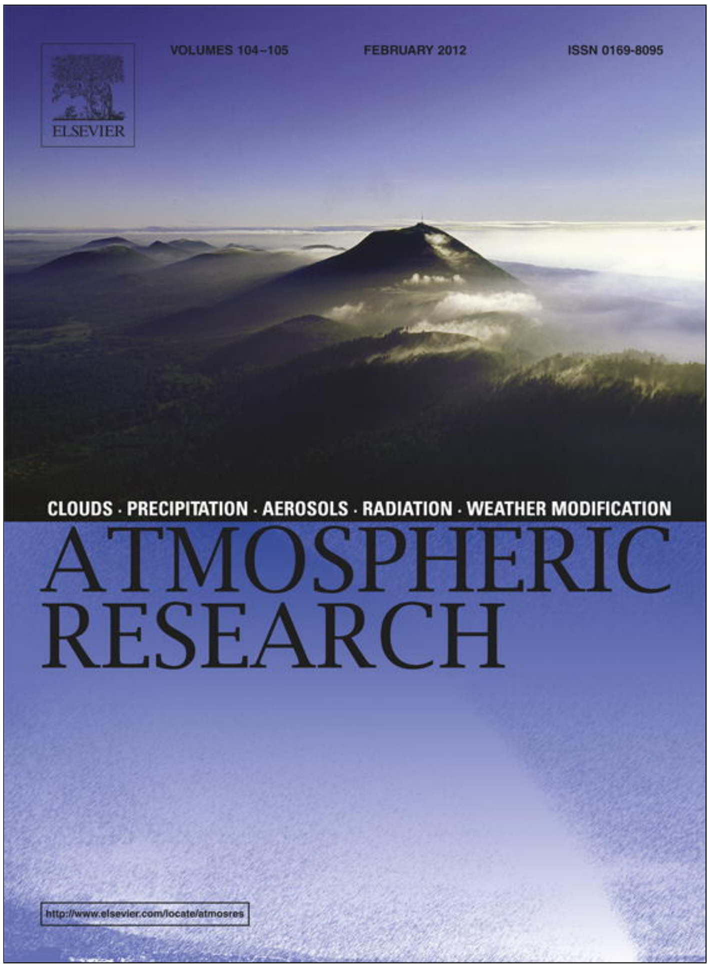

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Climatology of hail in Argentina

Romina N. Mezher [a], Moira Doyle [b,c,*], Vicente Barros [b,c]

[a] Climate and Water Institute, National Institute of Agricultural Technology, Nicolas Repetto y Los Reseros s/n, Hurlingham, 1686, Buenos Aires, Argentina
[b] Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA), UMI IFAECI/CNRS, Argentina
[c] Departmento de Ciencias de la Atmósfera y los Océanos, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón II, 2do piso, 1428, Buenos Aires, Argentina

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A B S T R A C T

The annual cycle, annual and seasonal frequency and geographical distribution of hail in Argentina during the 1960–2008 period are examined. Eight regions covering the whole territory were defined based on the correlation of the mean annual hail frequency between all weather stations. Regions lying between 30° and 40°S as well as those dominated by mountains present the highest hail frequencies in Argentina. The eastern and coastal areas of the country experience hail events mainly during springtime but they may start in late winter and continue through the beginning of summer. Events in western and central Argentina also predominate in spring but the maximum frequencies are observed during summer months. Trends in the annual number of hail events calculated for each region indicate that events in northwestern and northeastern Argentina have been increasing as well as in southern Patagonia. On the other hand, in central Argentina, southern Buenos Aires–La Pampa, northern Buenos Aires–Litoral and northern Patagonia trends are negative and statistically significant in the first two regions, basically by the decrease of events during spring and summer.

1. Introduction

Hailstorm damages cause serious losses on some of Argentina's regional and economic sectors, both in urban and rural areas. In 2002, just in one province (Entre Rios) it was reported that soybean, sunflower, and corn crop losses for U$S 5 million were attributable to hail damage (Almada et al., 2005). In 2010 a hailstorm in the city of Buenos Aires caused car damages with an estimated economic cost of U$S 15 millions in only 7 min (Santiago, 2010). Moreover, wine and fruit production experience yearly losses of U$S 50 million and U$S 30 million respectively in the western provinces of the country (PROSAP, 2009).

Statistics based on synoptic and climate observations have been used in hail studies. Although in most cases due to the lack of appropriate data, these statistics cannot be used to determine hail severity or damage, they at least permit to identify hail frequency and seasonality as well as the most affected areas. During recent years, studies for different countries in Europe, Asia and America have been published; for instance Etkin and Brun (2001) for Canada, Vinet (2001) for France, Webb et al. (2001) for the United Kingdom, Tuovinen et al. (2009) for Finland, García-Ortega et al. (2007) for Spain and Giaiotti et al. (2003) in the plain of Fiuli Venezia Guilia. Zhang et al. (2008) for China updated a hail climatology and showed that hail frequency is highest over the central Tibetan Plateau. An older paper by Changnon (1978) presented a detailed climatology of hail for the United States. In general and according to these papers, mid latitudes during the warm season were found to have the highest hail frequency. Moreover, recently Berthet et al. (2011) found that the frequency did not change significantly during 1989–2009, while the intensity increased by 70% during April and May where an increase in the mean minimum temperature is also observed.

As for Argentina, there have only been regional studies until now, most of which have focused on the western province of

* Corresponding author at: Dto. Cs. de la Atmósfera y los Océanos, Ciudad Universitaria, Pabellón II, 2do piso, 1428, Buenos Aires, Argentina. Tel.: +54 11 4576 3398; fax: +54 11 4576 3356.
E-mail addresses: rmezher@cnia.inta.gov.ar (R.N. Mezher), doyle@cima.fcen.uba.ar (M. Doyle), barros@cima.fcen.uba.ar (V. Barros).

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Mendoza since it is the one most severely affected by hail damages. Saluzzi and Nuñez (1975) found that for the central part of the country, hail occurred with maximum frequency during the evening hours 1600–1800 LT, mainly between September and November. Herrera (2000) and Perez and Puliafito (2006) focused on the damages hail had caused in vineyards in the western province of Mendoza and Prieto et al. (2001) explored periodicities in the hail intensity in the Andes region and found interdecadal oscillations with a 20 year period. Meteorological conditions and synoptic patterns related with convection in Mendoza were first studied by Grandoso (1966) and later by Nicolini and Norte (1977). García-Ortega et al. (2009) studied two hailstorm cases in Mendoza with numerical simulations and radar data and found that the Andes mountain range and the solar radiation could have played an important role in triggering convection in the study zone.

Regarding other regions of the country, Lassig (2006) analyzed hail damages to fruit plantations of the northern Patagonian province of Rio Negro using a 100 hail-pad network. He estimated the hail impact on the local economy to be about U$S 6–8 million a year.

However, a complete climatology for the country has been a pending issue which this paper attempts to fulfill, although with the limitation of being restricted to the frequency of hail events because there are not sufficient reliable information on hail size, except for the provinces of Mendoza in the west of the country and in Rio Negro in northern Patagonia and in this last case, the information is only for a few years. A second objective of this paper is to assess if there has been a discernible trend in the hail frequency in some regions of Argentina. As background, it is worth to mention that there have been important positive trends and changes in annual rainfall during the last decades of the past century over southeastern South America (Barros et al., 2000, 2008) as well as an increase in heavy precipitation frequency (Re and Barros, 2009; Penalba and Robledo, 2009; Doyle et al., 2011) which might be linked to global warming. Regarding trends, it is interesting to mention that southeastern China, at a similar latitude and with a similar type of climate as eastern Argentina, i.e. humid subtropical with more precipitation in summer, but without a dry season, had a negative trend in annual hail days due to an increase in the freezing-level height related to global warming (Xie et al., 2008).

The present article is structured as follows. Data and methodology are described in Section 2. Section 3 discusses the annual and seasonal spatial distribution of hail frequency, which is higher in the latitude band between 30° and 40° S, while Section 4 deals with the annual cycle in the different regions. Section 5 analyzes the atmospheric conditions associated to hail events in the eastern part of the mentioned latitude band since several studies have already addressed the western part. Section 6 shows trends in hail events while the main conclusions are summarized in Section 7.

2. Data and methodology

The National Meteorological Service of Argentina has records of hail data as far back as 1908. However, not all of these observations were included in their digital database; therefore the first step was to complete the hail dataset, which finally included data from weather stations of the National Meteorological Service network and climate stations from the National Agricultural Technology Institute from 1908 to 2008. Some records are incomplete or present lack of homogeneity due to some cases of changes in location, or other problems that make them unreliable. Thus, only 93 stations with less than 20% of missing data in the 1960–2008 period were retained for this study (Table 1 and Fig. 1). Hail day was defined as days on which at least one event is recorded in the station.

The annual average of hail days and the total number of monthly and seasonal events were calculated for each station adding the observed daily events. The mean monthly frequency was calculated for each station; then these 12 values for a given station were correlated with the remaining 92 stations. These correlation results were used to divide the country into regions according to the annual cycle of the hail frequency distribution. When the correlation coefficient was 0.8 or higher between neighboring stations, these stations were considered to belong to the same region. Moreover, some neighbor stations were included in the region when they reached the correlation threshold with at least half of the initial stations. This second criterion was taken in order to reduce the number of possible regions. Six stations not complying with these two criteria, most of them in the mountainous areas, were discarded for the regional averaging because they were considered non representative of the region. This does not mean that their values were considered wrong or unreliable. Thus, eight regions were identified: southern Patagonia (A), northern Patagonia (B), southern Buenos Aires and La Pampa (C), Cuyo (D), Central Argentina (E), northern Buenos Aires and Litoral (F), Northeastern Argentina (G) and Northwestern Argentina (H), Fig. 1.

Linear trends of hail events were obtained for each of the eight regions. Trend significance was determined using the nonparametric Kendall's Tau test (Kendall, 1975).

The combination of hail frequency, exposed assets and production makes the risk to this hazard highest in the central latitudinal band that stretches through regions D, C, E and F. In region D, hail frequently affects the most important vineyards and fruit production of the country, while in the C, E and F region, hail causes important losses in maize, soybean and wheat production as well as urban damages. The composites of tropospheric fields were computed to assess the meteorological conditions associated to the occurrence of hail in the months with highest frequency of hail events, namely during the months from August to January. The tropospheric fields were analyzed for the period 1980–2008 because radiosonde information in the region was sparse and sometimes discontinued; therefore the inclusion of satellite information after the second half of the 1970 decade was very important to make tropospheric data reliable. Temperature between 1000 and 200 hPa was taken from the NCEP/NCAR Reanalysis Project (Kalnay et al., 1996). The composite of vertical temperature profiles was calculated for the 63 events in the area extending between 24° and 40°S and averaged between 64° and 57°W.

3. Mean annual hail frequency

Table 1 presents the mean annual hail frequency for the 1960–2008 period and its spatial pattern can be seen in Fig. 2.

Table 1
Meteorological stations with hail records used in this study.

Station name	Latitude	Longitude	Annual mean	Autumm mean	Winter mean	Spring mean	Summer mean
San Pedro INTA	−33.68	−59.68	0.90	0.10	0.30	0.30	0.20
La Quiaca Obs.	−22.10	−65.60	4.47	0.90	0.04	1.24	2.29
Las Lomitas	−24.70	−60.58	0.62	0.09	0.14	0.31	0.07
Salta	−24.85	−65.48	0.80	0.10	0.04	0.24	0.41
Tucuman	−26.85	−65.10	0.63	0.04	0.02	0.24	0.33
Roque Saenz Peña	−26.82	−60.45	0.65	0.16	0.14	0.22	0.12
Catamarca	−28.60	−65.77	0.44	0.08	0.00	0.10	0.26
Obera	−27.48	−55.13	1.29	0.04	0.47	0.63	0.14
General Paz	−27.75	−57.63	0.89	0.06	0.29	0.37	0.17
Sant. del Estero	−27.77	−64.30	0.53	0.12	0.06	0.22	0.12
Tinogasta	−28.07	−67.57	0.49	0.12	0.00	0.07	0.30
Bella Vista INTA	−28.43	−58.92	0.75	0.08	0.23	0.38	0.06
La Rioja	−29.38	−66.82	0.51	0.08	0.00	0.10	0.33
Ceres	−29.88	−61.95	0.73	0.16	0.04	0.47	0.06
V. M. Del Rio Seco	−29.90	−63.68	1.78	0.16	0.29	0.86	0.47
Jachal	−30.25	−68.75	0.54	0.07	0.05	0.10	0.32
Monte Caseros	−30.27	−57.65	0.67	0.04	0.24	0.37	0.02
Cordoba Obs	−31.40	−64.18	2.86	0.31	0.10	1.39	1.06
San Juan	−31.60	−68.55	0.64	0.06	0.02	0.16	0.39
Pilar	−31.67	−63.88	2.73	0.45	0.16	1.33	0.80
Parana	−31.78	−60.48	0.90	0.06	0.16	0.47	0.20
Villa Dolores	−31.95	−65.13	1.45	0.31	0.10	0.43	0.61
Mendoza Aero	−32.83	−68.78	1.31	0.16	0.02	0.40	0.73
Mendoza Obs	−32.88	−68.85	1.31	0.07	0.07	0.37	0.78
Rosario	−32.92	−60.78	0.71	0.06	0.14	0.31	0.20
Gualeguaychu	−33.00	−58.62	0.78	0.10	0.24	0.29	0.14
Rio Cuarto	−33.12	−64.23	2.16	0.37	0.10	0.88	0.82
San Luis	−33.27	−66.35	1.24	0.33	0.04	0.33	0.55
San Carlos	−33.77	−69.03	1.06	0.21	0.02	0.34	0.49
Pergamino INTA	−33.93	−60.55	2.38	0.30	0.43	1.11	0.55
Laboulaye	−34.13	−63.37	1.78	0.37	0.14	0.57	0.69
Tolhuin	−54.70	−67.25	1.42	0.11	0.00	0.68	0.63
San Miguel	−34.55	−58.73	2.33	0.24	0.71	0.88	0.49
Bs As	−34.58	−58.48	1.70	0.26	0.49	0.66	0.30
Junin	−34.58	−60.93	1.16	0.18	0.20	0.53	0.24
El Palomar	−34.60	−58.60	1.06	0.14	0.22	0.37	0.33
Ezeiza	−34.82	−58.53	1.82	0.18	0.43	0.84	0.37
La Plata	−34.97	−57.93	0.73	0.12	0.20	0.29	0.12
Punta Indio	−35.37	−57.28	0.95	0.10	0.36	0.28	0.20
Nueve de Julio	−35.45	−60.88	0.93	0.14	0.14	0.43	0.23
Malargue	−35.50	−69.58	2.86	0.51	0.14	0.78	1.43
Trenque Lauquen	−35.97	−62.73	1.98	0.26	0.15	0.85	0.72
Las Flores	−36.03	−59.10	1.00	0.13	0.15	0.33	0.38
Bolivar	−36.25	−61.10	0.82	0.03	0.18	0.31	0.31
Dolores	−36.35	−57.73	0.92	0.12	0.31	0.20	0.29
Santa Rosa	−36.57	−64.27	2.55	0.39	0.12	1.02	1.02
Azul	−36.80	−59.90	1.12	0.14	0.31	0.37	0.31
Coronel Suarez	−37.43	−61.88	0.54	0.11	0.08	0.14	0.22
Pigue	−37.60	−62.38	1.05	0.29	0.05	0.37	0.34
Mar del Plata	−38.13	−57.55	1.00	0.12	0.24	0.27	0.37
Tres Arroyos	−38.38	−60.27	2.17	0.23	0.30	0.77	0.87
Bahia Blanca	−38.73	−62.17	1.14	0.08	0.37	0.35	0.35
Neuquen	−38.95	−68.13	0.82	0.10	0.06	0.33	0.33
Trelew	−43.20	−65.27	1.37	0.14	0.16	0.63	0.43
Com. Rivadavia	−45.78	−67.50	2.63	0.31	0.65	0.98	0.69
Perito Moreno	−46.60	−70.93	1.16	0.21	0.47	0.32	0.16
Puerto Deseado	−47.73	−65.92	2.06	0.31	0.37	0.86	0.53
Gdor. Gregores	−48.78	−70.17	1.95	0.27	0.23	1.15	0.31
San Julian	−49.32	−67.75	3.04	0.35	0.44	1.44	0.81
Lago Argentino	−50.33	−72.30	0.91	0.18	0.00	0.36	0.36
Rio Gallegos	−51.62	−69.28	3.55	0.33	0.27	1.84	1.12
Rio Grande	−53.80	−67.75	1.98	0.16	0.16	0.79	0.86
Esquel	−42.93	−71.15	0.82	0.10	0.10	0.45	0.16
Paso de Indios	−43.82	−68.88	0.56	0.07	0.04	0.24	0.22
Reconquista	−29.18	−59.70	0.73	0.10	0.22	0.27	0.14
Tandil	−37.23	−59.25	0.88	0.02	0.18	0.24	0.43
Bariloche	−41.15	−71.17	0.33	0.02	0.08	0.12	0.10
San Rafael	−34.58	−68.40	3.18	0.49	0.14	0.71	1.84
Tartagal	−22.65	−63.82	0.75	0.06	0.06	0.25	0.38

Table 1 (*continued*)

Station name	Latitude	Longitude	Annual mean	Autumm mean	Winter mean	Spring mean	Summer mean
Aeroparque	−34.57	−58.42	1.16	0.14	0.31	0.49	0.22
Oran	−23.15	−64.32	0.33	0.02	0.00	0.23	0.08
Paso de los Libres	−29.68	−57.15	0.63	0.10	0.16	0.33	0.04
Iguazu	−25.73	−54.47	0.67	0.17	0.19	0.26	0.05
Castelar	−34.67	−58.65	0.76	0.10	0.27	0.22	0.17
Posadas	−27.37	−55.97	0.82	0.06	0.14	0.47	0.14
M. Juarez Aero	−32.70	−62.15	1.06	0.22	0.06	0.57	0.20
San Martin	−33.08	−68.42	1.96	0.29	0.06	0.53	1.08
Santa Fe (CAP.)	−31.70	−60.82	0.96	0.16	0.16	0.47	0.16
Pehuajo	−35.87	−61.90	1.35	0.18	0.22	0.49	0.45
Corrientes	−27.45	−58.77	0.64	0.04	0.13	0.38	0.09
Oliveros INTA	−32.55	−60.85	1.41	0.34	0.24	0.49	0.34
Chamical	−30.37	−66.28	0.79	0.02	0.02	0.42	0.33
Concordia	−31.30	−58.02	0.67	0.10	0.10	0.32	0.15
Formosa	−26.20	−58.23	0.62	0.07	0.09	0.42	0.04
Resistencia	−27.45	−59.05	0.82	0.07	0.21	0.41	0.14
Jujuy	−24.38	−65.08	0.85	0.10	0.05	0.39	0.31
Viedma	−40.85	−63.02	1.36	0.27	0.51	0.34	0.24
M. Juarez INTA	−32.68	−62.15	1.95	0.32	0.22	1.15	0.25
Bdo de Irigoyen	−26.25	−53.65	4.84	0.51	1.44	2.33	0.56
Ushuaia	−54.80	−68.32	1.39	0.22	0.18	0.57	0.41
San Ant. Oeste	−40.73	−64.95	1.24	0.22	0.14	0.57	0.31
Famailla INTA	−27.01	−65.42	0.68	0.05	0.03	0.40	0.20
Coronel Pringles	−37.98	−61.38	1.40	0.20	0.07	0.67	0.47

An ordinary Kriging algorithm was used to interpolate the irregularly spaced station data to a 5-km resolution grid. Hail is very random in time and space and though the 49 year averaging tends to smooth the field, abrupt gradients may still be expected, especially in mountain and coastal regions. Therefore, when applying the Kriging algorithm to interpolate the station data, the parameters were chosen to reduce the smoothing as much as possible. Even so, maps of Figs. 2 and 3 should be considered only as indicative of the large scale features and not necessarily valid at specific locations.

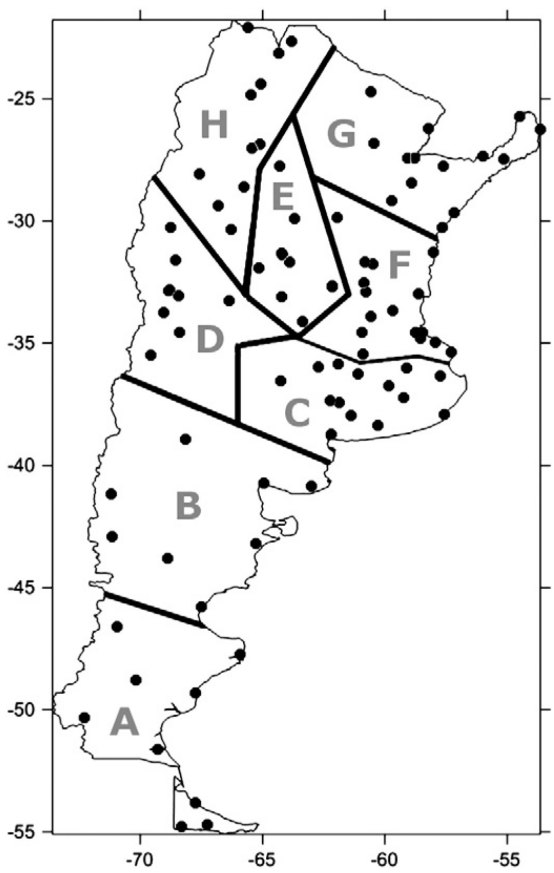


Fig. 1. Stations and regions used in this study.

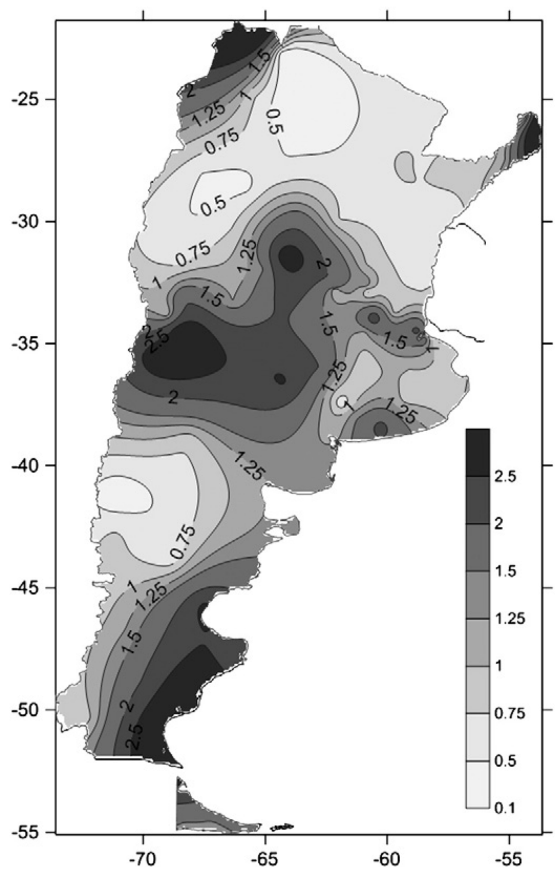


Fig. 2. Mean annual hail events.

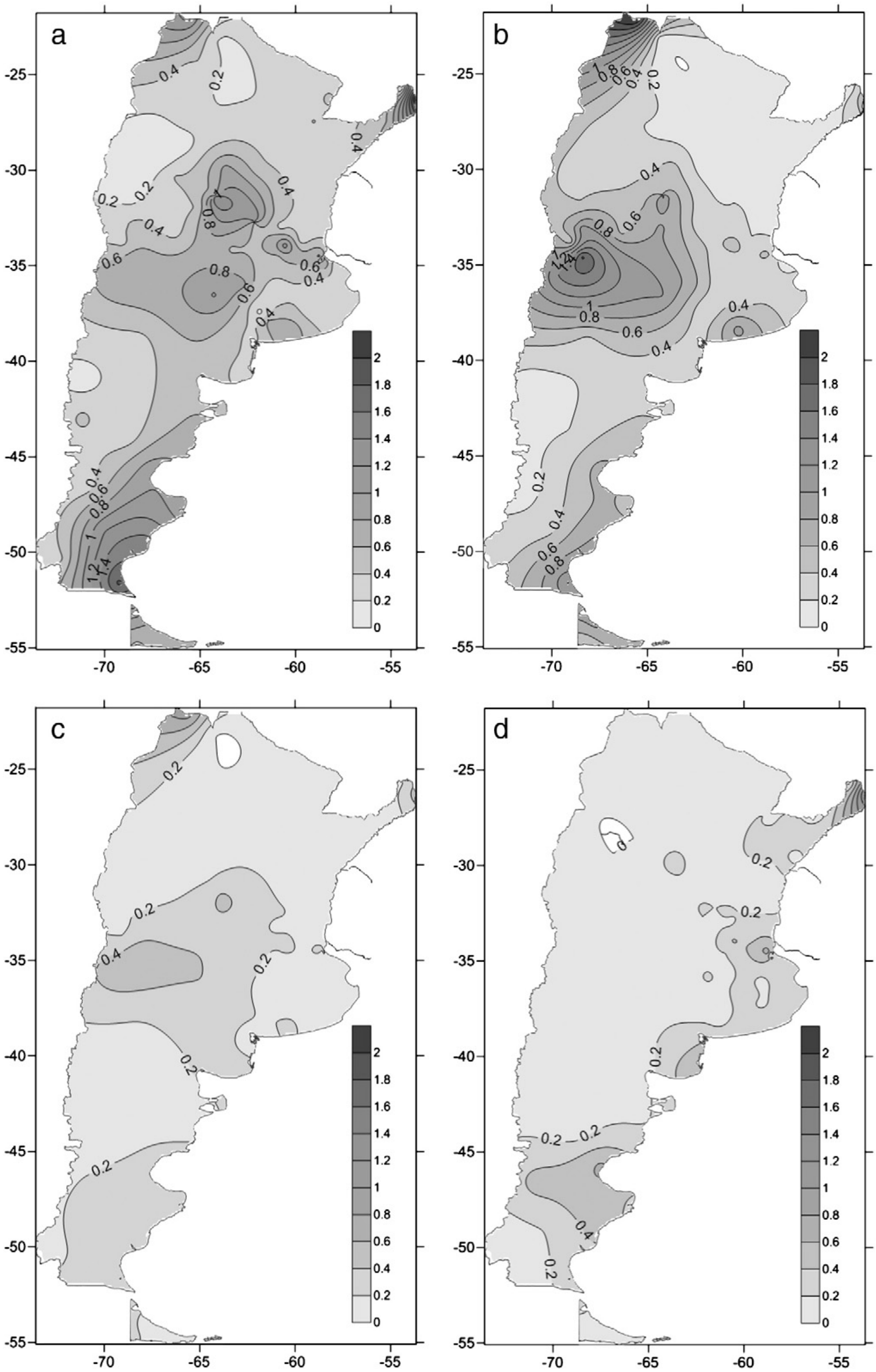


Fig. 3. Mean seasonal hail events. a) Spring, b) Summer, c) Autumn, d) Winter.

Fig. 2 indicates that there are two large regions with maximum hail frequency. The first one stretches over the provinces of Mendoza, La Pampa and Cordoba in central-western Argentina; the second one extends over southern coastal Patagonia. The highest frequency in the first region is in the south of the province of Mendoza at the foothills of the

Andes Cordillera with 3.2 events per year. The spatial distribution of annual frequency in the province of Mendoza in Fig. 2 is approximately similar to that resulting from Grandoso (1966). This area of maximum frequency extends eastward, until approximately 64° W, where no data was available; thus the figure shows high frequency values simply due to the interpolation method that took into account the value at Santa Rosa station, located to the east at 36°S 64°W. Though, for this area values depicted in Fig. 2 have a considerable uncertainty, there is certain possibility that they may not be too erroneous given the easterly path followed by storms and the genesis area existing east of the Andes. A secondary maximum is found immediately to the east of the Córdoba Mountain range at Pilar (2.7 events/year) and at Córdoba airport (2.9 events/year). West of this mountain range, where the climate is drier, Villa Dolores and San Luis have annual frequencies of 1.4 and 1.2 respectively. Thus, this secondary maximum seems associated with the convective activity enhanced by the mountains that favor the uplift of the low level humid air brought from the Atlantic Ocean by easterly wind components.

The second area of maximum frequencies is located in the southeastern sector of Patagonia. Its highest frequencies, reaching up to 3.6 events/year, are found in the coastal area and decrease westward towards the Andes Mountains. However, it is possible that some of the events registered as hail in this region might in reality correspond to graupel events since convective clouds are infrequent in this region. Therefore, cold air mass cloud cells with small vertical extension are probably responsible for the high number of events reported as hail at these southern stations.

In addition to these regional areas of maximum frequencies there are two stations, both located in northern Argentina, which report the highest annual mean hail frequencies of all the country. La Quiaca is situated in the extreme northwest Andes Mountains at 3459 m above sea level while Bernardo de Irigoyen (815 m) lays on the hilly formation which crosses the province of Misiones in the farthest northeastern Argentina. Their annual means are 4.5 and 4.8 events respectively. Marcelino et al. (2004) studied hail events in the neighboring Brazilian state of Santa Catarina, finding a maximum regional frequency at Sao Jose do Cedro, a city very near Bernardo de Irigoyen on the Brazilian side, with a mean annual value of 5 event/year, which the authors attributed to regional topography. Therefore these maxima cannot be attributable to data errors.

Therefore, the most outstanding features of the hail frequency spatial pattern in Argentina are the association of the high frequencies with mountain and coastal regions and to the latitude band between 30° and 40° S. The link between high frequency of hail and mountain areas was also found in other countries, for instance Etkin and Brun (2001) reported the highest values in Canada in central British Columbia and Alberta, with maxima east of the Rockies and, in China, Zhang et al. (2008) found that the highest frequencies are registered in the Tibetan Plateau and Qilian mountain areas.

4. Seasonal frequency

There is a clear seasonal variation in the geographic pattern of hail frequency as can be seen from Fig. 3. The annual cycle of hail events with monthly resolution for the eight regions defined in Section 2 is presented in Fig. 4. With some exceptions, the overall pattern of hail events in Argentina is such that it varies from summer prevalence in the west to spring in the east. The monthly resolution, which will be discussed later, shows that in the east of the country there are also important frequencies in late winter.

In western Argentina north of 38° S, the summer months have the greatest frequency of hail events, followed by spring (Fig. 3). Both seasons account for 80 to 90% of the total annual events. From May to July the hail has almost null frequency and the season with greatest occurrence starts in November and ends in March. In central Argentina the highest frequency takes place during spring, but is also important during summer. This annual cycle is a direct consequence of the seasonal pattern of precipitation that, in these regions presents a monsoon type with scarce or null rainfall in winter and autumn months, while convective precipitation that sometimes produces hail, is enhanced during the warmer months by topography at the foothills of the Andes Mountains and the mountains in the Central region.

In Northeastern Argentina the highest number of hail events is registered during spring (Fig. 3a), with values ranging from 40 to 70%, and in late winter, namely August and September (Fig. 4c, f, g). The total percent frequency of hail events for this area during these two seasons amounts to approximately 80–85%. In winter the important percentages extend toward the south, up to 40° S in the eastern part of Buenos Aires and are also relevant in Patagonia near the Andes where some stations present their maximum frequencies during this season (25–30%). This feature is also present in the Litoral, namely in the eastern and northeastern regions, where hail frequency starts increasing in July and peaks in October (Fig. 4f, g). The annual cycle of the central region of the country represents a transition regime between those from the Litoral and the western regions, with a maximum in November and minimum in winter, Fig. 4h.

5. Atmospheric circulation associated to hail events

The atmospheric circulation associated to hail events is likely to vary from one region to another, although some features may be common. The lack of a sufficiently dense observation network and the random features of hail make it uncertain to draw conclusions from every one of the regions here discussed. Moreover, since there are already several studies that focused on the Cuyo region, for example recently de la Torre et al. (2011), the analysis of atmospheric circulation associated to hail events is limited to the regions with a denser number of weather stations, namely, southern Buenos Aires–La Pampa, northern Buenos Aires–Litoral and central Argentina regions (region C, E and F). In addition, these regions have a practical interest because of their considerable exposure of their agricultural production assets.

Days where hail events were observed in more than two locations in the Pampa Region (regions C, E, and F) during the warm periods between 1980 and 2008 were selected to compose the atmospheric circulation fields; they amounted to 63. As explained previously, the starting year 1980 was chosen to ensure more reliable tropospheric fields. Fig. 5 shows the longitudinal vertical cross-section of the mean

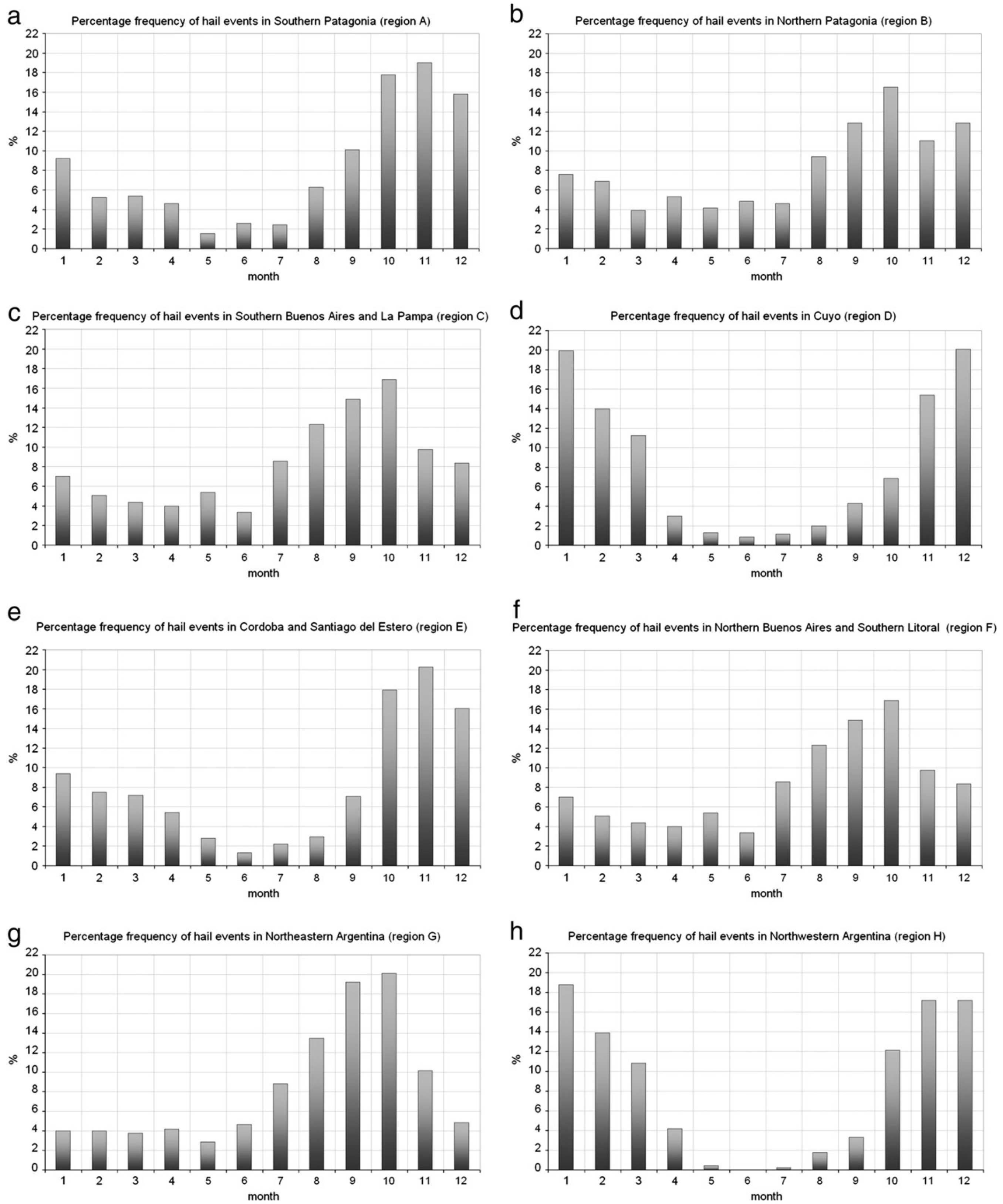


Fig. 4. Percentage frequency of monthly hail events in different regions of Argentina. a) southern Patagonia, b) northern Patagonia, c) southern Buenos Aires and La Pampa, d) Cuyo, e) central Argentina, f) northern Buenos Aires and southern Litoral, g) northeastern Argentina and h) northwestern Argentina.

temperature anomaly averaged over 57º–64ºW for the 63 hail cases, indicating that hail events in the Pampa region are associated to warm anomalies at the lower levels of the troposphere and slightly cool anomalies at the highest tropospheric levels. The warm anomalies are more pronounced during the late winter-early spring period (Fig. 5b),

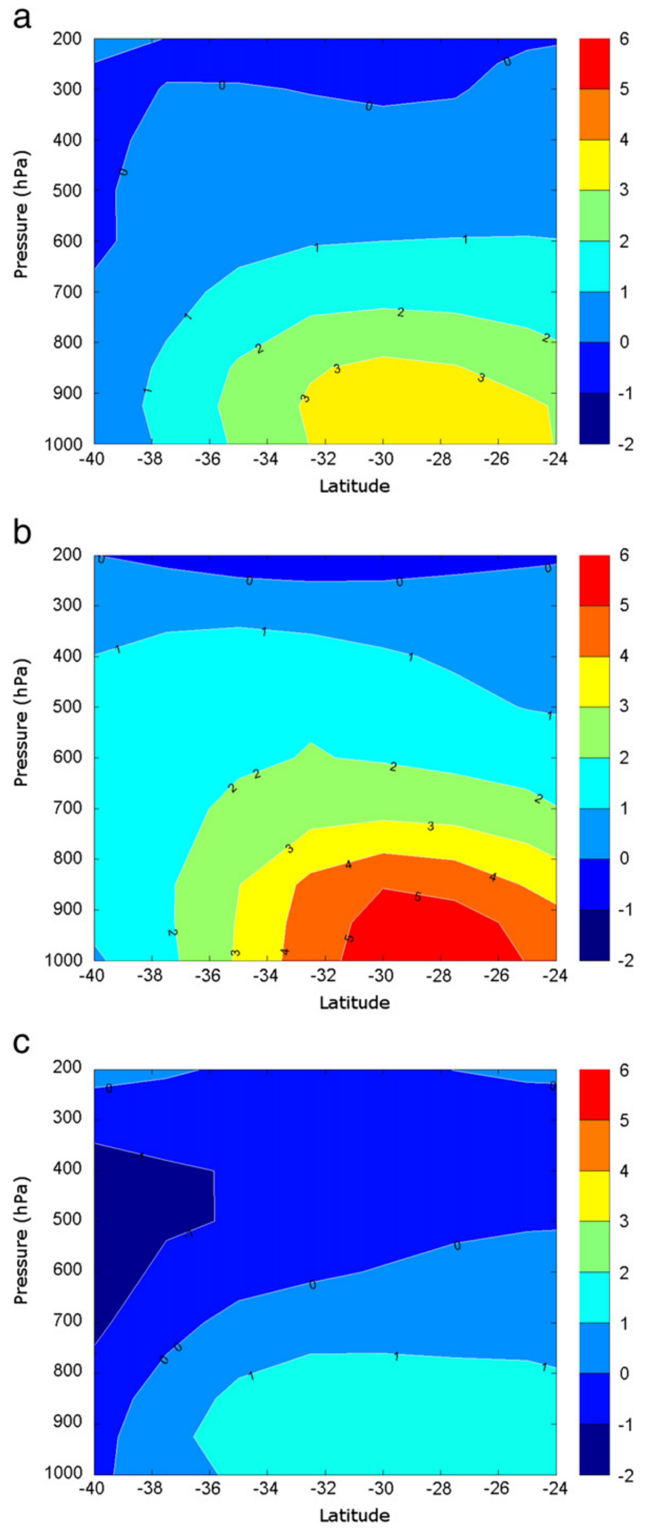


Fig. 5. Longitudinal vertical cross-section of the mean temperature anomaly averaged over 57º–64ºW: a) annual, b) August–September–October, and c) November–December–January.

while the cool anomalies at the upper troposphere are more marked in late spring early summer period (Fig. 5c).

The spring maximum and even the important hail frequency in some winter months, especially in August throughout the country, with the exception of the west and central regions, can result from the fact that in spring the upper circulation over Argentina retains the winter features with a northward extension of the western circulation, while at low levels there are frequent intrusions of warm and humid air from the tropics; this northerly flow even occurs during winter, especially since August. Such synoptic situations can lead to cold anomalies in the upper troposphere and warm ones at low levels, which are associated to hail events (Fig. 5b). These conditions lead to a more unstable vertical lapse rate in the troposphere, which is needed to develop the strong convective clouds that may produce hail. Although, these situations take place also in the west, the lack of moisture prevents the triggering of convection in winter and even in early spring.

Fig. 6 shows the composite of 1000 and 500 hPa geopotential height anomalies associated to the 63 events. The negative anomalies in the 500 hPa level linked to the low pressures in 1000 hPa indicate that hail events are usually associated to an intense trough centered over the Chilean coast, and extending over Patagonia in the Argentine territory where the 500 hPa geopotential height anomalies reach values of 100 gpm. At low levels the negative anomaly regions are present over north-central Argentina and the Pacific coast. In the first case, this is indicative of the presence of cold frontal systems.

Critical factors for the development of severe storms capable of producing hail are vertical wind shear (Browning, 1978) and low level warm advection. Hence, the zonal and meridional anomaly wind components at 250 hPa and 925 hPa are shown in Fig. 7. The composite of 250 hPa zonal anomaly field has a jet stream with a maximum positive value of 6 m/s (Fig. 7d) and an intense northern component reaching an anomaly of 10 m/s (Fig. 7b) at the core of the jet stream located aloft over central Argentina. At 925 hPa a low level jet crosses Paraguay southerly into Argentina with a peak of −6 m/s (Fig. 7a). This configuration confirms the presence of the cold frontal system over central Argentina where severe convection is highly favored by the presence of the low level jet in the warm mass and the associated vertical wind shear. Similar results are observed in other parts of the world, for example García-Ortega et al. (2007) discuss hailstorms occurring in an environment with a thermal mesolow that favors the entrance of warm and humid air from the Mediterranean Sea, while García-Ortega et al. (2011) through a classification of atmospheric patterns corresponding to hailstorm days in the Middle Ebro Valley (Spain) identified a strong low or trough to the west of the peninsula and a zone of maximum cyclonic vorticity.

6. Trends in hail events

Fig. 8 shows the annual number of hail events for the different regions, as well as a 5-year moving average and the linear fit. The large region with highest hail frequency and impacts, namely Cuyo (D), does not show any trend, but a considerable inter decadal variability (Fig. 8d). The northwest region (H) had a positive linear trend with a 90% significance level (Fig. 8h), as well as in Northeastern Argentina (G) (Fig. 8g). This trend resulted only from the one observed in the February–July semester (not shown) and not from the spring, the season with highest frequency of hail

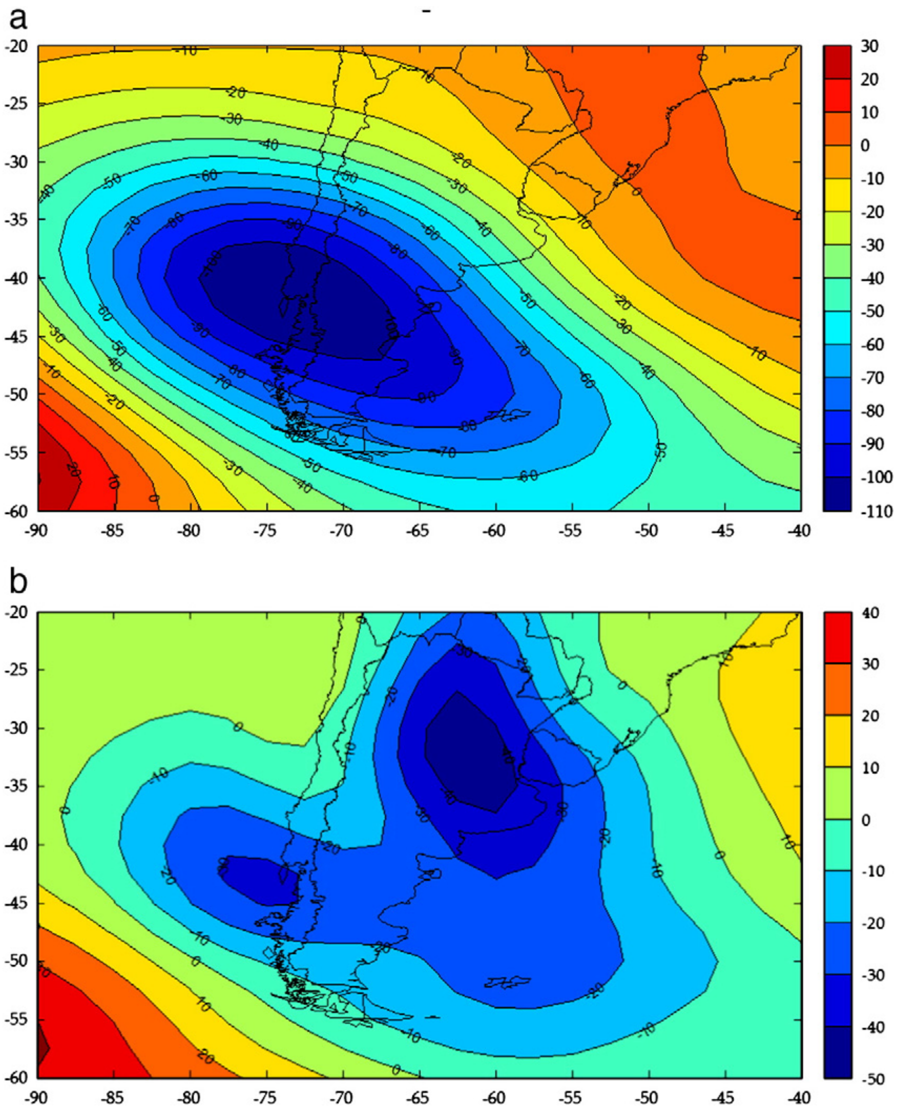


Fig. 6. Geopotential height anomalies (gpm) associated to 63 hail events during the 1980–2008 warm season for a) 500 hPa and b) 1000 hPa.

events in this region. Both northern regions (H and G) share not only the strong and positive trend, but also some features of the inter decadal variability; they show maximum frequencies in the 1993–2003 period and minimum frequencies during the early seventies and eighties, indicating that the hail frequency in both regions responds, at least partially, to the same large scale climate variability.

Hail events in central Argentina (E) as well as southern Buenos Aires–La Pampa (C) had significant negative trends at a 95% level (Fig. 8e, c). These trends resulted in an overall end to end reduction of over 30% in the number of events during the 1960–2008 period. They came from negative trends, both in spring and summer and in late winter in the case of southern Buenos Aires–La Pampa (C), which are the seasons with highest hail frequency (not shown).

The northern Buenos Aires and Litoral region (F) had also a negative trend, but very small and non significant (Fig. 8f) showing an intermediate behavior between the northeastern (G) and the central (E) and southern Buenos Aires–La Pampa (C) regions, and sharing with those regions a period of high frequencies during the nineties. The negative trend comes mainly from the trend in the period August to October, while in summer there is almost no trend (not shown).

Trends in central and eastern Argentina, regions C, E and F are predominantly negative, except for summer in northern Buenos Aires–Litoral (F) (not shown). The average of the 3 regions presents an annual trend of −0.394 events/year, significant at a 95% level.

Hail frequency trends in southern (A) and northern (B) Patagonia, present different signs, in both cases non significant (Fig. 8a, b). In the second region(Fig. 8b) there is a slight negative and inter decadal variability, similar, but attenuated, to that of the neighboring region of southern Buenos Aires–La Pampa (C) with an increase in the number of events at the end of the 90s. In southern Patagonia (A) there was a positive trend that may respond to a strong inter decadal variability with an outstanding increase in the number of events between late 90s and the beginning of 2000 decade, while the least number of events took place during the mid 80s (Fig. 8a).

Since hail events are related to low level warm anomalies and cold or very small anomalies at the upper troposphere, it

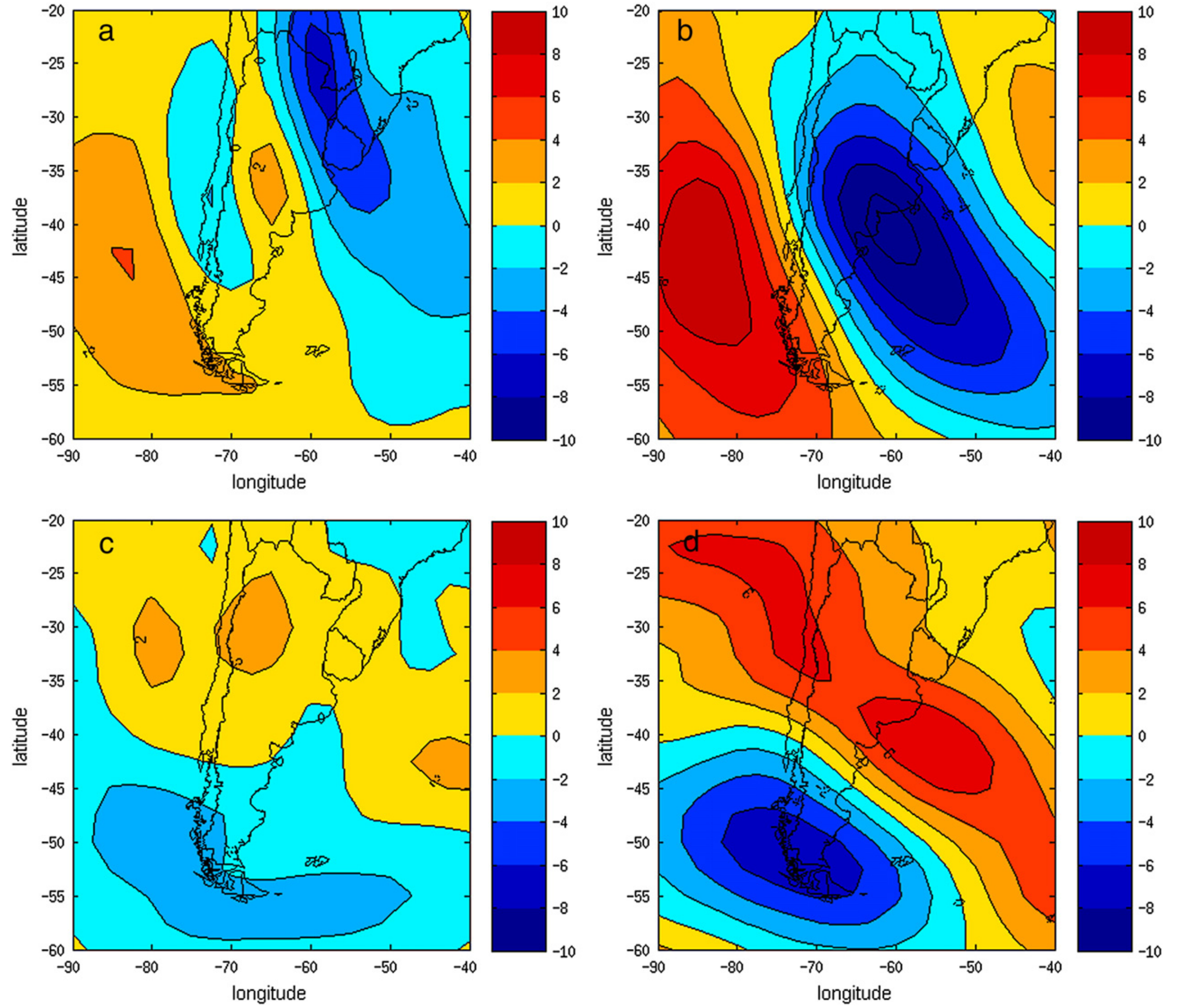


Fig. 7. Anomaly fields (m/s) associated to 63 hail events during the 1980–2008 warm season for a) 925 hPa meridional wind, b) 250 hPa meridional wind, c) 925 hPa zonal wind and d) 250 hPa zonal wind component.

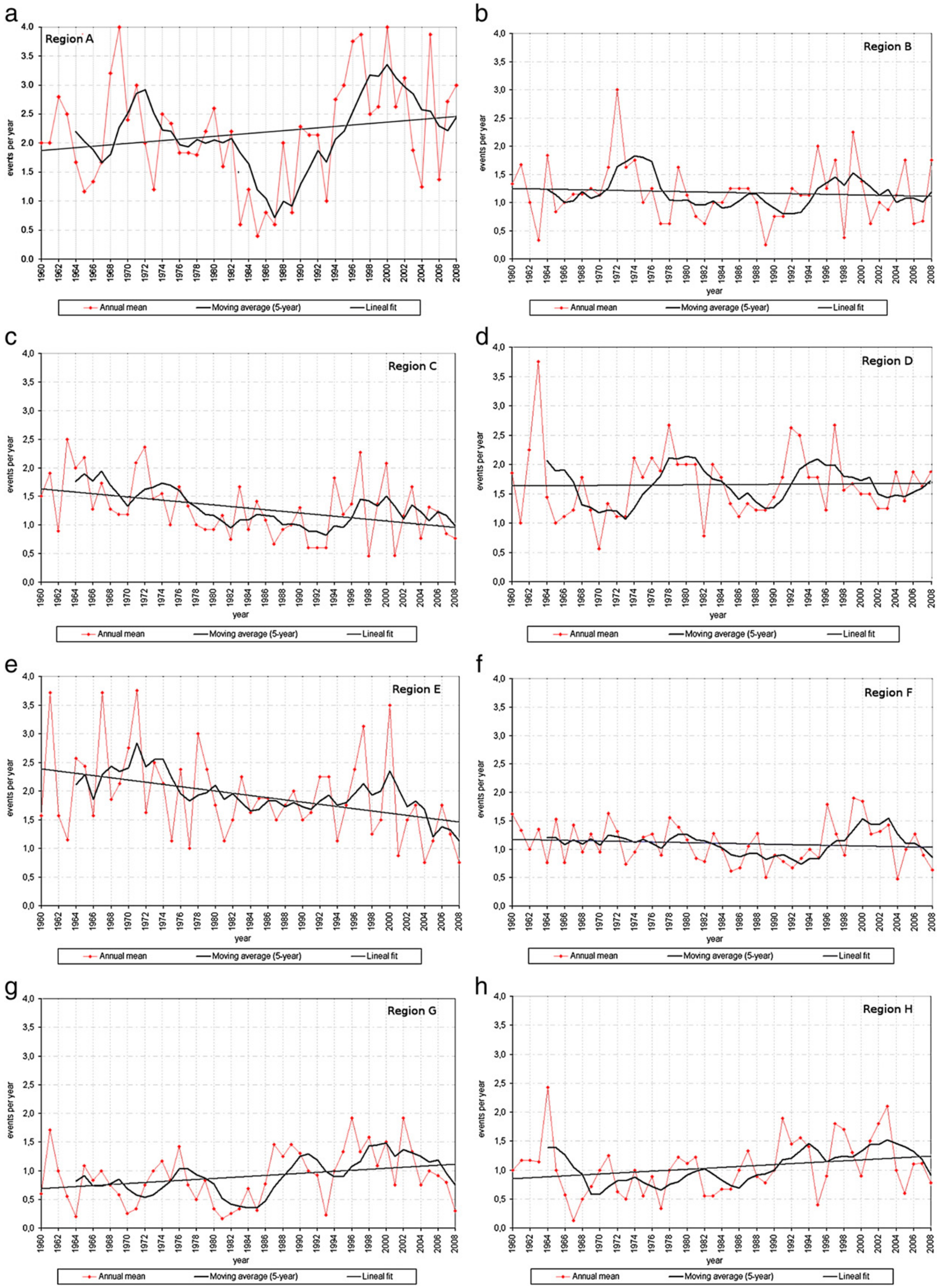
was intended to relate their trends with the trend of the difference in temperature between 925 hPa and 250 hPa averaged over the box delimited by 25°–32.5°S, 65°–57.5°W. However this cannot be done for the whole period starting in 1960 because initially tropospheric data from radiosonde in South America (SA) were rather sparse in space and in most of the cases with one daily observation. Hence, satellite information greatly contributed to improve the quality of reanalysis, but at the same time might have introduced discontinuities. In fact, Sturaro (2003) found that the period 1975–1979 was the most affected by inhomogeneities in the reanalysis resulting of the introduction of the global coverage of satellite infrared and microwaves.

The trend in the temperature difference between 925 hPa and 250 hPa was strongly negative, almost one degree in the 28 year period between 1980 and 2008, with a greater trend in the period August to October and a rather small one in November to January (Fig. 9), which are the two trimesters of the year with highest hail frequency. This trend is consistent only with the negative hail frequency trend of region E, because the respective negative trends of regions C and F were caused by changes prior to 1980 and none afterwards. In addition, the correlation of the temperature difference between 925 hPa and 250 hPa with hail frequency in region C is small and not statistically significant.

7. Conclusions

The comparison of the regional annual cycle of hail frequency shows certain continuity between neighboring

Fig. 8. Mean number of events per year and per station, 5-year moving-mean and linear trend for a) southern Patagonia , b) northern Patagonia, c) southern Buenos Aires and La Pampa, d) Cuyo, e) central Argentina, f) northern Buenos Aires and southern Litoral, g) northeastern Argentina and h) northwestern Argentina.


a
Region A
events per year
Annual mean
Moving average (5-year)
Lineal fit
b
Region B
events per year
year
Annual mean
Moving average (5-year)
Lineal fit
c
Region C
events per year
year
Annual mean
Moving average (5-year)
Lineal fit
d
Region D
events per year
year
Annual mean
Moving average (5-year)
Lineal fit
e
Region E
events per year
year
Annual mean
Moving average (5-year)
Lineal fit
f
Region F
events per year
year
Annual mean
Moving average (5-year)
Lineal fit
g
Region G
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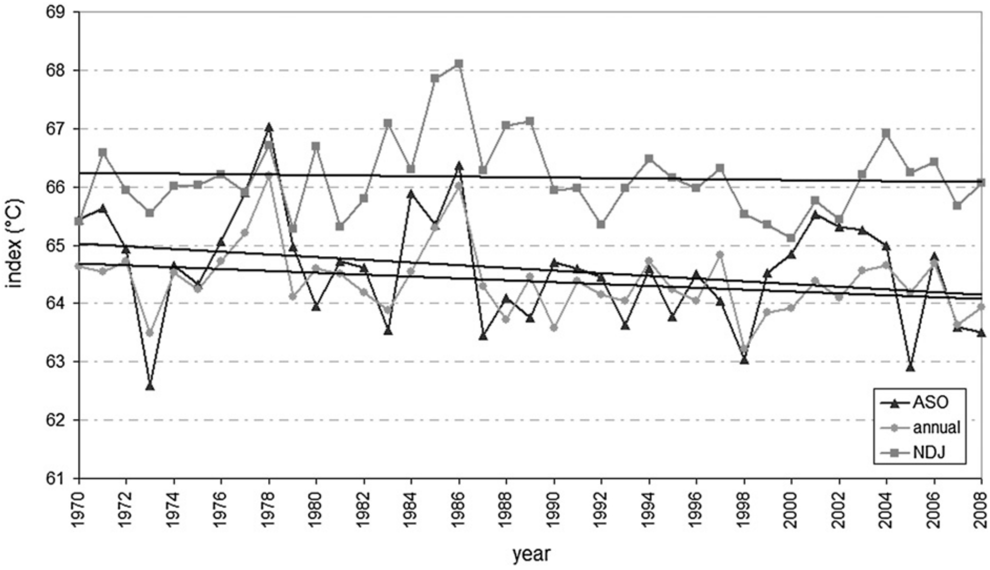

Fig. 9. Annual temperature difference between 925 hPa and 250 hPa and for August–September–October (ASO) and November–December–January (NDJ) trimesters. Temperatures were averaged over the box between 25°–32.5°S and 65°–57.5°W.

regions, though with expected differences driven by different precipitation cycles (Fig. 4). The same can be said respect to the annual trends (Fig. 8) and to the interannual variability; for instance, correlations between annual hail frequency of regional events between the neighboring regions C, E and F range from 0.44 to 0.48 for both the raw and the detrended series. These features indicate that, even though the random nature of hail makes it difficult to draw conclusions, especially when there is a rather sparse network of observing stations with reliable data, the large scale results described here can be considered robust.

The first conclusion is that the regions with higher hail frequency in Argentina are those associated either with mountain and coastal regions or fall in the latitude band between 30° and 40°S (Fig. 2). The annual cycle responds in west and central Argentina to the monsoonal characteristics of the precipitation with almost all hail events during the summer and spring season. In the east of the country and Patagonia, the higher frequency of hail events is in spring and early summer, with even important frequencies starting in July or August (Fig. 4).

The conditions associated with hail events in regions C, E and F show the known features of a strong vertical shear in the zonal wind and low level warm and humid advection as indicated by the northerly wind component (Fig. 7). Hail events were in average accompanied by a vertical stability reduction because of warming at low levels and with little warming or even cooling (in the months of November to January) in the upper troposphere (Fig. 5).

Finally, except for the Cuyo region, there were trends since 1980 in the hail event frequencies that appear ordered by latitudinal bands. The Northern regions, both in the West and East had a positive trend and so did the southernmost region of southern Patagonia; quite the opposite, in the latitude band between 30° and 45° S, the trend was negative and statistically significant in some regions (Fig. 8).

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