

Characteristics of Hail Events near the Sierras de Córdoba, Argentina

Jeremiah Piersante

Academic Affiliation, Fall 2017: Senior, Hobart and William Smith Colleges

SOARS ® Summer 2017

Science Research Mentors: Deanna Hence, Sarah Tessendorf, Roy Rasmussen

Writing and Communication Mentor: Annareli Morales

Computing Mentor: Bill Anderson

Coach: Ran Feng

Peer Mentor: Amy Chen

ABSTRACT

Argentina is a global hotspot for severe hailstorms, especially within the vicinity of the Andes Mountains and the Sierras de Córdoba. This hail activity results in substantial damage and economic loss in both urban areas and farms in the region. The RELAMPAGO (Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations) field campaign, which will take place during the austral summer of 2018, aims to deepen the understanding of the lifecycle of the region's convective storms through direct observations. To assist in locating equipment and personnel for the project, this study presents a hail climatology which addresses the diurnal, annual, and spatial patterns of the region's hail as well as trends in hail size and the type of damage. Thirty years of meteorological surface station data between 1 June 1987 and 31 May 2017 from 20 stations in the Mendoza, San Luis, and Córdoba provinces were supplemented with online newspaper and social media reports from 1 June 2013 to 31 May 2017. Both datasets show that hail reports peaked in the summer for Mendoza and San Luis, but this peak occurred in the spring for Córdoba, which was the province with the most hail reports. The two datasets disagree on the time of day hail most frequently occurred, however. The combined effects of topography and population likely influenced the spatial distribution of hail reports. This, in addition to the role of population density in hail reporting, highlights the potential for bias among the results.

This work was performed under the auspices of the Significant Opportunities in Atmospheric Research and Science Program. SOARS is managed by the University Corporation for Atmospheric Research and is funded by the National Science Foundation, the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, the Woods Hole Oceanographic Institute, the Constellation Observing System for Meteorology, Ionosphere, and Climate and the University of Colorado at Boulder.

1. Introduction

South America is home to some of the most intense convection on the planet. The first global climatology of tornadoes established initial recognition of the continent's potential for severe weather (Fujita 1973). Modern global analysis using the Tropical Rainfall Measuring Mission (TRMM) satellite confirmed this potential while also highlighting Argentina and the foothills of the Andes Mountains as the most frequent location of deep convection (Zipser et al. 2006). The combined influences of the diurnal cycle and complex topography likely explain the recurrent severe weather events in the region (Romatschke and Houze 2010). Topographic influences are not limited to the Andes Mountains, however. Rasmussen and Houze (2011) found that wide convective core (WCC) storms are most common in north-central Argentina, often forming near the Sierras de Córdoba.

Commonly associated with WCC storms (Rasmussen et al. 2014), hailstorms are perhaps the most destructive result of Argentina's deep convection. The grape yield of the Mendoza Province, Argentina's largest wine-producing region, is dependent on the amount and type of precipitation that occurred in the summer prior to the current harvest. Thus hail, particularly in January and March, causes partial or total damages before crops have fully developed (Agosta et al. 2012). Because hail events peak in the summer followed by the spring (Mezher et al. 2012), agricultural losses are common. Mendoza averaged 18,565 ha of crops damaged by hail from the 2004/05 season to 2015/16 (DACC 2016). Although this average has been decreasing in recent decades due to innovations designed to combat the impacts of hail, the number of severe storms has not. There was an average of 184 storm cells in Mendoza throughout this same timeframe with 331 and 316 during the 2014/15 and 2015/16 seasons, respectfully (DACC 2016). To help the producers with these damages, the province was granted 30 million Argentine pesos (approximately 1.9 million U.S. dollars) in 2016 (Naineck 2016).

Cecil and Blankenship (2011) in a global hail climatology illustrated that northern Argentina has one of the highest hailstorm rates per area. These events typically occur in the mountainous (30-40°S) and coastal regions with two maxima in Mendoza and Córdoba (Mezher et al. 2012). Furthermore, substantial hail events are reported along the Andes foothills and the Sierras de Córdoba (Rasmussen et al. 2014). Case studies of three severe hail events in Mendoza reveal that mountain waves often act as trigger mechanisms, further recognizing the importance of topography (De la Torre et al. 2011). Because Mendoza's crop output heavily depends on hail, Herrera (2000) analyzed hail event patterns in the northern oasis, the primary area for agriculture in the province. He found that from 1887-1986, reports of hail events were most frequent in the south while the spatial distribution of hail event intensity lacked a clear pattern. Both Herrera (2000) and Rasmussen et al. (2014) relied on various newspaper reports to pinpoint the location and intensity of each event, with the latter also using Precipitation Radar (PR) data from TRMM.

It is clear that the Andes Mountains and Sierras de Córdoba have a substantial influence in producing and positioning hail events in Argentina. García-Ortega et al. (2009) also recognized the role of solar radiation as they found that convection with intense precipitation, including hail, peaks in the late afternoon and late evening. However, they concluded that topography is the primary trigger mechanism, explaining why they observed many hail events throughout the night. Because no relationship between the location and size of hail with respect to these mountain ranges and the diurnal cycle has been established, this current study provides a climatology of hail in the vicinity of these mountain ranges. Since surface stations in the regions are scarce, data is supplemented by a combination newspaper reports and social media.

This research serves as a preliminary hail investigation for the Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) field campaign which will take place in 2018. Its objective is to deepen the understanding of severe weather in South America by analyzing its rarely observed deep convection near the Sierras de Córdoba (Córdoba study region; Fig. 1a) and the Andes Mountains (Mendoza study region; Fig. 1b). Our results will help properly position equipment and personnel by detecting trends in the spatial distribution and diurnal cycle of hail. RELAMPAGO is made possible by the joint collaboration of various organizations from the U.S., Argentina, Brazil, and Chile.

2. Methodology

To analyze the spatial distribution and diurnal cycle of hail, two datasets were used to identify hail events: meteorological surface station data (1 June 1987 - 31 May 2017) and online newspaper/social media reports (1 June 2013 - 31 May 2017). Only reports from the Mendoza, San Luis, and Córdoba provinces (Fig. 2) were included as these are the provinces whose weather is most directly impacted by the two mountain ranges.

2a. Surface station data

With data obtained from the National Centers for Environmental Information (NCEI; online at: <https://gis.ncdc.noaa.gov/maps/ncei/cdo/hourly>), we examined 20 meteorological surface stations (Table 1) for hail reports distributed throughout the region of interest from 1 June 1987 to 31 May 2017. There are gaps in data for 7 of the 20 stations throughout the timeframe; these instances are noted in Table 1.

This study focused on eleven elements included with station hail reports: location, time, air temperature, dewpoint temperature, wind direction, wind speed, hail, past weather observation summary of day, present weather automated, present weather automated occurrence (ASOS/AWOS only), and present weather observation manual. The last five elements indicate if hail of any type occurred while the first six provide background information about the report. It is possible that hail events were not reported simply because the stations do not cover every area of the region. We discuss this and other limitations of this study in section four.

2b. Online report data

Unlike surface station data, online storm reports from social media and newspapers are not fixed to a specific location; we counted the number of hail report days for each department (county) of Mendoza, San Luis, and Córdoba using these nonconventional sources. This combination of the two datasets allowed for a more robust analysis of hail reports within the region. Both Herrera (2000) and Rasmussen et al. (2014) used newspapers to collect hail data in Argentina. Since many Twitter users report hail with descriptions, images, and/or links to external newspaper articles, the keywords “granizo” (Spanish for hail) and “Argentina” were used to search for tweets from 1 June 2013 to 31 May 2017. When possible, information from multiple reports of the same event were combined.

Newspaper and social media reports were considered only if the date/time and province of the event were given. Additional elements included: part of day (morning, afternoon, night), province, department, size, source type, URL, and date of access. Exact measurements of some elements, such as size, were not always included in the online reports and had to be assessed based on images if possible. For example, tweets often included a common object such as a golf ball for scale. Thus, it was necessary to assign index values with predetermined ranges. Table 2 provides the index values and their descriptions for size, part of day, and source type. Often, however, online reports did not always include an element; in this case, the element could not be considered. These limitations are discussed in section four.

3. Results

Surface station and online report data identify various temporal and spatial distribution hail patterns. This section also addresses trends of reported hail sizes and some environmental conditions at the time of hail events. Results from the two datasets are presented separately but analyzed in tandem in section four.

3a. Temporal Distribution

Part of this study was to identify when, with respect to the annual and diurnal cycles, hail events are most frequently reported. Seasons in the Southern Hemisphere are as follows: spring consists of September, October, November; summer is December, January, February; autumn is March, April, May; winter is June, July, August. Based solely on surface station data, hail reports were most frequent in the summer followed by the spring with the Córdoba province maximizing in both seasons (Fig. 3). The same trend is evident from with the online reports (Fig. 4).

Each hail report from the surface stations included the exact time of day. The diurnal cycle was divided into four six-hour segments starting at 12am local time to identify the times of day hail was reported most. According to this dataset, 6pm-12am had the most reports followed by 12pm-6pm while the morning hours of 6am-12pm had the fewest (Fig. 5). On the other hand, online hail reports maximized during the afternoon hours, 12pm-8pm (Fig. 6). One limitation of online reports is that specific times are not always included. Thus, we sorted reports based on the generic times of day of “morning” (4am-12pm), “afternoon” (12pm-8pm), and “night” (8pm-4am). This means that the “afternoon” category overlaps two hours into the 6pm-12am segment of the surface station dataset. This time overlap complicates direct comparison between these two results.

3b. Spatial Distribution

The location of hail reports differed for each dataset; surface station reports are limited to the locations of stations whereas online reports could be from anywhere. Throughout the 30 year timeframe, stations located within the capital city of each province had the most reports: Ambrosio L V Taravella (Córdoba), San Luis (San Luis), and El Plumerillo (Mendoza), respectfully (Fig. 7). Two stations in southern Mendoza along the Andes Mountains (Malargue and San Rafael) had the second highest number of reports (Table 3).

Dividing the spatial distribution relative to the diurnal cycle revealed common locations of hail reports throughout the day. From 12am-6am, hail was most frequent in San Luis and Córdoba (Fig. 8a). San Luis stations decreased in reports the most moving into 6am-12am, leaving Córdoba with the most at this time (Fig. 8b). These shifts in location show that hail reports were most common in the eastern side of the region during the first 12 hours of the day. Hail reports became more frequent more in the west in Mendoza throughout the afternoon and evening hours (Fig. 8c-d).

There was, however, substantial variation in results between stations within close proximity. The four stations all within 60km of the capital city of Córdoba is a clear example (Fig. 7); Ambrosio L V Taravella reported over six times more events than any of the other three (Table 4). This station was also the only to show the typical diurnal cycle (Fig. 9a). A similar trend occurred with stations in Mendoza. El Plumerillo, Malargue, and San Rafael reported the most hail events, clearly demonstrating the expected diurnal pattern (Fig. 9b). These three stations are spread throughout the province (Fig. 7) so the remaining four are relatively close to at least one; however, they reported much fewer events and do not have the expected diurnal trend (Fig. 9b).

Since online reports are not fixed to locations like stations, we counted the number of days with hail reports in the departments of each province. The three most frequent departments were in Córdoba, the first being the capital department (Fig. 10). The next three consisted of two in Mendoza and one in San Luis. Departments of western Mendoza, closer to the Andes Mountains, received more reports than the departments of eastern Mendoza. Similarly, departments just east of the Sierras de Córdoba received more reports than those to the north and further east. The distribution of hail reports is very similar to population density (Fig. 11), where five of the six aforementioned departments have at least 10 people per km². This spatial distribution suggests that the more populated areas report hail more frequently.

3c. Hail Size

All information regarding hail size came from the online report dataset because surface stations did not provide the diameter. Of the 180 events reported online, only 80 provided the size of hail, with Córdoba departments the most frequent (Table 5). Golf ball/egg sized hail was the most reported followed by quarter sized (Fig. 12). This does not necessarily mean that these sizes were the most frequent rather the most frequently reported.

3d. Environmental Conditions

Surface station reports also included temperature, dewpoint temperature, and wind direction. The distributions of these variables are illustrated by time of day and province in boxplots (Fig. 13). Temperatures resemble the diurnal heating cycle with highest values in the afternoon and evening hours (Fig. 13a). Mendoza and San Luis peaked in the evening but Córdoba peaked in the afternoon. No province seemed to be the greatest or smallest for each time of day. However, Córdoba had the highest dewpoint temperatures for all four times of day (Fig. 13b). Mendoza tended to be the driest except for the afternoon hours. Finally, a common pattern across all provinces and times of day was wind direction where winds were mainly at 180°, or southerly (Fig. 13c).

4. Discussion

The results of this study outline the location and timing of hail reports, the hail sizes typically reported, and several environmental conditions associated with hail events within Mendoza, San Luis, and Córdoba. Seasonally, both the surface station and the online reports peaked during the summer followed by spring. Mezher et al. (2012) found the same for Argentina as a whole. This means that the region of focus for this study is broad enough to match the trends of a larger region.

The two datasets did not completely agree with diurnal cycle trends, however: surface stations most frequently reported hail from 6pm-12am where online reports were most common in the afternoon hours, 12pm-8pm. This disagreement gives rise to the possibility of human-based reporting bias; people are likely to report more hail during the day because they are awake and/or more easily able to recognize its impacts. This nonconventional source also has some limitations. Because specific times were not always provided in online reports, reports were divided into three eight-hour periods: morning, afternoon, and night. This “afternoon” period for online reports overlaps with the 6pm-12am segment for the station data, further adding to the ambiguity at the transition from afternoon to evening. Interestingly, the combined results of these two datasets align with the findings of Cecil and Blankenship (2011) who determined that hailstorms in northern Argentina peak during 3pm-12am.

The spatial distribution of the surface station dataset illustrated that stations in populated areas east of one of the two mountain ranges reported the most hail (Fig. 7). A drawback to this is the substantial variation among neighboring stations. Since reports at stations are done manually, this could simply be a result of no one being present during an event. Showing these results in six-hour increments illustrated an eastward progression of hail report frequency from the evening hours into the night and early morning. Rasmussen et al. (2014) found a similar trend using lightning rates within TRMM-identified convective cores: storms within 36°S-28°S during the evening hours before 12am were present closer to the Andes Mountains then shifted eastward towards the longitude of the Sierras de Córdoba. This previous study also highlighted the role of the have mountains in forming terrain-locked back-building Mesoscale Convective Systems (MCSs). From our results, it seems likely that MCSs influence the diurnal distribution of hail in the region as well.

The online report data allowed for a more holistic spatial distribution because the number of reports was counted for each department rather than a fixed station. Mendoza departments along the Andes Mountains and Córdoba departments just east of the Sierras de Córdoba reported the most hail (Figs. 10 & 11). This distribution is strongly correlated to population which suggests that, in addition to the influence of mountains, areas with more people report more hail. This result in tandem with the surface station distribution shows that the capital region of Córdoba, located just east of the Sierras de Córdoba, will serve as the most consistent location for RELAMPAGO.

Although golf ball/egg sized hail was the most frequently reported, it cannot be concluded that hail in this region is most typically this size. This result suggests that there is human-based reporting bias towards larger, more damaging, and ultimately more interesting hail. In the end, online reports from Twitter and newspapers do not accurately capture the distribution of hail size.

The diurnal variation of temperature for the three provinces largely reflects the diurnal heating cycle as temperatures peak in the afternoon and evening. Dewpoint temperature was the greatest in Córdoba for all times of the day. It is possible that moisture leads to more hail events since Córdoba reported the most. Mendoza had the least moisture overall, but this difference can be due to the elevation of Mendoza being much greater than that of Córdoba. The almost universal southerly direction of surface wind is supported by Mezher et al. (2012) which indicate positive anomalies in the 925 hPa meridional wind direction during hail events for most of our region of interest. Interestingly, however, they observed a northerly wind anomaly within the vicinity of the Sierras de Córdoba. It is likely that the northerly low-level jet transports warmer, moister air into the region, juxtaposing the drier air from the south. Further investigation on a smaller scale is required to make certain conclusions.

5. Conclusions and Future Work

According to 30 years of surface station data and 4 years of online reports within the Argentine provinces of Mendoza, San Luis, and Córdoba, hail reports most frequently occurred in the summer followed by the spring with reports peaking in the evening and afternoon. The most reliable location for hail reports was the greater capital region of Córdoba, just east of the Sierras de Córdoba. Although these results show that more hail reports occurred east of the Andes Mountains and the Sierras de Córdoba, there are other factors that could influence the location and timing of reports. These results suggested that a bias in human-based reporting contributes to more reports during the day and in areas of greater population. Similarly, the reported hail sizes online do not accurately reflect the actual distribution of hail size. Another limitation to this study was the substantial variation among neighboring stations, possibly due to the absence of workers during a hail event, because these stations were active at the same times.

Unfortunately, there is little that can be done to account for the various biases in this study. To help future research projects like RELAMPAGO, Argentina needs a more effective method of severe weather reporting that engages more citizens and makes more data accessible such as CoCoRaHS. Much remains to be learned about the differences in dynamics and environmental conditions between the Andes and Sierras de Córdoba. Comparing soundings on hail days and non-hail days at these locations in addition to examining multiple damaging cases via radar, satellite, and ground reports will paint a better picture of where and when these storms occur.

6. Acknowledgements

This work was performed under the auspices of the Significant Opportunities in Atmospheric Research and Science Program. SOARS is managed by the University Corporation for Atmospheric Research and is funded by the National Science Foundation, the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, the Woods Hole Oceanographic Institute, the Constellation Observing System for Meteorology, Ionosphere, and Climate and the University of Colorado at Boulder. I would like to thank my research mentors Sarah Tessendorf, Deanna Hence, and Roy Rasmussen, as well as my computing mentor and coach, Bill Anderson and Ran Feng, for all their help this summer. Thank you to Jake Mulholland at UIUC for creating two key figures.

REFERENCES

- Agosta, E., P. Canziani, and M. Cavagnaro, 2012: Regional climate variability impacts on the annual grape yield in Mendoza, Argentina. *J. Appl. Meteor. Climatol.*, **51**, 993-1009.
- 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.
- De la Torre, A., R. Hierro, P. Llamedo, A. Rolla, and P. Alexander, 2011: Severe hailstorms near the Southern Andes in the presence of mountain waves. *Atmos. Res.*, **101**, 112-123.
- Dirección de Agricultura y Contingencias Climáticas, 2016: Evolución de superficie afectada por granizo (al 100%) Provincia de Mendoza. Mendoza Nuevo Gobierno: Ministerio de Economía, Infraestructura, y Energía. Accessed 7 June 2017. [Available online at <http://www.contingencias.mendoza.gov.ar/web1/pdf/Gr%C3%A1ficos%20para%20la%20web.pdf>.]
- Dirección de Agricultura y Contingencias Climáticas, 2016: Número de células de tormenta severas en áreas cultivadas de Mendoza – período 2004-2005 a 2015-2016. Mendoza Nuevo Gobierno: Ministerio de Economía, Infraestructura, y Energía. Accessed 7 June 2017. [Available online at <http://www.contingencias.mendoza.gov.ar/web1/pdf/Gr%C3%A1ficos%20para%20la%20web.pdf>.]
- Fujita, T. T., 1973: Tornadoes around the world. *Weatherwise*, **26**, 56-83.
- García-Ortega, E., L. López, and J. L. Sánchez, 2009: Diagnosis and sensitivity study of two severe storm events in the Southeastern Andes. *Atmos. Res.*, **93**, 161-178.
- Herrera, R. G., 2000: Distribución espacial del granizo en el norte de la provincia de Mendoza, Argentina. *Geo Crítica*, **IV**, 1-25.
- Mezher, R. N., M. Doyle, and V. Barros, 2012: Climatology of hail in Argentina. *Atmos. Res.*, **114-115**, 70-82.
- Naineck Prensa Digital, 2016: Mendoza: Otorgan \$30 millones para asistir a productores afectados por granizo. Accessed 19 June 2017. [Available online at <http://www.naineckprensadigital.com/mendoza-otorgan-30-millones-para-asistir-a-productores-afectados-por-granizo/>]
- Rasmussen, K. L., M. D. Zuluaga, and R. A. Houze Jr., 2014: Severe convection and lightning in subtropical South America. *Geophys. Res. Lett.*, **40**, 7359-7366.
- Rasmussen, K. L. and R. A. Houze, 2011: Orographic convection in subtropical South America as seen by the TRMM satellite. *Mon. Wea. Rev.*, **139**, 2399-2420.

Romatschke, U. and R. A. Houze, 2010: Extreme summer convection in South America. *J. Clim.*, **23**, 3761-3791.

Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Am. Meteorol. Soc.*, **87**, 1057-1071.

Tables and Figures

Table 1. List of surface stations with their location, period of record, and province (M for Mendoza, S for San Luis, and C for Córdoba).

| Station Name | Latitude (degrees) | Longitude (degrees) | Elevation (meters) | Period of Record | Province |
|-----------------------------|--------------------|---------------------|--------------------|-------------------|----------|
| Ambrosio L V Taravella | -31.324 | -64.208 | 488.9 | Complete | C |
| Cordoba Observatorio | -31.4 | -64.183 | 426 | 2008/09 - 2017/03 | C |
| Escuela de Aviacion Militar | -31.445 | -64.283 | 502 | 2001/09 - 2017/05 | C |
| Marcos Juarez | -32.684 | -62.158 | 110 | Complete | C |
| Pilar Observatorio | -31.667 | -63.883 | 338 | Complete | C |
| Rio Cuarto Area de Material | -33.085 | -64.261 | 420.9 | Complete | C |
| Villa Dolores | -31.945 | -65.146 | 583.7 | Complete | C |
| Villa Mara del Rio | -29.9 | -63.683 | 341 | Complete | C |
| Laboulaye | -34.135 | -63.362 | 136.9 | Complete | C |
| El Plumerillo | -32.832 | -68.793 | 704.1 | Complete | M |
| Malargue | -35.494 | -69.574 | 1430.1 | Complete | M |
| Mendoza Observatorio | -32.883 | -68.85 | 827 | Complete | M |
| San Carlos | -33.767 | -69.033 | 940 | 1973/01 - 2017/03 | M |
| San Martin | -33.083 | -68.417 | 653 | 1973/01 - 2017/03 | M |
| San Rafael | -34.588 | -68.403 | 752.9 | Complete | M |
| Uspallata | -32.6 | -69.333 | 1844 | 1973/01 - 2017/03 | M |
| San Luis | -33.273 | -66.356 | 709.9 | Complete | S |
| Santa Rosa de Conlara | -32.383 | -65.183 | 615 | 2007/06 - 2017/03 | S |
| Valle Del Conlara | -32.385 | -65.187 | 616 | 2004/08 - 2017/04 | S |
| Villa Reynolds | -33.73 | -65.387 | 484.9 | Complete | S |

Table 2. Indices used for elements in online reports that did not necessarily provide specific values.

| Index | Size | Part of Day | Source |
|-------|---|----------------------|-----------------------------|
| 1 | Pea size or smaller: $\sim < 0.65\text{cm}$ | Morning (4am-12pm) | Online newspaper |
| 2 | Dime-penny size: $\sim 1.00\text{-}2.00\text{cm}$ | Afternoon (12pm-8pm) | Social Media (i.e. Twitter) |
| 3 | Quarter-half dollar: $\sim 2.50\text{-}3.10\text{cm}$ | Night (8pm-4am) | - |
| 4 | Golf ball-pool ball: $\sim 3.80\text{-}5.40\text{cm}$ | - | - |
| 5 | Baseball or larger: $\sim > 6.50\text{cm}$ | - | - |
| 99 | Unknown | Unknown | Unknown |

Table 3. Total number of hail reports from the top five stations between 1 June 1987 and 31 May 2017. Provinces labeled as: M is Mendoza, S is San Luis, and C is Córdoba.

| Station Name | Province | Total Reports |
|------------------------|----------|---------------|
| Ambrosio L V Taravella | C | 64 |
| San Luis | S | 64 |
| El Plumerillo | M | 41 |
| Malargue | M | 39 |
| San Rafael | M | 32 |

Table 4. Total number of reports as recorded by the four stations within 60km of the capital city of Córdoba.

| Station | Reports |
|-----------------------------|---------|
| Ambrosio L V Taravella | 64 |
| Cordoba Observatorio | 0 |
| Escuela de Aviacion Militar | 3 |
| Pilar Observatorio | 10 |

Table 5. Number of online reports per province: total and those with hail size provided.

| Province | Total Reports | Reports with Hail Size |
|---------------|---------------|------------------------|
| All Provinces | 189 | 80 |
| Mendoza | 54 | 19 |
| San Luis | 32 | 12 |
| Córdoba | 103 | 49 |

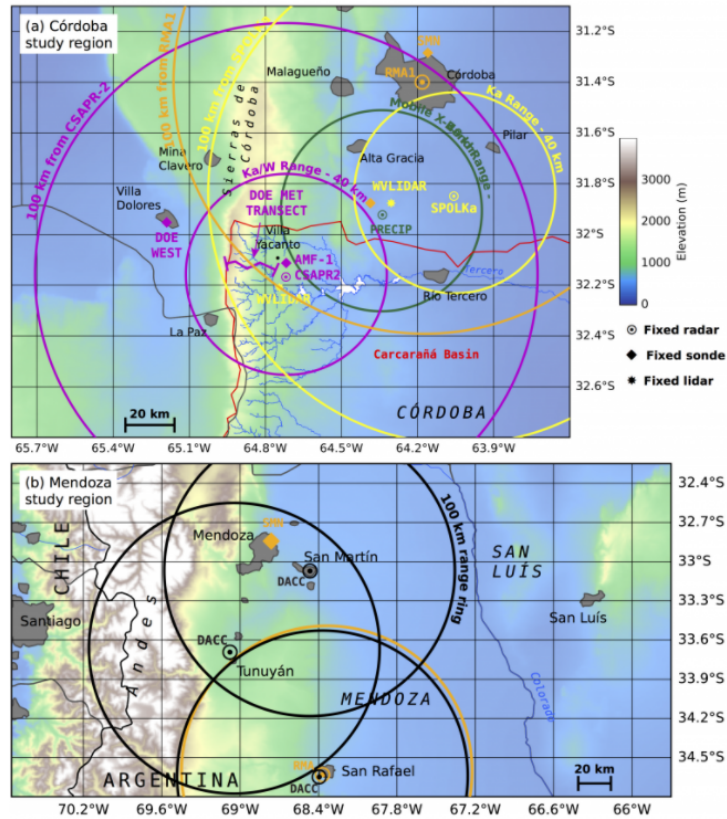


Figure 1. The Córdoba (a) and Mendoza (b) study regions for RELAMPAGO. Elevation (meters), cities, and ground instrument locations are shown. This image was taken from the RELAMPAGO information website (<https://publish.illinois.edu/relampago/>).

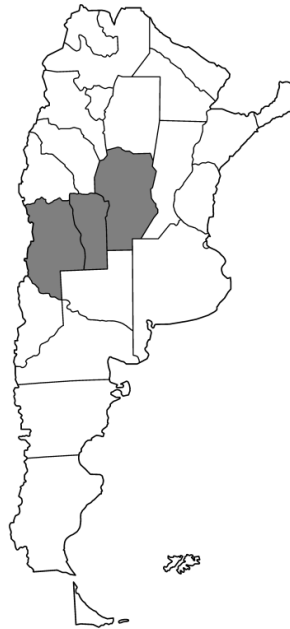


Figure 2. Map of Argentina with the three provinces examined for this study. From left to right: Mendoza, San Luis, Córdoba.

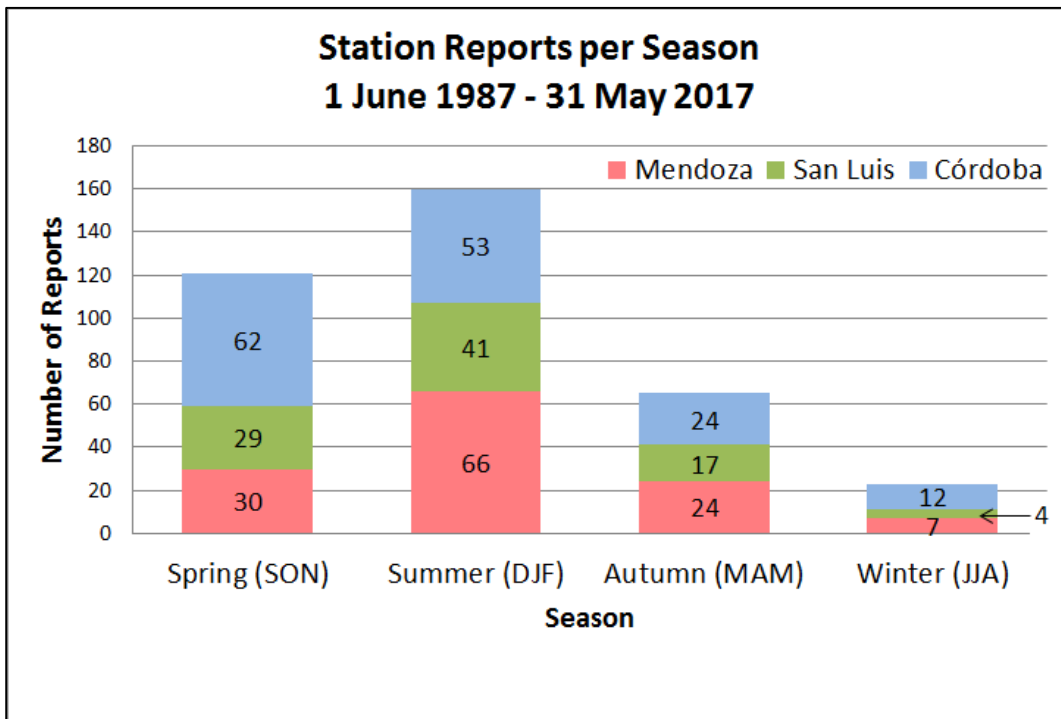


Figure 3. Number of hail reports per austral season among surface stations in Mendoza (red), San Luis (green), and Córdoba (blue) between 1 June 1987 and 31 May 2017.

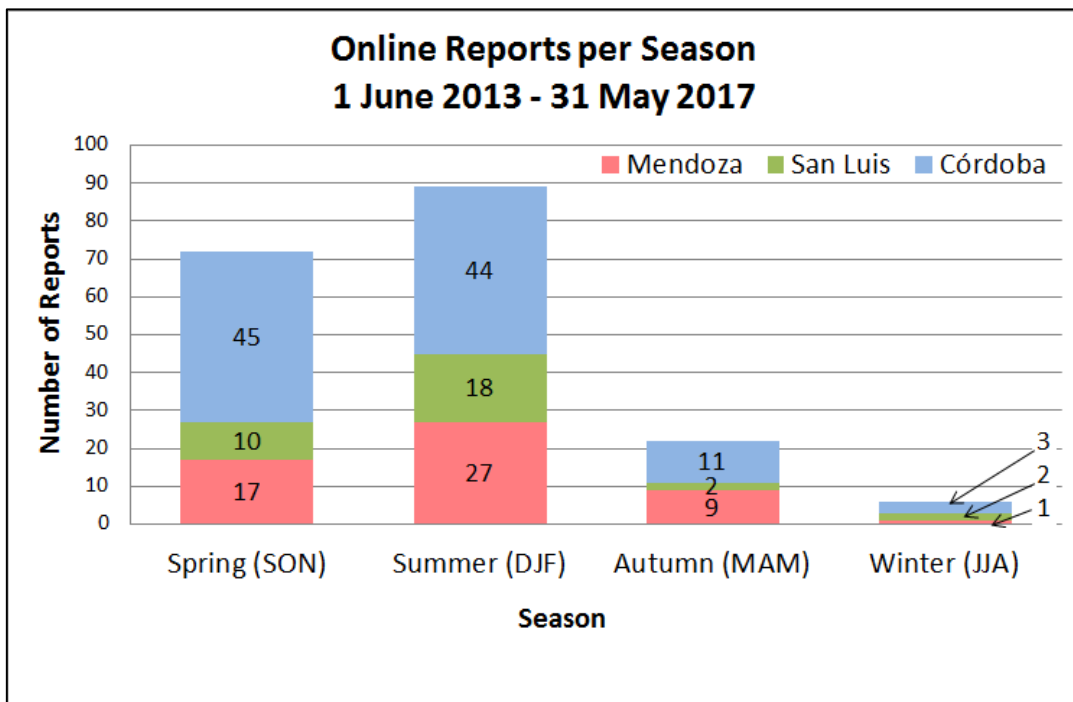


Figure 4. Number of hail reports per austral season from online social media and newspaper reports between 1 June 2013 and 31 May 2017. Hail was reported from the three provinces Mendoza (red), San Luis (green), and Córdoba (blue).

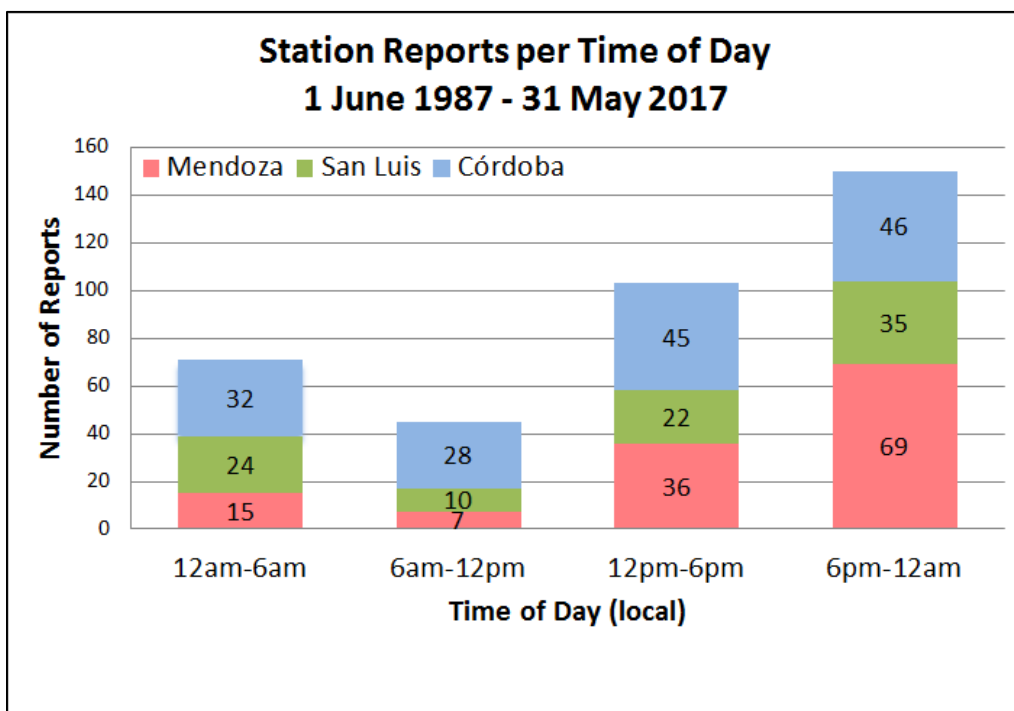


Figure 5. Number of hail reports per local time of day among surface stations in Mendoza (red), San Luis (green), and Córdoba (blue) between 1 June 1987 and 31 May 2017.

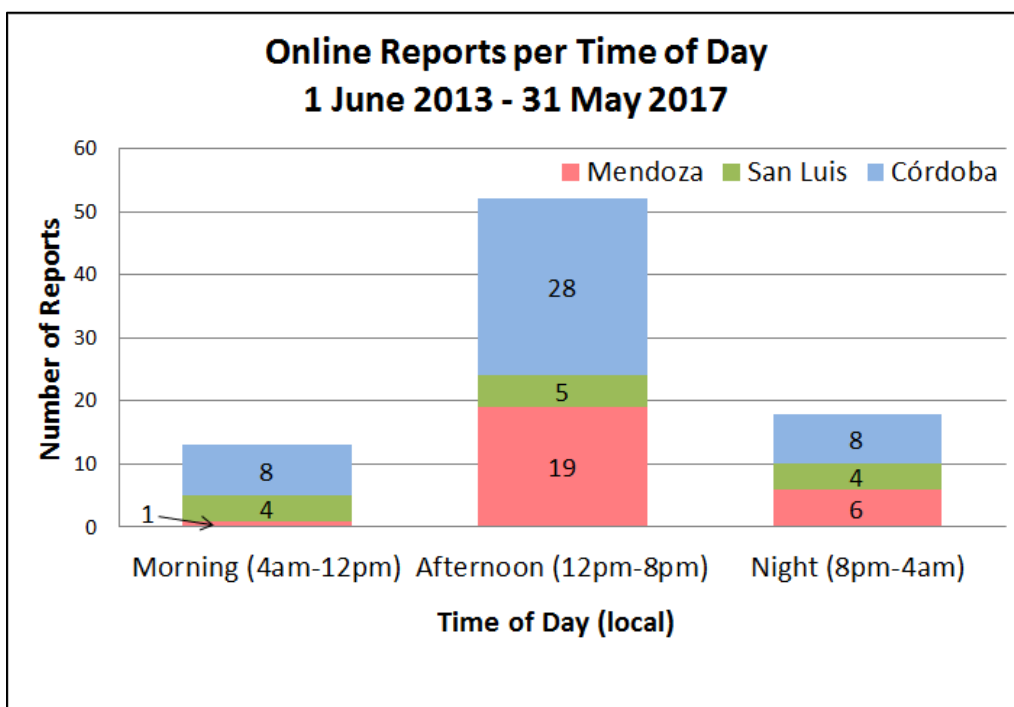


Figure 6. Number of hail reports per local time of day from online social media and newspaper reports between 1 June 2013 and 31 May 2017. Hail was reported from the three provinces Mendoza (red), San Luis (green), and Córdoba (blue).

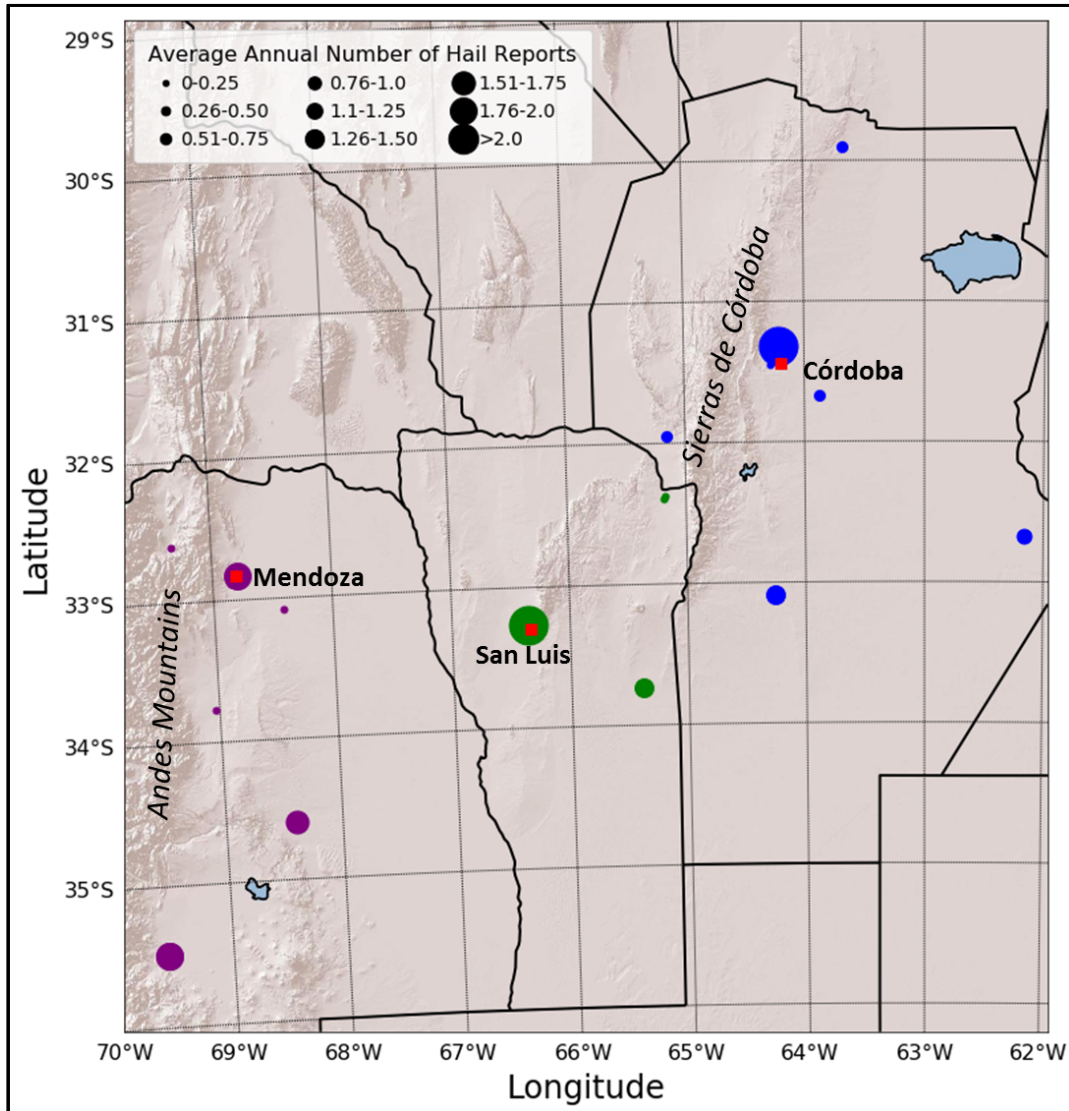


Figure 7. Spatial distribution of hail events reported from stations between 1 June 1987 and 31 May 2017. Purple stations are within the Mendoza province, green in San Luis, and blue in Córdoba. The size of the station as shown on this map is proportional to its average annual number of hail reports. The capital city for each province is provided with a red square marker.

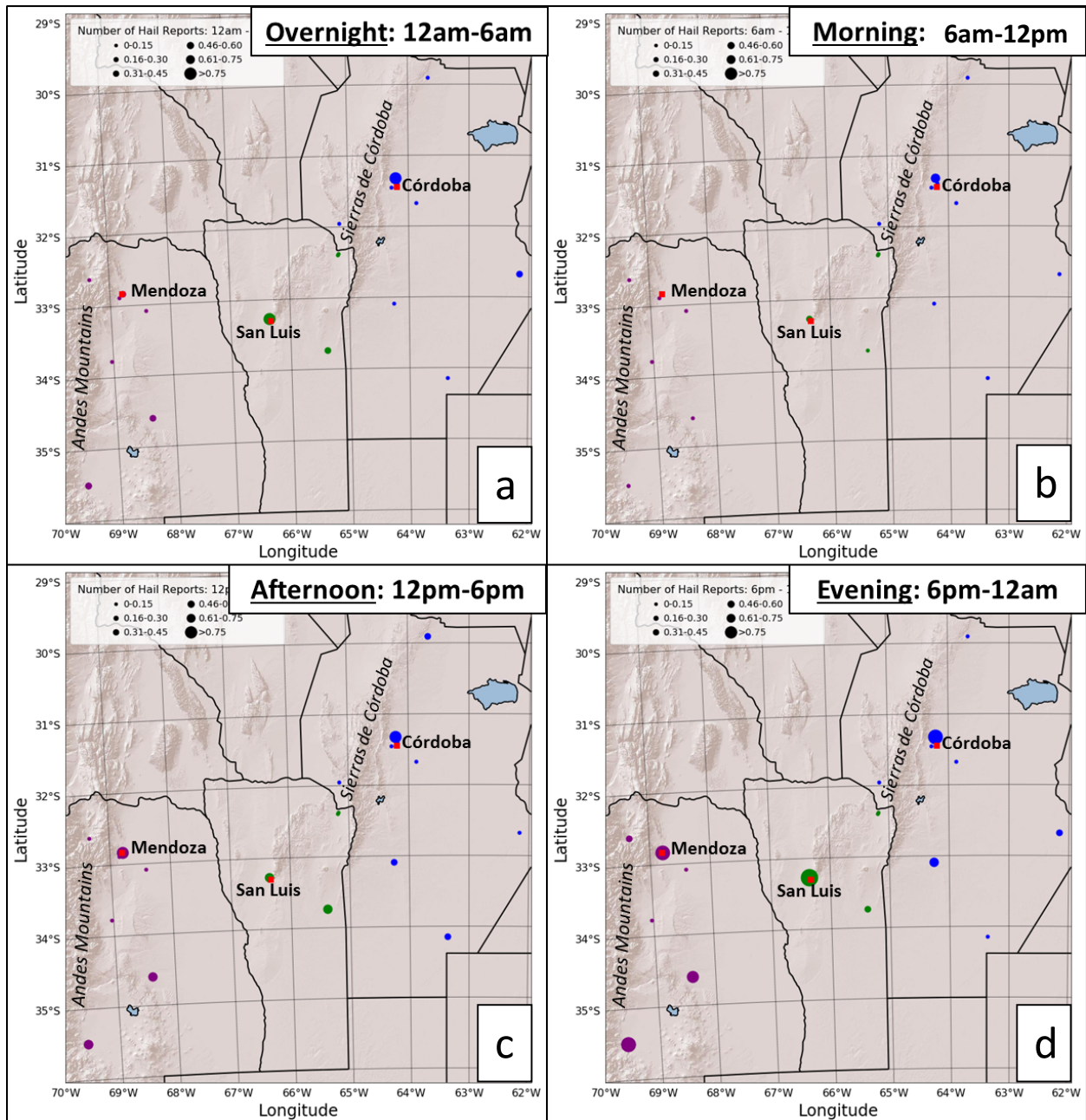


Figure 8. As in Fig. 7 but separated into four 6-hour periods of the diurnal cycle: 12am-6am (a) , 6am-12pm (b), 12pm-6pm (c), and 6pm-12am (d).

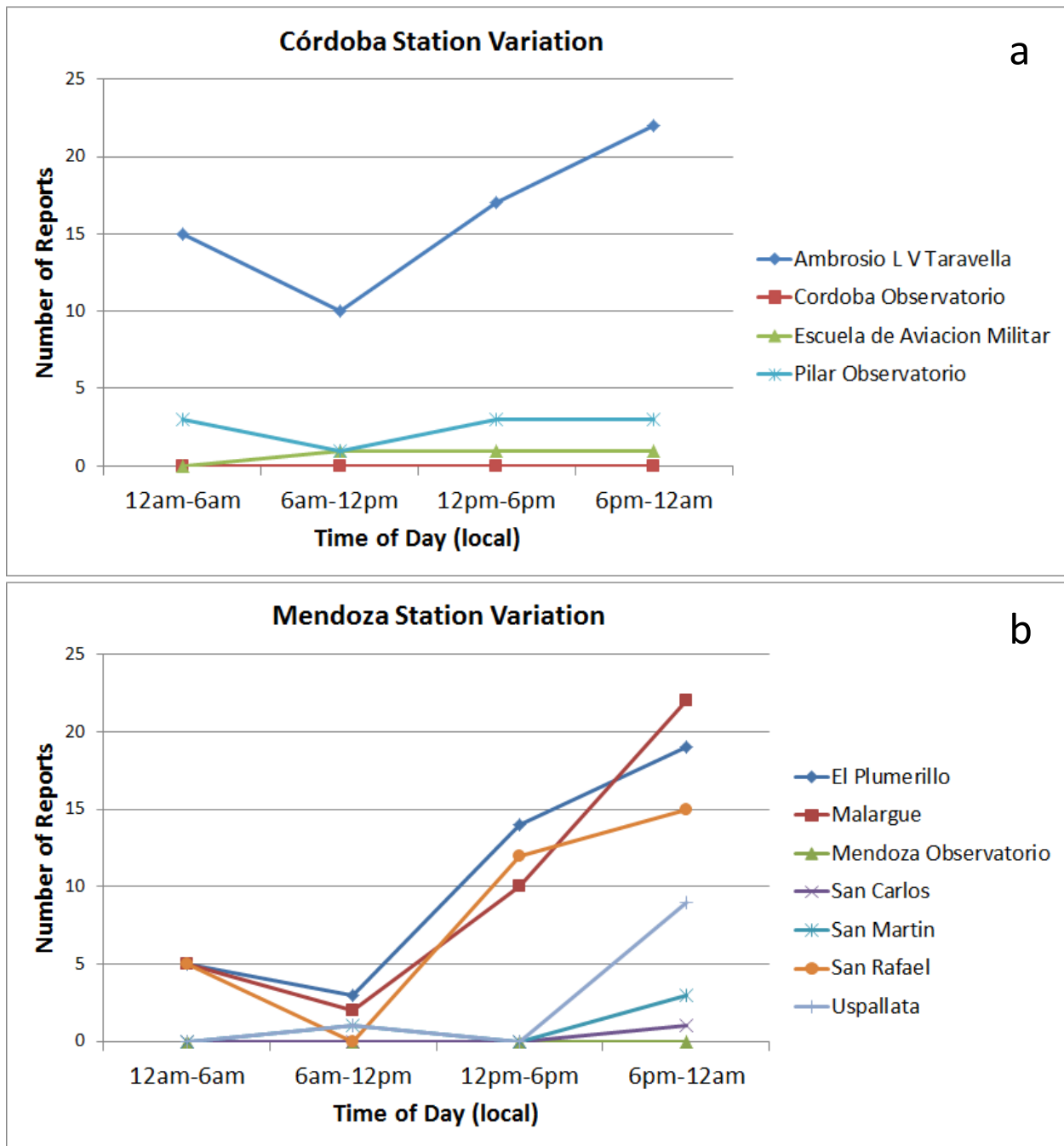


Figure 9. Diurnal distribution of hail reports from four stations within 60km of the capital of Córdoba (a) and the diurnal distribution of hail reports within all stations of Mendoza (b).

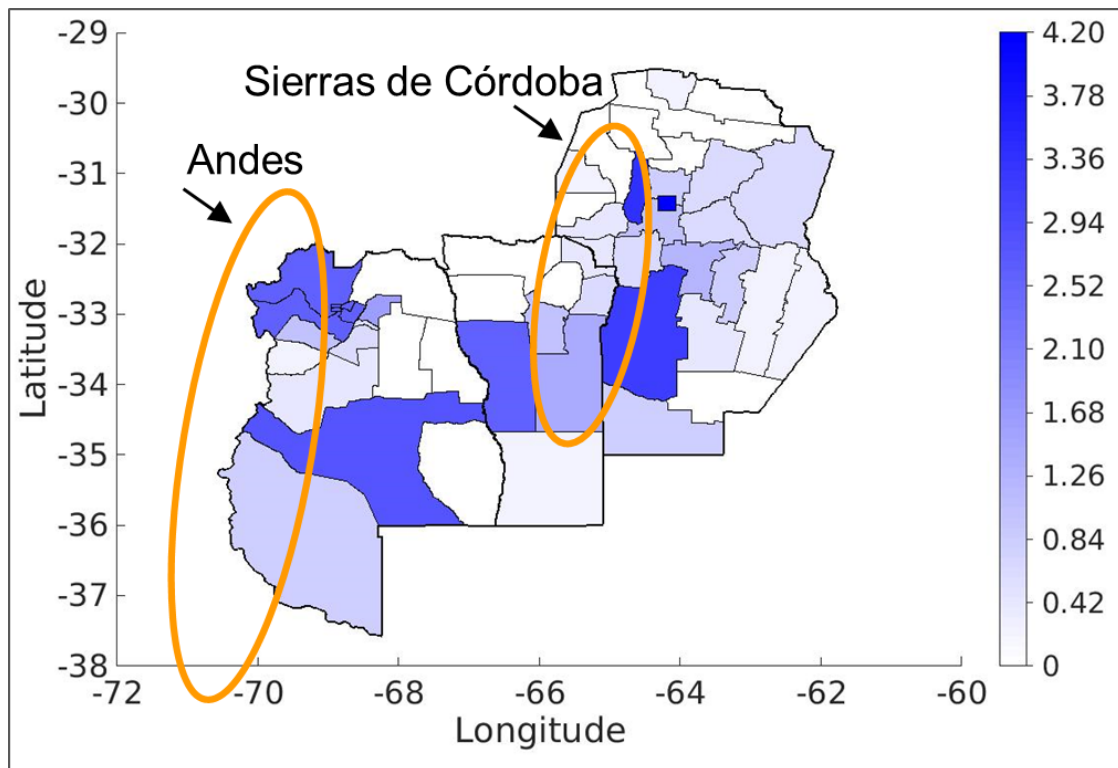


Figure 10. Mean annual days with hail reports per department. Darker shades indicate greater values. The locations of the Andes Mountains and the Sierras de Córdoba are shown by orange ovals.

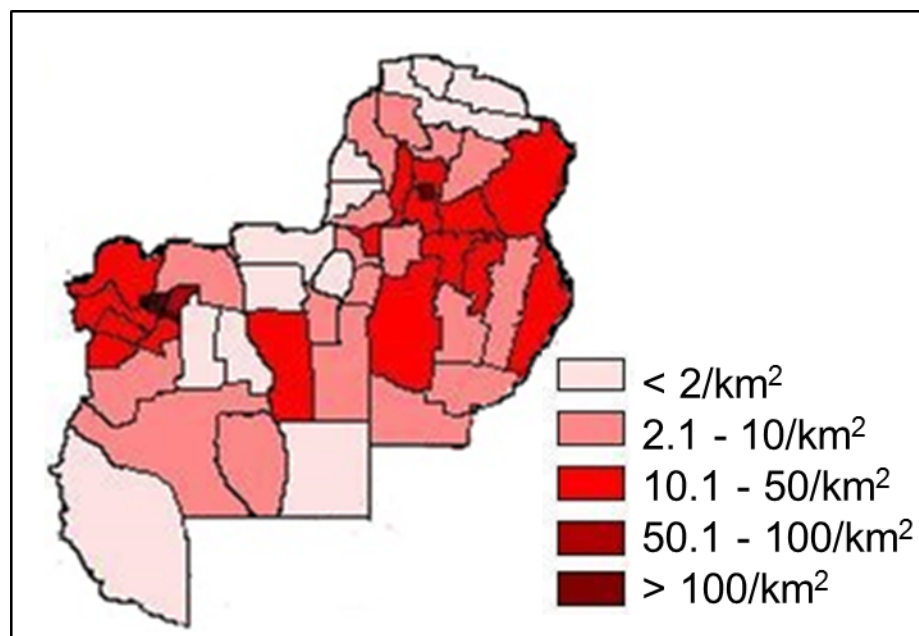


Figure 11. Population density of the departments of Mendoza, San Luis, and Córdoba in 2001. Darker shades of red indicate greater population density. Source: Instituto de Estadísticas y Censos.

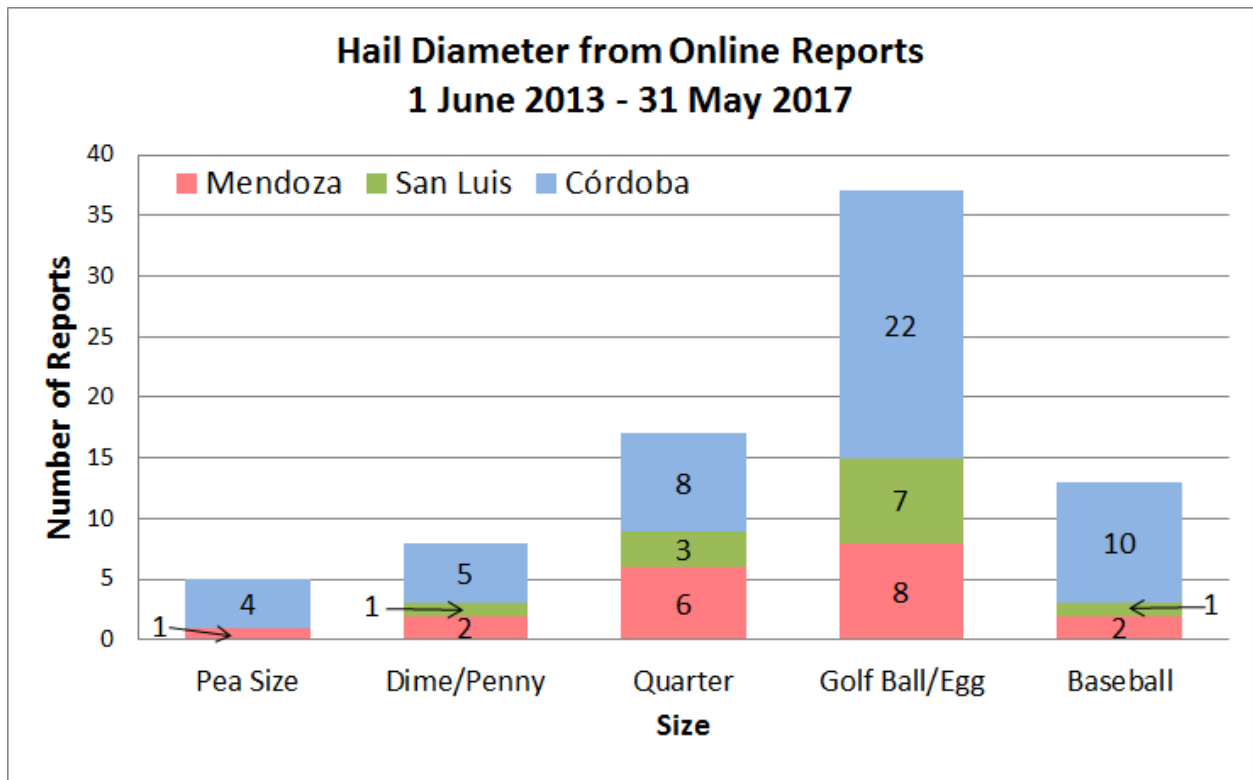
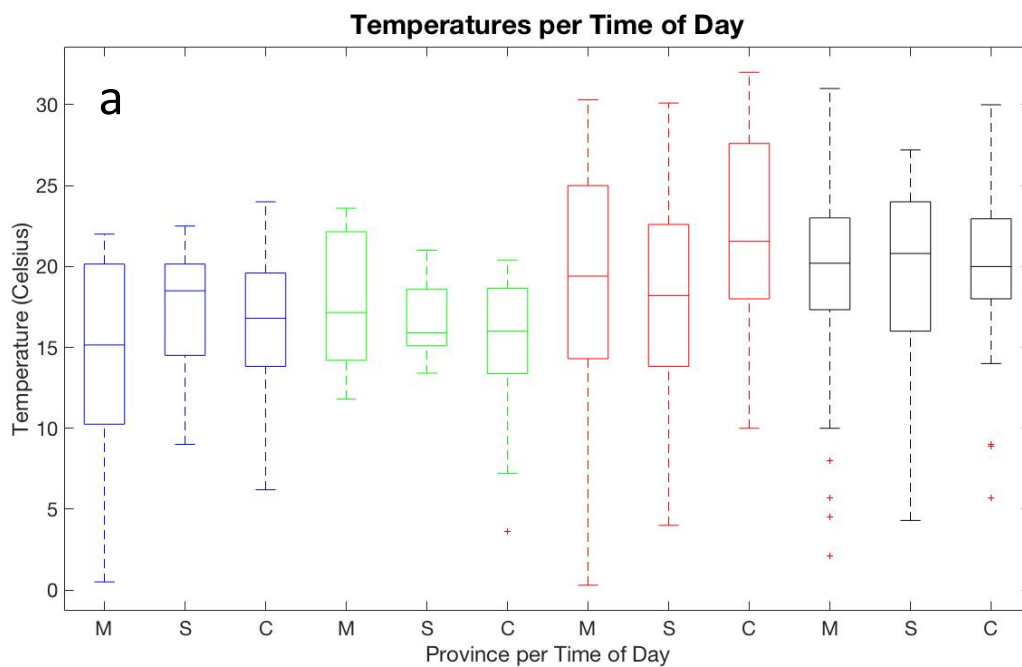


Figure 12. The distribution of hail size as reported online between 1 June 2013 and 31 May 2017. Reports from Mendoza are red, San Luis green, and Córdoba blue.



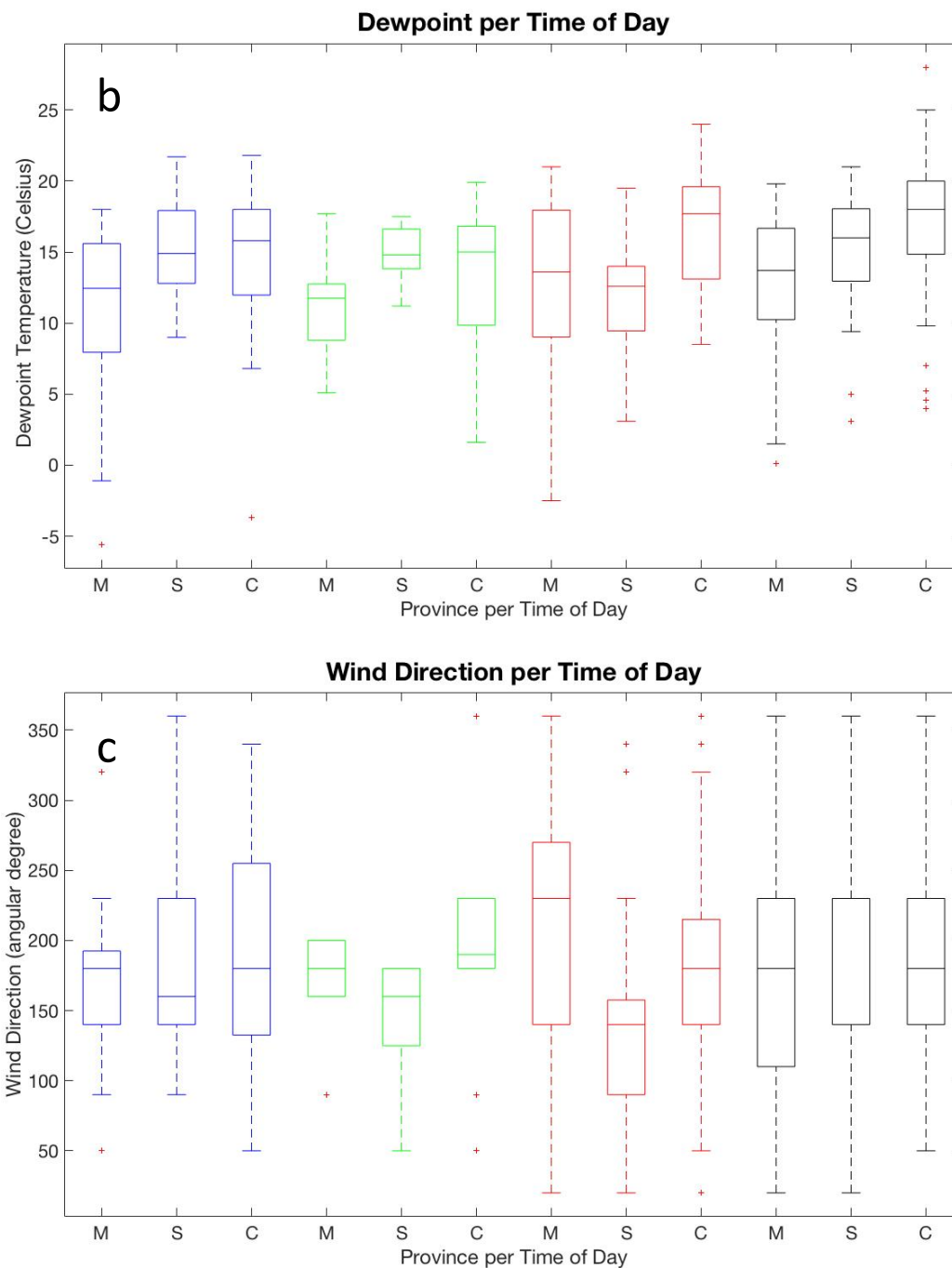


Figure 13. Temperature (a), dewpoint (b), and wind direction (c) per time of day and province. Blue: 12am-6a; green: 6am-12pm; red: 12pm-6pm; black: 6pm-12am. Three boxplots, one per province, are present for each timeframe where M is Mendoza, S is San Luis, and C is Córdoba.