentation during a typical CI IOP is shown in Fig. 9a. Instruments were deployed several hours prior to the forecasted CI time. Mobile radiosondes were deployed at locations spaced approximately 15–40 km apart, as permitted by the local road network, performing synchronized launches, typically at an hourly frequency. The hourly launches permit a detailed view of the evolution of stability and moisture surrounding the convective events, including deepening of the boundary layer, detection of probable layers of ascent/descent via tracking of lapse rate and mixing ratio tendency, and erosion of CIN associated with the capping inversion (Fig. 9b). Nelson et al. (2021) analyze considerable spatiotemporal mesoscale heterogeneity among

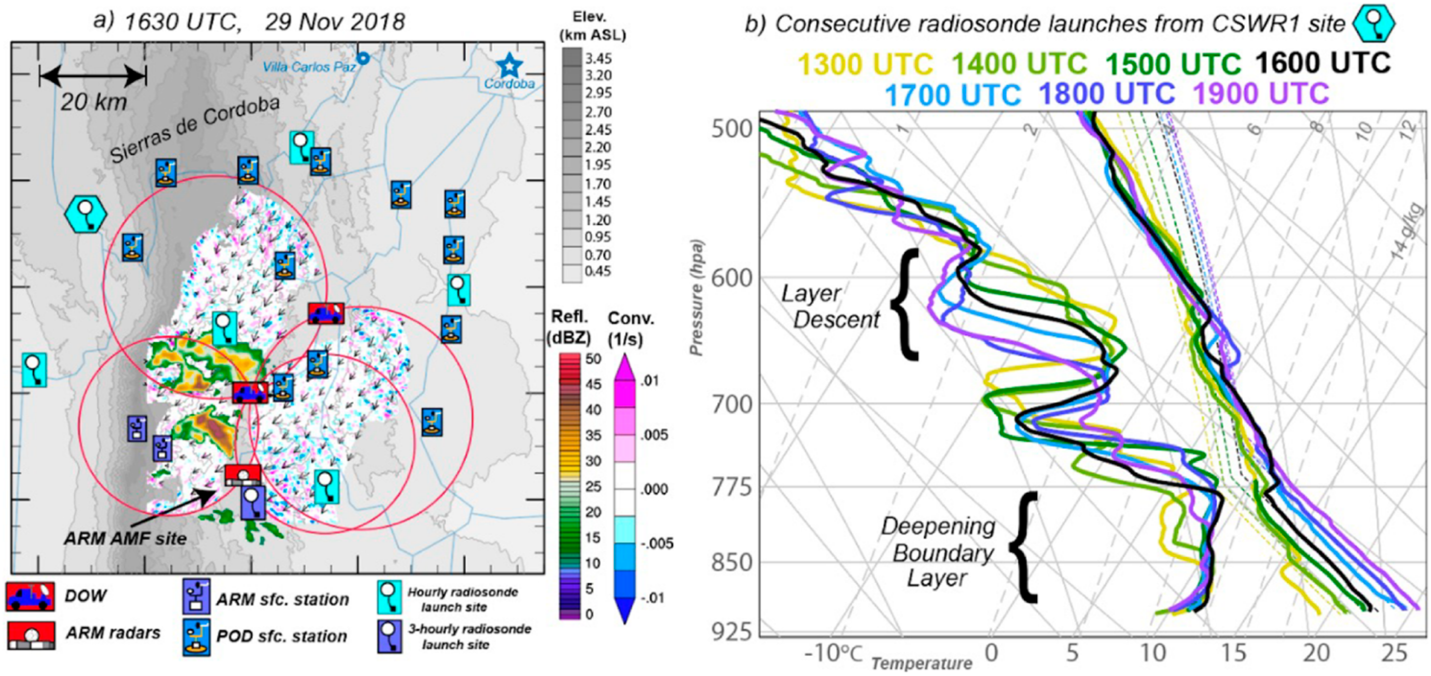

Fig. 9. (a) Deployment map of mobile and fixed assets on 29 Nov 2018, typifying a RELAMPAGO mission targeting terrain-focused CI. Dual-Doppler wind synthesis lobes (red circles), low-level radar reflectivity, and retrieved horizontal flow convergence are overlaid upon topography. (b) Consecutive hourly radiosonde soundings launched from one of the mobile facilities during the deployment. Lifted-parcel profiles assume parcels with mean properties of the lowest 100 hPa of the atmosphere.

neighboring soundings collected by the radiosonde array during the CI missions and characterize the statistically significant differences between near-cloud environments supporting or suppressing CI among a sample of 44 radiosondes. Mobile radars were deployed to measure the onset and evolution of precipitation in high resolution during CI, but also targeted clear-air, low-level convergence features (e.g., airmass boundaries and orographic circulations) via dual-Doppler wind retrievals within the boundary layer surrounding CI events (Fig. 9a), revealing the role of initial updraft width in distinguishing successful CI events (Marquis et al. 2021).

Severe convective storms. Severe IOPs were focused on collection of environmental, in situ, and radar-based storm-scale data to address hypotheses on convective-storm intensity and hazard generation. Because many of the severe-weather hypotheses had linkages to CI and upscale growth, attempts were made for coordinated data collection and mission transfers. IOP selection was prioritized for days on which the meteorological conditions appeared favorable for supercell thunderstorm formation. Three specific mission objectives, namely, 1) the sampling of updrafts, downdrafts, and cold pools to investigate convective-storm dynamics, 2) sampling of hail-growth region to investigate storm microphysics and kinematics, and 3) sampling of severe-wind generation to investigate wind hazards (including tornadic and non-tornadic severe winds), required similar observing strategies. Trapp et al. (2020) details the supercell observed during the 10 November 2018 IOP4. Figure 10 shows the IOP4 deployment, the *GOES-16* visible image, low-level winds, mid-level updrafts from a DOW multi-Doppler synthesis and *GOES-16* overshooting top, and the hail and damage to the COW radar during this storm.

During RELAMPAGO, five IOPs were dedicated to the severe objectives; one of these took place in the Mendoza domain and the remaining four were within the Córdoba domain. In contrast to the supercell occurrence near the SDC during 2015 and 2016 (Mulholland et al. 2018), such occurrence was infrequent during 2018, with supercells observed in only two Córdoba IOPs, regardless of the mission objective (Trapp et al. 2020). Of the supercells observed, rotation primarily was confined to the mid- and upper levels, with low-level rotation observed only in IOP4, aided by the presence of a preexisting boundary. Hail occurred in five IOPs and was typically <1 cm in maximum dimension (but was as large as 4.3 cm). The two storms observed during the two IOPs in the Mendoza domain were supercells and produced hail; one from the 26 November 2018 IOP 10 is shown in Fig. 11. A supercell resulting from sufficiently strong environmental instability and low-level shear, tracked over the DOW network and produced a long swath of hail. Quantification of the hail fall using drone video and ground reports are described in Soderholm et al. (2020). No tornadoes or widespread severe wind events were observed during any of the IOPs. The five severe IOPs, coupled with observations from some of the other IOPs, provide a rich dataset to examine numerous relationships regarding boundary-storm interactions, relationships between updraft width and overshooting tops, cold pool properties, and storm mode transitions.

Upscale growth. The overall objective of the upscale-growth-related missions in RELAMPAGO was to observe convective life cycle from initiation through a period of upscale growth, and determine the environmental and terrain-related processes responsible for the rapid growth of these systems. This strategy included using the DOWs, C-band radars, disdrometers, and 1-min GOES observations to document storm structures and organization, as well as the three-dimensional hydrometeor distributions throughout convective system

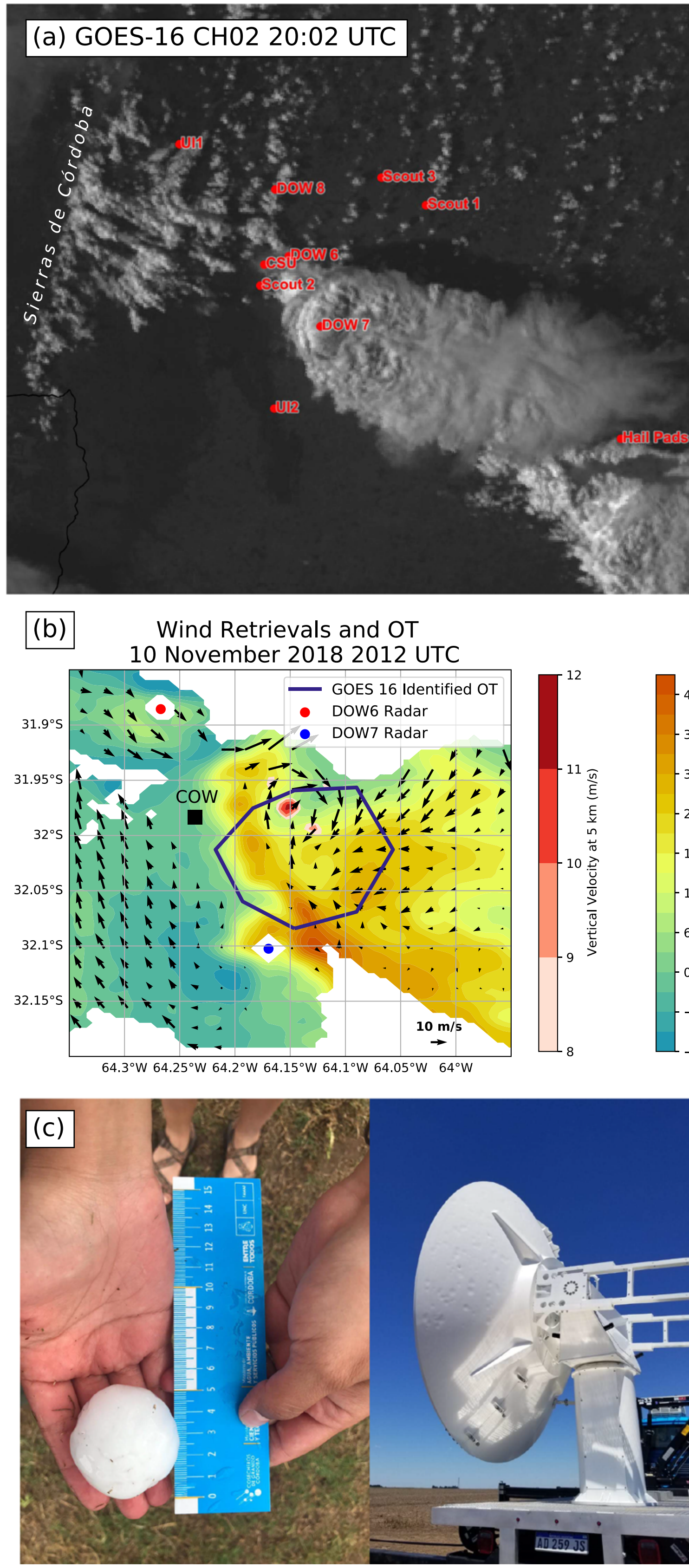

Fig. 10. (a) ***GOES-16*** **channel 2 visible (red; 0.64 μm) image from 2002 UTC 10 Nov along with RELAMPAGO mobile asset locations showing the supercell with overshooting top and above-anvil cirrus plume. (b) DOW6 reflectivity, dual-Doppler synthesis from DOW6 and DOW7, and** ***GOES-16*** **overshooting top at 2012 UTC, as well as the location of the COW radar. (c) (left) Hail observation near the COW and (right) COW rear-side antenna damage.**

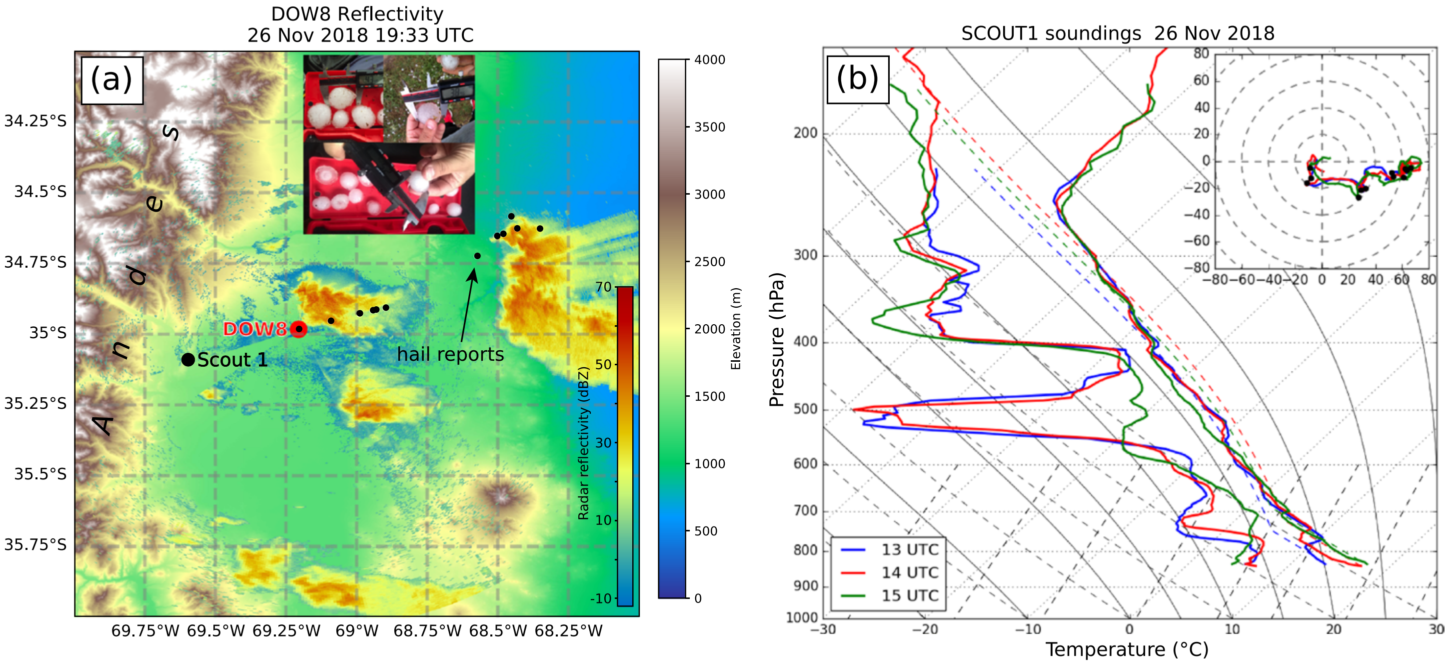

Fig. 11. (a) DOW8 0.9° radar reflectivity at 1933 UTC 26 Nov 2018, topography (shaded), and hail reports from spotters and hail pads (black markers) and SCOUT1 mobile sounding unit (white symbol). (b) Skew *T*–log*p* diagram showing temperature and dewpoint (solid lines), and lifted-parcel paths (dashed lines) and hodographs (knots; 1 kt ≈ 0.51 m s^{-1}) from the SCOUT1 soundings at 1300, 1400, and 1500 UTC 26 Nov 2018.

evolution. Soundings, mesonet, PODs, and multiple-Doppler wind syntheses are used to describe observed storm structures including convective drafts, cold pools, and gravity waves relative to the topography, the evolution of the synoptic to mesoscale environments, including the role of the SALLJ, and documented processes relevant to backbuilding.

Upscale-growth missions collected observations during a variety of MCSs during five IOPs in Córdoba with all mobile resources, and one IOP (IOP 9b) that documented over 12 h of MCS evolution with the C-band radar network near the SDC while the mobile teams were deployed in Mendoza province. In addition, several MCSs were observed in January during the extended CSU radar operations, CACTI, and enhanced soundings at Córdoba. Figure 12 shows the backbuilding portion of a massive convective system that stretched to the Atlantic Coast sampled near the SDC during IOP14 on 13–14 December 2018. Convective cells developed within the multi-Doppler domain as shown by the COW image. Mobile soundings indicated adequate conditional instability and deep shear for organized convective structures, with significant local wind profile variability in the SALLJ near the SDC as indicated by the soundings launched at Córdoba and UI1. Upscale growth continued into the evening as the system propagated slowly north, observed by the CSU and RMA1 radars.

Inclusivity, education, and outreach

Beyond the invaluable field experience that RELAMPAGO students and early-career scientists experienced during RELAMPAGO, an NSF-funded Advanced Studies Institute called Field Studies of Convection in Argentina (ASI-FSCA; Rasmussen et al. 2021) brought 16 students from U.S. graduate programs to Argentina. An NSF Geosciences Opportunities for Leadership in Diversity (GOLD) training program in preventing harassment during field campaigns was required of all RELAMPAGO participants (Fischer et al. 2021), and the campaign adopted a code of conduct and harassment policy.

RELAMPAGO was a generational opportunity for South American scientists and students, working together on forecasting, observation, and continuing data analysis (Fig. 13; see

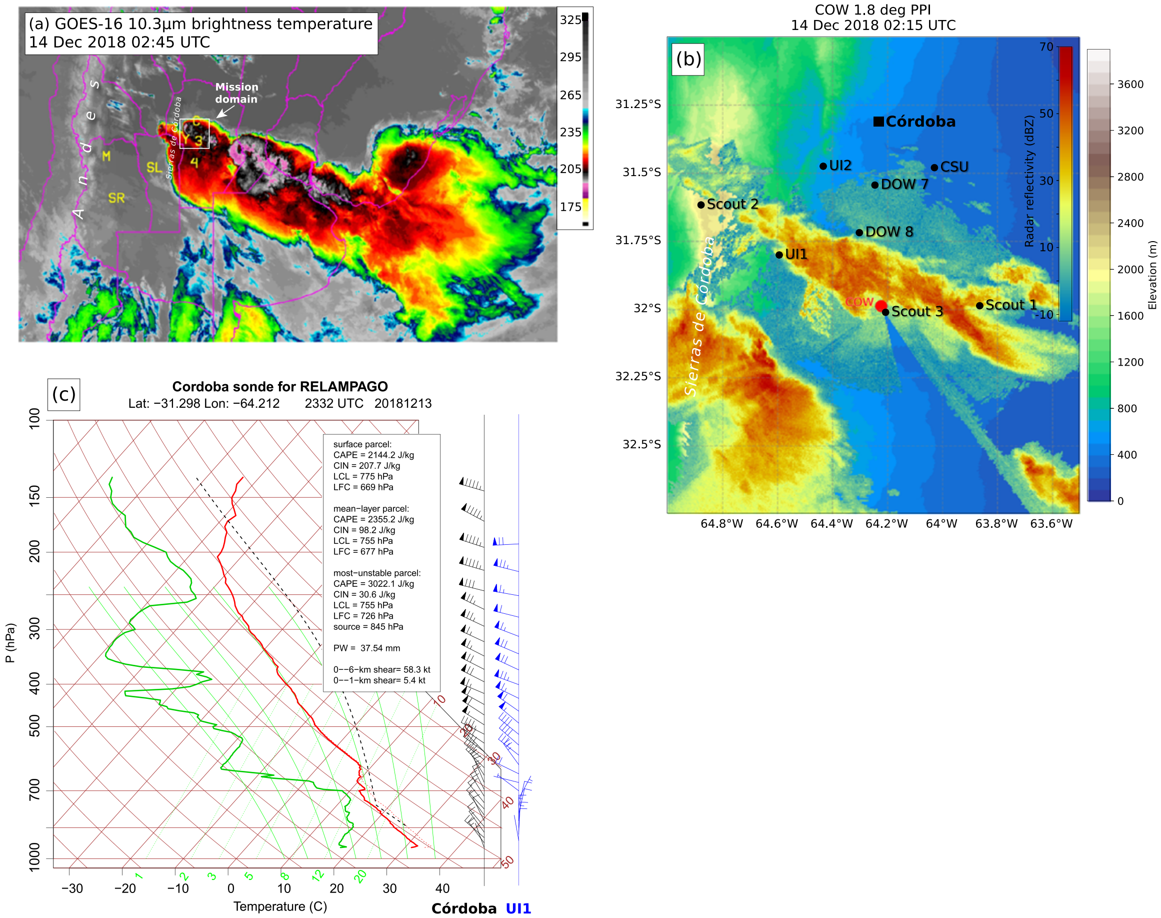

Fig. 12. (a) *GOES-16* "clean IR" image showing the IOP14 convective system. (b) COW 1.8° radar reflectivity at 0215 UTC 14 Dec 2018, topography (shaded), and hail reports from spotters and hail pads (black markers) and selected assets (black symbols) within the mission domain [see white box in (a)]. (c) Skew *T*–log*p* diagram showing temperature and dewpoint (solid lines), and lifted-parcel paths (dashed lines) from the 0000 UTC 13 Dec 2018 Córdoba sounding, and winds from the 0000 UTC Córdoba (black) and UI1 soundings (blue); a full barb is 10 kt.

Fig. 13. Photos from RELAMPAGO education and outreach activities.

"RELAMPAGO's legacy in Argentina and Brazil: From education to infrastructure" sidebar). A RELAMPAGO open house was held at the Centro Cívico del Bicentenario in downtown Córdoba on 31 October 2018. Several K–12 events reached more than 2,000 students in 15 schools and 3 community centers in Córdoba and Sao Borja. During these activities, RELAMPAGO displayed the DOW radars, surface instrumentation, and launched radiosondes with the participants. These events were also accompanied with science talks about hail and flooding from U.S., Argentine, and Brazilian researchers.

The @RELAMPAGO2018 Twitter account gained over 5,500 followers, and shared tweets in English and Spanish. The @RelampagoEdu Twitter account promoted citizen participation in Spanish and gathered 690 trustable and geolocated reports used to determine hail size. The Twitter account promoted, together with the Province of Córdoba crowdsourcing project *Cosecheros de Granizo* ("hail harvesters"), the dissemination of ~10,000 hail rulers and hail report instructions in Argentina. RELAMPAGO, through sales of campaign T-shirts, donated 15 weather stations and 20 commercial rain gauges to *proyecto MATTEO*, which promotes weather observation in Argentina at local schools. Also, the crowdsourcing campaign *Cazadores de Crecidas* ("flood chasers") allowed the detection of extreme hydrological events by using mobile phones or digital cameras.

Eight scientific videos were created as part of the NCAR Explorer Series that highlight the science and operations of RELAMPAGO–CACTI, as well as career opportunities within the atmospheric and related sciences. These videos show interviews in both English and Spanish, and include Spanish subtitles to reach a Spanish speaking audience. The videos are available at https://ncar.ucar.edu/what-we-offer/education-outreach/public/ncar-explorer-series-field-campaigns/relampago.

RELAMPAGO's legacy in Argentina and Brazil: From education to infrastructure

Severe weather researchers and field campaigns that concentrated on deep convection in South America can be counted on the fingers of one hand. The remarkable synergy among participants in RELAMPAGO planted the seed of a new generation of scientists in SESA interested in the understanding of deep moist convection through observations and models. Active interactions during and after the campaign keeps this collaboration strong. RELAMPAGO was the first time that SMN engaged in an international field campaign, which is a milestone in scientific and educational cooperation between the SMN, universities, and funding agencies in Argentina to support observations. A large group of SMN forecasters had the opportunity to improve their knowledge on nowcasting tools that has improved the weather warning system at SMN. SMN forecasters interacted during RELAMPAGO participants outside of classical forecast operations for the first time. The use of advanced modeling techniques such as model ensembles, data assimilation, and rapid refresh models, as well as the collaborative development process undertaken for RELAMPAGO, has enabled and will enable new operational forecast tools and techniques in Argentina.

In addition to training in the use of state-of-the-art nowcasting and forecasting tools, participants from different backgrounds (hydrologists, engineers, and others) took advantage of the forecast briefings at the Operational Center to understand HIW forecasting and learned how weather forecast tools could be applied to infrastructure. This motivated the implementation of real-time forecasts for water resources management and hydrologic risk mitigation in the flash flood–prone river basins in the SDC.

Summary

RELAMPAGO, together with CACTI, documented continental convection, its internal processes, and its impacts on society in a geographically unique region defined by its significant and complex topography. The observations reveal the unique character of convective systems across the convective spectrum in Argentina that produce high-impact weather including hail, flash flooding, and high lightning flash rates in a global convective hotspot.

Together with CACTI, RELAMPAGO has enabled the observation of processes related to orographic CI success and failure with detailed multi-Doppler radar analyses and dense, frequent radiosonde observations that will be used to robustly examine these processes in multiscale models. The unique storm environments, the role of orographic flows, and storm-internal processes in producing tall, wide convective updrafts, hail-producing but nontornadic severe convective storms, high lightning flash rates, and rapid convective mode transitions and upscale growth were documented with detailed and comprehensive observations, allowing connections between storm environment, kinematics, and microphysical processes in intense convection to be revealed. Detailed case study analysis and modeling studies of convective storm life cycle will continue to elucidate how SESA storms fit into the global intense convective spectrum, as well as help meteorological services in SESA improve societal resilience to extreme weather. RELAMPAGO observations have and will continue to help us understand the physical processes in severe storms and their impacts, including heavy precipitation and hydrometeorological processes in Argentina, aiding the global monitoring and prediction of HIW and land–atmosphere interactions on weather and climate time scales.

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Data availability statement. All RELAMPAGO data are cataloged at the NCAR EOL RELAMPAGO data archive: https://data.eol.ucar.edu/project/RELAMPAGO.

References

Altinger de Schwarzkopf, M. L., and L. C. Rosso, 1982: Severe storms and tornadoes in Argentina. Preprints, *12th Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 59–62.

Anabor, V., D. J. Stensrud, and O. L. L. de Moraes, 2008: Serial upstream-propagating mesoscale convective system events over southeastern South America. *Mon. Wea. Rev.*, **136**, 3087–3105, https://doi.org/10.1175/2007MWR2334.1.

——, ——, and ——, 2009: Simulation of a serial upstream-propagating mesoscale convective system event over southeastern South America using composite initial conditions. *Mon. Wea. Rev.*, **137**, 2144–2163, https://doi.org/10.1175/2008MWR2617.1.

Antunes de Sa, A., R. A. Marshall, A. P. Sousa, and W. Deierling, 2020: An array of low-cost, high-speed autonomous electric field mills for thunderstorm research. *Earth Space Sci.*, **7**, e2020EA001309, https://doi.org/10.1029/2020EA001309.

Bang, S. D., and D. J. Cecil, 2019: Constructing a multifrequency passive microwave hail retrieval and climatology in the GPM domain. *J. Appl. Meteor. Climatol.*, **58**, 1889–1904, https://doi.org/10.1175/JAMC-D-19-0042.1.

Banta, R. M., and C. B. Schaaf, 1987: Thunderstorm genesis zones in the Colorado Rocky Mountains as determined by traceback of geosynchronous satellite images. *Mon. Wea. Rev.*, **115**, 463–476, https://doi.org/10.1175/1520-0493(1987)115<0463:TGZITC>2.0.CO;2.

Borque, P., P. Salio, M. Nicolini, and Y. García Skabar, 2010: Environment associated with deep moist convection under SALLJ conditions: A case study. *Wea. Forecasting*, **25**, 970–984, https://doi.org/10.1175/2010WAF2222352.1.

——, L. Vidal, M. Rugna, T. J. Lang, M. G. Nicora, and S. W. Nesbitt, 2020: Distinctive signals in 1-min observations of overshooting tops and lightning activity in a severe supercell thunderstorm. J. Geophys. Res. Atmos., **125**, e2020JD032856, https://doi.org/10.1029/2020JD032856.

Brooks, H., and C. A. Doswell, 2001: Some aspects of the international climatology of tornadoes by damage classification. *Atmos. Res.*, **56**, 191–201, https://doi.org/10.1016/S0169-8095(00)00098-3.

——, and J. Correia Jr., 2018: Long-term performance metrics for national weather service tornado warnings. *Wea. Forecasting*, **33**, 1501–1511, https://doi.org/10.1175/WAF-D-18-0120.1.

Cancelada, M., P. Salio, D. Vila, S. W. Nesbitt, and L. Vidal, 2020: Backward Adaptive Brightness Temperature Threshold Technique (BAB3T): A methodology to determine extreme convective initiation regions using satellite infrared imagery. *Remote Sens.*, **12**, 337, https://doi.org/10.3390/rs12020337.

Cecil, D. J., and C. B. Blankenship, 2012: Toward a global climatology of severe hailstorms as estimated by satellite passive microwave imagers. *J. Climate*, **25**, 687–703, https://doi.org/10.1175/JCLI-D-11-00130.1.

——, S. J. Goodman, D. J. Boccippio, E. J. Zipser, and S. W. Nesbitt, 2005: Three years of TRMM precipitation features. Part I: Radar, radiometric, and lightning characteristics. *Mon. Wea. Rev.*, **133**, 543–566, https://doi.org/10.1175/MWR-2876.1.

Cifelli, R., N. Doesken, P. Kennedy, L. D. Carey, S. A. Rutledge, C. Gimmestad, and T. Depue, 2005: The community collaborative rain, hail, and snow network: Informal education for scientists and citizens. *Bull. Amer. Meteor. Soc.*, **86**, 1069–1078, https://doi.org/10.1175/BAMS-86-8-1069.

Coniglio, M. C., D. J. Stensrud, and L. J. Wicker, 2006: Effects of upper-level shear on the structure and maintenance of strong quasi-linear mesoscale convective systems. *J. Atmos. Sci.*, **63**, 1231–1252, https://doi.org/10.1175/JAS3681.1.

Davis, C., and Coauthors, 2004: The Bow Echo and MCV Experiment: Observations and opportunities. *Bull. Amer. Meteor. Soc.*, **85**, 1075–1094, https://doi.org/10.1175/BAMS-85-8-1075.

Doswell, C. A., H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581, https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2.

Durkee, J. D., T. L. Mote, and J. M. Shepherd, 2009: The contribution of mesoscale convective complexes to rainfall across subtropical South America. *J. Climate*, **22**, 4590–4605, https://doi.org/10.1175/2009JCLI2858.1.

Fischer, E. V., and Coauthors, 2021: Leveraging field-campaign networks to identify sexual harassment in atmospheric science and pilot promising interventions. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-19-0341.1, in press.

Geerts, B., and Coauthors, 2017: The 2015 Plains Elevated Convection at Night field project. *Bull. Amer. Meteor. Soc.*, **98**, 767–786, https://doi.org/10.1175/BAMS-D-15-00257.1.

Goodman, S. J., T. J. Schmit, J. Daniels, and R. J. Redmon, Eds., 2019: *The GOES-R Series: A New Generation of Geostationary Environmental Satellites*. Academic Press, 306 pp.

Groenemeijer, P., and Coauthors, 2017: Severe convective storms in Europe: Ten years of research and education at the European Severe Storms Laboratory. *Bull. Amer. Meteor. Soc.*, **98**, 2641–2651, https://doi.org/10.1175/BAMS-D-16-0067.1.

Hamada, A., Y. N. Takayabu, C. Liu, and E. J. Zipser, 2015: Weak linkage between the heaviest rainfall and tallest storms. *Nat. Commun.*, **6**, 6213, https://doi.org/10.1038/ncomms7213.

Herman, G. R., E. R. Nielsen, and R. S. Schumacher, 2018: Probabilistic verification of storm prediction center convective outlooks. *Wea. Forecasting*, **33**, 161–184, https://doi.org/10.1175/WAF-D-17-0104.1.

Houze, R. A., K. L. Rasmussen, M. D. Zuluaga, and S. R. Brodzik, 2015: The variable nature of convection in the tropics and subtropics: A legacy of 16 years of the tropical rainfall measuring mission satellite. *Rev. Geophys.*, **53**, 994–1021, https://doi.org/10.1002/2015RG000488.

Kumjian, M. R., and K. Lombardo, 2020: A hail growth trajectory model for exploring the environmental controls on hail size: Model physics and idealized tests. *J. Atmos. Sci.*, **77**, 2765–2791, https://doi.org/10.1175/JAS-D-20-0016.1.

——, A. P. Khain, N. Benmoshe, E. Ilotoviz, A. V. Ryzhkov, and V. T. J. Phillips, 2014: The anatomy and physics of Z_{DR} columns: Investigating a polarimetric radar signature with a spectral bin microphysical model. *J. Appl. Meteor. Climatol.*, **53**, 1820–1843, https://doi.org/10.1175/JAMC-D-13-0354.1.

——, Y. P. Richardson, T. Meyer, K. A. Kosiba, and J. Wurman, 2018: Resonance scattering effects in wet hail observed with a dual-X-band-frequency, dual-polarization Doppler on Wheels radar. *J. Appl. Meteor. Climatol.*, **57**, 2713–2731, https://doi.org/10.1175/JAMC-D-17-0362.1.

——, and Coauthors, 2020: Gargantuan hail in Argentina. *Bull. Amer. Meteor. Soc.*, **101**, E1241–E1258, https://doi.org/10.1175/BAMS-D-19-0012.1.

Lang, T. J., and Coauthors, 2020: The RELAMPAGO Lightning Mapping Array: Overview and initial comparison with the Geostationary Lightning Mapper. *J. Atmos. Oceanic Technol.*, **37**, 1457–1475, https://doi.org/10.1175/JTECH-D-20-0005.1.

Marengo, J. A., W. R. Soares, C. Saulo, and M. Nicolini, 2004: Climatology of the low-level jet east of the Andes as derived from the NCEP–NCAR reanalyses: Characteristics and temporal variability. *J. Climate*, **17**, 2261–2280, https://doi.org/10.1175/1520-0442(2004)017<2261:COTLJE>2.0.CO;2.

Markowski, P., and Y. Richardson 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley-Blackwell, 430 pp., https://doi.org/10.1002/9780470682104.

Marquis, J. N., A. Varble, P. Robinson, T. C. Nelson, and K. Friederich, 2021: Low-level mesoscale and cloud-scale interactions promoting deep convection initiation. *Mon. Wea. Rev.*, **149**, 2473–2495, https://doi.org/10.1175/MWR-D-20-0391.1.

Martinez, J. A., and F. Dominguez, 2014: Sources of atmospheric moisture for the La Plata River basin. *J. Climate*, **27**, 6737–6753, https://doi.org/10.1175/JCLI-D-14-00022.1.

Matsudo, C. M., and P. Salio, 2011: Severe weather reports and proximity to deep convection over northern Argentina. *Atmos. Res.*, **100**, 523–537, https://doi.org/10.1016/j.atmosres.2010.11.004.

Mezher, R., M. Doyle, and V. Barros, 2012: Climatology of hail in Argentina. *Atmos. Res.*, **114–115**, 70–82, https://doi.org/10.1016/j.atmosres.2012.05.020.

Mulholland, J. P., S. W. Nesbitt, R. J. Trapp, K. L. Rasmussen, and P. V. Salio, 2018: Convective storm life cycle and environments near the Sierras de Córdoba, Argentina. *Mon. Wea. Rev.*, **146**, 2541–2557, https://doi.org/10.1175/MWR-D-18-0081.1.

National Academies of Sciences, Engineering, and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The National Academies Press, 186 pp., https://doi.org/10.17226/21852.

Nelson, T. C., J. Marquis, A. Varble, and K. Friedrich, 2021: Radiosonde observations of environments supporting deep moist convection initiation during RELAMPAGO-CACTI. *Mon. Wea. Rev.*, **149**, 289–309, https://doi.org/10.1175/MWR-D-20-0148.1.

Nesbitt, S. W., R. Cifelli, and S. A. Rutledge, 2006: Storm morphology and rainfall characteristics of TRMM precipitation features. *Mon. Wea. Rev.*, **134**, 2702–2721, https://doi.org/10.1175/MWR3200.1.

Nicolini, M., and A. C. Saulo, 2006: Modeled Chaco low-level jets and related precipitation patterns during the 1997–1998 warm season. *Meteor. Atmos. Phys.*, **94**, 129–143, https://doi.org/10.1007/s00703-006-0186-7.

——, and Y. García Skabar, 2011: Diurnal cycle in convergence patterns in the boundary layer east of the Andes and convection. *Atmos. Res.*, **100**, 377–390, https://doi.org/10.1016/j.atmosres.2010.09.019.

——, C. Saulo, J. C. Torres, and P. Salio, 2002: Strong South American low-level jet events characterization during warm season and implications for enhanced precipitation. *Meteorologica*, **27**, 59–69.

Peters, J. M., and R. S. Schumacher, 2015: The simulated structure and evolution of a quasi-idealized warm-season convective system with a training convective line. *J. Atmos. Sci.*, **72**, 1987–2010, https://doi.org/10.1175/JAS-D-14-0215.1.

Peterson, M. J., Lang, T. J., Bruning, E. C., Albrecht, R., Blakeslee, R. J., Lyons, W. A., et al, 2020: New World Meteorological Organization certified megaflash lightning extremes for flash distance (709 km) and duration (16.73 s) recorded from space. *Geophys. Res. Lett.*, **47**, e2020GL088888, https://doi.org/10.1029/2020GL088888.

Rasmussen, E. N., J. M. Straka, R. Davies-Jones, C. A. Doswell III, F. H. Carr, M. D. Eilts, and D. R. MacGorman, 1994: Verification of the Origins of Rotation in Tornadoes Experiment: VORTEX. *Bull. Amer. Meteor. Soc.*, **75**, 995–1006, https://doi.org/10.1175/1520-0477(1994)075<0995:VOTOOR>2.0.CO;2.

Rasmussen, K. L., and R. A. Houze Jr., 2011: Orogenic convection in subtropical South America as seen by the TRMM satellite. *Mon. Wea. Rev.*, **139**, 2399–2420, https://doi.org/10.1175/MWR-D-10-05006.1.

——, and ——, 2016: Convective initiation near the Andes in subtropical South America. *Mon. Wea. Rev.*, **144**, 2351–2374, https://doi.org/10.1175/MWR-D-15-0058.1.

——, M. D. Zuluaga, and R. A. Houze, 2014: Severe convection and lightning in subtropical South America. *Geophys. Res. Lett.*, **41**, 7359–7366, https://doi.org/10.1002/2014GL061767.

——, M. M. Chaplin, M. D. Zuluaga, and R. A. Houze, 2016: Contribution of extreme convective storms to rainfall in South America. *J. Hydrometeor.*, **17**, 353–367, https://doi.org/10.1175/JHM-D-15-0067.1.

——, M. A. Burt, A. Rowe, R. Haacker, D. Hence, L. M. Luna, S. W. Nesbitt, and J. Maertens, 2021: Enlightenment strikes! Broadening graduate school training through field campaign participation. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-20-0062.1, in press.

Rauber, R. M., and S. W. Nesbitt, 2018: *Radar Meteorology: A First Course*. Wiley, 461 pp.

Ribeiro, B. Z., and L. F. Bosart, 2018: Elevated mixed layers and associated severe thunderstorm environments in South and North America. *Mon. Wea. Rev.*, **146**, 3–28, https://doi.org/10.1175/MWR-D-17-0121.1.

Rosenfeld, D., W. L. Woodley, T. W. Krauss, and V. Makitov, 2006: Aircraft microphysical documentation from cloud base to anvils of hailstorm feeder clouds in Argentina. *J. Appl. Meteor. Climatol.*, **45**, 1261–1281, https://doi.org/10.1175/JAM2403.1.

Rudlosky, S. D., S. J. Goodman, K. S. Virts, and E. C. Bruning, 2018: Initial geostationary lightning mapper observations. *Geophys. Res. Lett.*, **46**, 1097–1104, https://doi.org/10.1029/2018GL081052.

Salio, P., M. Nicolini, and A. C. Saulo, 2002: Chaco low-level jet events characterization during the austral summer season. *J. Geophys. Res.*, **107**, 4816, https://doi.org/10.1029/2001JD001315.

——, M. Nicolini, and E. J. Zipser, 2007: Mesoscale convective systems over southeastern South America and their relationship with the South American low-level jet. *Mon. Wea. Rev.*, **135**, 1290–1309, https://doi.org/10.1175/MWR3305.1.

São Sabbas, F., and Coauthors, 2017: LEONA for TLE and HEET research in South America. *2017 Fall Meeting*, New Orleans, LA, Amer. Geophys. Union, Abstract AE21A-05.

Saulo, A. C., M. E. Seluchi, and M. Nicolini, 2004: A case study of a Chaco low-level jet event. *Mon. Wea. Rev.*, **132**, 2669–2683, https://doi.org/10.1175/MWR2815.1.

——, J. Ruiz, and Y. G. Skabar, 2007: Synergism between the low-level jet and organized convection at its exit region. *Mon. Wea. Rev.*, **135**, 1310–1326, https://doi.org/10.1175/MWR3317.1.

Schmit, T. J., P. Griffith, M. M. Gunshor, J. M. Daniels, S. J. Goodman, and W. J. Lebair, 2017: A closer look at the ABI on the GOES-R series. *Bull. Amer. Meteor. Soc.*, **98**, 681–698, https://doi.org/10.1175/BAMS-D-15-00230.1.

——, S. S. Lindstrom, J. J. Gerth, and M. M. Gunshor, 2018: Applications of the 16 spectral bands on the Advanced Baseline Imager (ABI). *J. Oper. Meteor.*, **06**, 33–46, https://doi.org/10.15191/nwajom.2018.0604.

Schumacher, R. S., 2015: Sensitivity of precipitation accumulation in elevated convective systems to small changes in low-level moisture. *J. Atmos. Sci.*, **72**, 2507–2524, https://doi.org/10.1175/JAS-D-14-0389.1.

——, and Coauthors, 2021: Convective-storm environments in subtropical South America from high-frequency soundings during RELAMPAGO-CACTI. *Mon. Wea. Rev.*, **149**, 1439–1458, https://doi.org/10.1175/MWR-D-20-0293.1.

Seluchi, M. E., A. C. Saulo, M. Nicolini, and P. Satyamurty, 2003: The northwestern Argentinean low: A study of two typical events. *Mon. Wea. Rev.*, **131**, 2361–2378, https://doi.org/10.1175/1520-0493(2003)131<2361:TNALAS>2.0.CO;2.

Shapiro, M. A., 1981: Frontogenesis and geostrophically forced secondary circulations in the vicinity of jet stream-frontal zone systems. *J. Atmos. Sci.*, **38**, 954–973, https://doi.org/10.1175/1520-0469(1981)038<0954:FAGFSC>2.0.CO;2.

Soderholm, J. S., M. R. Kumjian, N. McCarthy, P. Maldonado, and M. Wang, 2020: Quantifying hail size distributions from the sky – Application of drone aerial photogrammetry. *Atmos. Meas. Tech.*, **13**, 747–754, https://doi.org/10.5194/amt-13-747-2020.

Spuler S., K. Repasky, B. Morley, D. Moen, T. Weckwerth, M. Hayman, and A. Nehrir, 2015: Advances in diode-laser-based lidar for profiling atmospheric water vapor. *OSA Tech. Dig.*, ATu4J.7, https://doi.org/10.1364/CLEO_AT.2015.ATu4J.7.

Thompson, R. L., B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments. *Wea. Forecasting*, **27**, 1136–1154, https://doi.org/10.1175/WAF-D-11-00116.1.

Trapp, R. J., 2013: *Mesoscale-Convective Processes in the Atmosphere*. Cambridge University Press, 346 pp, https://doi.org/10.1017/CBO9781139047241.

——, N. S. Diffenbaugh, H. E. Brooks, M. E. Baldwin, E. D. Robinson, and J. S. Pal, 2007: Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA*, **104**, 19 719–19 723, https://doi.org/10.1073/pnas.0705494104.

——, and Coauthors, 2020: Multiple-platform and multiple-Doppler radar observations of a supercell thunderstorm in South America during RELAMPAGO. *Mon. Wea. Rev.*, **148**, 3225–3241, https://doi.org/10.1175/MWR-D-20-0125.1.

van der Ent, R. J., H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne, 2010: Origin and fate of atmospheric moisture over continents. *Water Resour. Res.*, **46**, W09525, https://doi.org/10.1029/2010WR009127.

Varble, A., and Coauthors, 2021: Utilizing a storm-generating hotspot to study convective cloud transitions: The CACTI experiment. *Bull. Amer. Meteor. Soc.*, **102**, E1597–E1620, https://doi.org/10.1175/BAMS-D-20-0030.1.

Velasco, I., and J. M. Fritsch, 1987: Mesoscale convective complexes in the Americas. *J. Geophys. Res.*, **92**, 9591–9613, https://doi.org/10.1029/JD092iD08p09591.

Vera, C., and Coauthors, 2006: The South American Low-Level Jet Experiment. *Bull. Amer. Meteor. Soc.*, **87**, 63–78, https://doi.org/10.1175/BAMS-87-1-63.

Vidal, L., 2014: Extreme convection over South America: Internal structure, life cycles and influence of topography on initiation. Ph.D. thesis, Faculty of Exact and Natural Sciences, University of Buenos Aires, 106 pp., http://hdl.handle.net/20.500.12110/tesis_n5573_Vidal.

Weckwerth, T. M., K. J. Weber, D. D. Turner, and S. M. Spuler, 2016: Validation of a Water Vapor Micropulse Differential Absorption Lidar (DIAL). *J. Atmos. Oceanic Technol.*, **33**, 2353–2372, https://doi.org/10.1175/JTECH-D-16-0119.1.

Wilson, J. W., and C. K. Mueller, 1993: Nowcasts of thunderstorm initiation and evolution. *Wea. Forecasting*, **8**, 113–131, https://doi.org/10.1175/1520-0434(1993)008<0113:NOTIAE>2.0.CO;2.

Wurman, J., J. Straka, E. Rasmussen, M. Randall, and A. Zahrai, 1997: Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar. *J. Atmos. Oceanic Technol.*, **14**, 1502–1512, https://doi.org/10.1175/1520-0426(1997)014<1502:DADOAP>2.0.CO;2.

——, D. Dowell, Y. Richardson, P. Markowski, E. Rasmussen, D. Burgess, L. Wicker, and H. B. Bluestein, 2012: The Second Verification of the Origins of Rotation in Tornadoes Experiment: VORTEX2. *Bull. Amer. Meteor. Soc.*, **93**, 1147–1170, https://doi.org/10.1175/BAMS-D-11-00010.1.

——, and Coauthors, 2021: The FARM (Flexible Array of Radars and Mesonets). *Bull. Amer. Meteor. Soc.*, **102**, E1499–E1525, https://doi.org/10.1175/BAMS-D-20-0285.1.

Zhu, Y., and Coauthors, 2020: Huntsville Alabama Marx Meter Array 2: Upgrade and capability. *Earth Space Sci.*, **7**, e2020EA00111, https://doi.org/10.1029/2020EA001111.

Zipser, E. J., C. Liu, D. J. Cecil, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Amer. Meteor. Soc.*, **87**, 1057–1072, https://doi.org/10.1175/BAMS-87-8-1057.