

1 Introduction

Recent volcanic crises (e.g. 2008 eruption of Chaitén, 2011 eruption of Cordón Caulle and 2015 eruption of Calbuco, Chile; 2010 eruption of Eyjafjallajökull, Iceland) clearly demonstrated that even small-moderate to subplinian eruptions, particularly if long-lasting, can paralyze entire sectors of societies with a significant economic impact. The increasing complexity of the impact of eruptions on modern societies, related to the interaction between natural, technological and social aspects, requires a shift in thinking in the field of risk analysis and management. As discussed in the Munich Re Topics Geo (2011) report: (i) integrated prevention on all levels is essential in view of the immense loss potential, (ii) specific research is needed to fill the gaps in our knowledge and analyse cause-and-effect chains, and (iii) loss prevention programmes must be implemented on a local, regional, national and international level, in both the private and the public sector. Actions necessary for preparedness require consideration of hazard, vulnerability and corresponding risk for the development of comprehensive and reliable contingency plans. In this paper we study the local impact of the 2011 eruption of Cordón Caulle volcano (Chile) that dispersed a large volume of rhyolitic tephra over Chile and Argentina during 9 months as far as the Atlantic and the Pacific Oceans (e.g. Collini et al., 2012; Pistolesi et al., 2015; Bonadonna et al., 2015a, b; Wilson et al., 2013). In particular, we report and discuss the effects of this well-studied eruption on the population, infrastructures and the environment to better constrain the relationship between natural phenomena and society response, which is a necessary first step to improve preparedness.

The Puyehue-Cordón Caulle Volcanic Complex (PCCVC) is located in the Southern Volcanic Zone of the Central Andes. This Pleistocene-Holocene complex comprises a 20 km-long, NW–SE oriented fissure system (Cordón Caulle; CC) and a stratovolcano topped by a summit caldera (Puyehue) to the SE, together with some remnants of other Pleistocene volcanoes (Lara et al., 2006; Singer et al., 2008). At least five historical eruptions have been recorded for the CC volcano (1759, 1893, 1921, 1960

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and 1990). The impact of the 2011 eruption was limited to areas close to the volcano in Chile, while in Argentina a wide area was affected by tephra dispersal and fallout, including important towns such as Bariloche, Villa La Angostura and Ingeniero Jacobacci, between 50 and 240 km from CC (Fig. 1).

In this study, we compile data from the newspapers, scientific reports and satellite images (see Appendix A for more details) mainly to reconstruct a precise chronology of events and the local and regional impact of the 2011 CC eruption, as well as the management of the crisis at different localities in Argentina, where ash dispersal and deposition strongly impacted environment, population and various economic sectors. Detailed studies on eruption impact are necessary to assess the damage and fragility of a system and better forecast the consequences of future eruptions (e.g. Wilson et al., 2010, 2011a; 2012, 2013). In the final part of this paper we also compare the impact of other moderate to large explosive eruptions in the Andes of the last century, and we present a probabilistic analysis of atmospheric and eruption conditions in order to evaluate the possible impact of future eruptions.

Terminology

Considering that some of the information is taken from newspapers and scientific reports, with the term “ash” we refer here to the general connotation of “tephra”, i.e. pyroclastic particles irrespective to size, morphology and composition injected into the atmosphere during volcanic explosions. In addition, we use the term lahar to indicate a mixture of rock debris and water, which encompasses a continuum from debris flow (sediment concentration $\geq 60\%$ per volume) to hyperconcentrated streamflows (sediment concentration from 20 to 60 % per volume) (Lavigne and Thouret, 2000). Finally, with re-suspension we describe aeolian remobilization of pyroclastic deposits (e.g. Wilson et al., 2011b; Folch et al., 2014).

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2 Ecosystem and local economic activities

In the area impacted by the eruption, three natural regions are present from west to east: South Andes, Andean foothills and Lowlands (Fig. 2) (Bran et al., 2000, 2002). South Andes present an average elevation at c. 2000 m, with the highest peak at Lanín volcano (3776 m a.s.l.). The landscape is characterized by glacially-sculpted steep slopes, glacial and tectonic lakes and flat valley floors of fluvial and glacio-fluvial outwash. The climate is cold, with an average temperature of 10 °C and an annual precipitation varying between 800 and 2500 mm, with most of the precipitation occurring in winter mainly as snowfall. The vegetation between CC volcano and Villa La Angostura is the Valdivian rain forest. Tourism is the most important activity in this area.

Andean foothills are located east from the south Andes; annual precipitation varies between 300 and 800 mm from west to east. The vegetation includes a steppe of grasses and shrubs, and wet-meadows covering 5–10% of the area. The main activity is the pastoral farming of cows and sheep. Lowlands (also called extra-Andean Patagonia) are located in the eastern sector; the climate is dry and cold with annual precipitation varying between 200 and 300 mm (Fig. 2). The area is characterized by a steppe of grasses and shrubs with wet-meadows covering 3% of the area. The main activity is the extensive pastoral farming of cows, sheep and goats.

3 Eruption chronology

The chronology described in this chapter includes both information on the pre-eruptive period as well as data collected during the eruption, i.e. National Service of Geology and Mining of Chile Volcano Observatory of the Southern Andes (SERNAGEOMIN-OVDAS, 2010–2012), Buenos Aires Volcanic Ash Advisory Center (VAAC Buenos Aires), and satellite imagery (MODIS-Aqua Terra, GOES).

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3.1 Pre-eruptive period

The SERNAGEOMIN–OVDAS has been monitoring the PCCVC since 2010. During the period between June 2010 and March 2011, all the monitoring reports on volcanic activity fixed an alert Level 1 (Table 1). The seismic record for that period mainly included volcano-tectonic (VT) earthquakes with magnitudes lower than 2.7 and depths of about 10 km (Table 1). From August 2010 seismic activity in the area of the Cordillera Nevada-Cordón Caulle increased, with long period (LP) earthquakes registered in September 2010 related to hydrothermal processes or release of magmatic gases at low pressure. From March 2011 OVDAS reported a significant further increase in seismicity peaking on 19 April, when the alert level was raised to Level 2-Green (Table 1). On 26 April, residents reported the presence of a gas and ash column rising from the area of International Chile-Argentina border (Cardenal Samoré pass). SERNAGEOMIN staff installed two additional seismographs and conducted an overflight that did not reveal any substantial change in the volcanic activity. On 27 April 2011 a seismic swarm below the CC system was recorded and the alert level was changed to Level 3-Yellow (Table 1). During the month of May seismic activity below the PCCVC increased, and both hybrid (HB) and LP earthquakes were recorded; on 4 and 17 May two events were recorded with local magnitudes of 3.6 and 4.2, respectively, which were clearly perceived by the population. SERNAGEOMIN warned about the possible destabilization of the volcanic system and the alert level remained at Level 3. On 1 June, a significant change in seismic activity was reported, with a seismic swarm characterized by LP and HB type events (c. 750 events in 32 h) located SE of CC and showing a migration of hypocentres toward shallower levels (2–5 km). On 2 June, an average of 25 earthquakes per hour was recorded, including a 3.8 magnitude, HB-type event. Due to this new escalation in seismic activity, the alert was raised to Level 4 - Orange (SERNAGEOMIN-OVDAS, 2010–2012). On 3 June seismic activity increased to an average of 60 earthquakes per hour (LP and HB-types). During the morning of 4 June, seismicity evolved to 230 earthquakes per hour, 12 of them with local magnitude

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greater than 4 and 50 with magnitudes greater than 3; seismic activity was also characterized by high-energy tremor located in the vicinity of the CC complex, between 1 and 4 km of depth. Alert level was changed to Level 5-Red (Table 1), implying imminent eruption (SERNAGEOMIN-OVDAS, 2010–2012).

5 3.2 Eruptive dynamics and volcanic cloud evolution

On 4 June, around 14:45 LT (local time) (i.e. 18:45 UTC), the eruption began with the generation of a 10–14 km a.s.l. high and 5 km wide plume. Alert level was raised to Level 6 (Moderate eruption, Table 2) (SERNAGEOMIN-OVDAS, 2010–2012). According to the local media, around 19:00 UTC, the ash cloud reached the Chile-Argentina international border, where “a rain of hail made of volcanic material” was reported. In Villa La Angostura (48 km from the vent), a fallout of “small stones” was reported in the afternoon, which evolved to fallout of finer material around midnight. In Bariloche (98 km SE of the vent) the sky became dark and ash began to fall at 19:10 UTC, accompanied by clearly audible explosions.

15 On 5 June the plume reached the Atlantic Ocean 1800 km ESE of the volcano, while a large area of Argentina territory was already affected by ash fall. In the morning, the intensity of tephra fall increased in Villa La Angostura, where the deposit of ash and fine lapilli reached a thickness of about 20 cm. In the town of Villa Traful (65 km east from the vent) ash began to fall at 22:00 UTC on 5 June, where the media reported intense ash fall and an accumulation of 2 cm of ash. On the same day, at 21:45 UTC 20 OVDAS reported the generation of at least 5 pyroclastic density currents (PDCs) that moved north of the vent along the river Nilahue valley (Fig. 1).

The southern part of Río Negro province was affected by ash fall since 5 June. Ash fall was reported at Pilcaniyeu, Comallo, Ingeniero Jacobacci, Maquinchao and Los 25 Menucos, referred to as “Línea Sur” (136, 168, 237, 300 and 344 km from the vent, respectively; Fig. 3). In Jacobacci, the media reported that ash reached a thickness of 4 to 10 cm and had a “talc-like” aspect. In the Chubut region (Fig. 2), the area covered by ash was estimated at 200 km². In Chile, ash fall was reported in the town of Entre

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Lagos and in Termas de Puyehue, and also affected the nearby rural areas of Lago Ranco.

On 6 June the plume abruptly changed direction toward NNE and then shifted direction again towards SE, at about 1000 km from the vent, reaching the Atlantic Ocean 5 about 3000 km downwind. Ash fall was recorded in the towns of San Martín de los Andes (from 05:00 to 08:00 UTC) where tephra accumulation was in the order of few millimetres up to 10 cm in some areas. In Bariloche and Villa La Angostura, ash fall was recorded since the morning and with greater intensity in the afternoon, although according to the press, the episode was less intense than that occurred on 4 June. The 10 tephra dispersal area reached the southern province of Buenos Aires and the provinces of San Luis, Mendoza, San Juan, La Pampa and Córdoba, between 800 and 1400 km from CC.

On 7 June the plume reached 5.5 to 9.8 km a.s.l. with ESE orientation (Buenos Aires VAAC). According to the media, on that day ash fall remained intense especially in 15 southern Neuquén region. In Villa La Angostura, ash fall mixed with rain was reported during the night.

On 8 June the volcanic cloud (10 km high a.s.l.) was dispersed towards NE with a bend toward SE 400 km away from the vent. OVDAS also reported PDCs in the Nilahue valley, where the river reached a temperature of 45 °C (SERNAGEOMIN-OVDAS, 20 2010–2012). The west portion of Neuquén and Río Negro Provinces was severely affected by ash fall, with strong winds remobilizing most of the deposited tephra.

On 9 June the plume had a NE direction. Ash reached Buenos Aires, Montevideo and southern Brazil, generating important flight cancellations. In Villa La Angostura and Villa Traful, rain reduced ash re-suspension.

25 On 10 June the plume was dispersed to the ESE. Ash resuspension was reported in many areas of the “Línea Sur”. Two lahars that affected main roads were generated, one close to the International border on the international road 231 and the second near Villa Traful on road 234. On 11 June the eruption column showed oscillating height and reached a maximum height of 4.5–6. km a.s.l. in the morning. From 19:00 UTC

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ash fell again in Bariloche, although with finer grain-size compared to the beginning of the eruption. Around 20:00 UTC, large explosions occurred associated with a column height up to 10 km a.s.l. (Table 2).

5 The direction of dispersal shifted again to the NE on 12 June. In Villa La Angostura, ash fell together with rain, aggravating the situation due to electric shortage and flooding. Explosions started to become more frequent.

10 On 13 June, OVDAS reported a change in eruptive activity characterized by episodes of increasing and decreasing tremor associated with changes of plume height. Ash fell in Bariloche, Villa La Angostura up to the “Línea Sur”, also affecting a large part of the province of Buenos Aires and of southern Uruguay. Oscillations of the eruptive column were accompanied by ballistic ejection, with bombs reaching distances up to 1 km from the crater. Direct visual observations revealed a crater with a diameter of 300–400 m (SERNAGEOMIN-OVDAS, 2010–2012). Oscillating activity continued throughout 14 June with the high-intensity events being characterized by very dense dark eruption column with heights up to 11 km a.s.l. and lightning observed during overnight. Sporadic formation of PDCs travelling down the Nilahue River was also reported.

15 During the 15 and 16 June occurred a continuous harmonic tremor suggesting a slow rise of magma along the conduit, which was shortly followed by outpouring of lava from the crater. The lava flow went westward from the pumice cone generated during the first phase of the eruption (Bertin et al., 2012; Tuffen et al., 2013). The harmonic tremor stopped on 23 June, when the alert level was lowered to Minor eruption (Table 2). During the rest of June, the plume height varied between 4 and 6 km a.s.l. Winds mainly dispersed ash over Argentina, except on 22, 23, 25 and 26 June, when the cloud was directed to NNW.

20 Lava effusion and low intensity ash emission continued for several months. On the 22 January 2012 a lahar affected the road 231 near the town of Villa La Angostura. One month later (21 February 2012) another lahar flowed down the Nilahue river and broke down a bridge. The alert level was lowered to Orange on 23 March 2012 and to Yellow a month later (23 April 2012), when OVDAS reported ash emission with

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minor explosions and ash plumes lower than 1 km. In August 2012 the alert level was lowered to Green, when OVDAS reported the absence of ash emission, with a gas column lower than 200 m and residual movements of the lava flows (SERNAGEOMIN-OVDAS, 2010–2012). In January 2013 the lava front was still slowly advancing, despite the lava effusion from the vent had already ceased 6–8 months earlier (Tuffen et al., 2013).

4 Evacuation

4.1 Chile

10 On 4 June, before the beginning of the eruption, ONEMI (Oficina Nacional de Emergencias de Chile) declared a Red alert and ordered the evacuation of 710 people from 5 municipalities of Lago Ranco and 6 municipalities from Puyehue area close to CVPCC (Fig. 1). They also ordered the temporal closure of Paso Cardenal Samoré and the evacuation of the customs staff. Once the eruption started, the evacuation was extended to 3647 people including the localities in the municipalities of Río Bueno, followed by the evacuation of 500 people from the area of Nilahue in the morning of 6 June (Fig. 1).

15 On 19 June, based on the information released by SERNAGEOMIN, the localities of Lago Ranco municipality (Fig. 1) were considered safe and residents were allowed to return. Conversely, the areas close to the upper part of Nilahue river and its branches were still considered under the threat of potential lahars and floods, the zones < 10 m above the river level remained forbidden. In total, 4270 people were evacuated for 16 days, with a large part hosted by family members living in safe zones and 609 lodged in shelters in the regions of Los Ríos and Los Lagos (Abumohor and Díaz, 2011).

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lahars affected the international road 231, one close to the International border and the other in the vicinity of Villa La Angostura. On 10 June, a lahar locally interrupted a route near Villa Traful. Street flooding and paralyzing vehicles were reported on 9 and 10 June in Villa La Angostura.

5 Due to the accumulation of tephra on Lake Nahuel Huapi and on its various branches (Fig. 4b), the Naval Prefecture banned the navigation and closed lake ports. The pumice raft, which according to the media reached thickness between 12 and 30 cm, damaged the boat engines.

6 Tourism

10 Tourism (National and International) is the most important source of income in Villa La Angostura, Bariloche and San Martín de los Andes. As a result, the economic impact of the eruption was significant during both winter 2011 and summer 2012 mainly due to: (i) air traffic restrictions in Bariloche, Neuquén and San Martín de los Andes airports (ii) regulation of the land access to these areas and (iii) cuts in electric power.
15 About 80 % of hotel reservations were cancelled in Bariloche during the second week of the eruption. Ski resorts of Cerro Bayo (Villa La Angostura) and Cerro Catedral (Bariloche) were covered by ash, damaging infrastructures such as lifts. 900 small enterprises and 3500 job places were threatened, and the Chamber of Commerce estimated a loss of 200 million pesos (nearly USD 48 million). Tourism decreased by ~ 52 % in the
20 Neuquén region and by ~ 37 % in the Río Negro region with respect to the previous year, causing a total loss of 800 million pesos (about USD 187 million) due to hotel cancellations only (Barbier, 2012).

7 Impact on communities

Urban systems were impacted at different levels, as described in the following sections and summarized in Table 5.

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7.1 Urban areas

The areas most affected by ash fall included southern Neuquén province and south-central Río Negro, as well as northern Chubut (Fig. 3). Among the most affected localities are Villa La Angostura, Villa Traful, Bariloche and others located in the Línea Sur
5 (Ingeniero Jacobacci, Maquinchao, Los Menucos, Pilcaniyeu and Comallo).

The impact on urban areas and infrastructures varied depending on the distance from the vent and from the average position of the plume axis (e.g. ash thickness and grain-size), weather conditions and topography of the affected area (Tables 5 and 6). Intense tephra fallout (that produced a 10–12 cm-thick deposit) in Villa La Angostura
10 caused blackouts and cuts of water supply, obstruction of streets, ash accumulation on roofs and problems for daily activities over a long period due to ash resuspension (Fig. 4c). Moreover, this area being characterized by high relief and abundant availability of water, lahars were frequently generated. After the first days of the eruption, a warning was raised in Villa La Angostura about the possibility of generation of lahars
15 triggered in the upper catchment of the area. The COE (Emergency Committee) reported 64 houses located on the fan and the river terraces exposed to lahars. Low wet areas close to the lake “Mallin” (old delta deposits) also experienced flooding.

Between 7 and 10 June, floods occurred in Bariloche following 30 mm of rain in the urban area and 10 cm of snow on the neighbouring hills, affecting several houses and educational establishments. Bariloche was also affected by 2–5 cm of ash fall. In the
20 southern part of the province of Río Negro, ash thickness varied between 3 and 8 cm (Table 7).

7.2 Disruption of communications and public activities

During the first few weeks of the eruption, communications, either fixed, mobile or Internet telephony were interrupted at various locations. In Villa La Angostura and Bariloche, shops, supermarkets and gas stations were saturated causing shortages of fuel and masks. Schools, public offices and even shops and banks remained closed
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in numerous localities. In Villa La Angostura classes and public administration were immediately suspended as the eruption started. Due to tephra accumulation making streets impracticable, shops were closed and public transports.

5 One 6 June, both educational and commercial activities were suspended in Bariloche, leaving only supermarkets and gas stations open, sourcing power through generators. Activities were resumed after 3 days, except for educational institutions that suffered some disruptions. Subsequently, discontinuous interruption of educational and public activities occurred during the days of ash fall and depending on the state of electric and water supplies. Health centres and hospitals suspended scheduled appointments and attended only emergency operations during days of high concentration of ash in suspension. By 19 June only 16 schools out of 65 could return to normal activity because cleanup was not completed.

10 On 6 June, educational and public activities were also suspended in Ingeniero Jacobacci. Shops were closed and health centres restricted to emergencies. At the local hospital, surgery was suspended because of the large amount of ash inside the building. On 10 June, commercial and public services were resumed, but schools remained closed. In the nearby towns, such as Los Menucos and Maquinchao, due to thinner ash deposit and strong winds, schools resumed classes during the second week of the eruption.

20 Educational and administrative activities were also suspended in more distal locations. In San Martín de los Andes, classes were suspended for a week and public activity was minimized. Health centres and hospitals continued working normally, and only scheduled surgeries were suspended. In Piedra del Águila, classes and public activities were suspended on 6 June. In the Upper Valley of Río Negro, in the towns of General Roca and Cipolletti, classes in schools and universities were suspended on 7 and 8 June, when plume was dispersed to NNE. In Chubut, 20 towns and settlements in the centre and north of the province suspended classes on 6 June. These resumed on 10 June with the exception of schools in rural communes.

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5 In the eastern province of Río Negro, the municipalities of Sierra Grande, Río Colorado and Cona Niyeu suspended classes for a week because of ash and strong winds. In the province of La Pampa classes were suspended on 9 June. During the first week, the meeting of ministers of Economy of the UNASUR (Unión de Naciones Sudamericanas – South American Nations Union) that was supposed to be held in Buenos Aires was also cancelled.

7.3 Isolation of towns and settlements

10 Disruption of land and water traffic isolated towns and settlements. On the outskirts of Villa La Angostura, people living on the coast of Brazo Rincon lake (about 70 people) were isolated due to impracticable roads and impossibility of lake navigation. At the beginning of the eruption about 20 families were evacuated, but others remained isolated and suffered from shortage of drinkable water and food for livestock. In Bariloche, 50 people were stranded on Victoria Island by the impossibility of navigation on Nahuel Huapi lake, and were rescued by the Coast Guards only on 9 June. Isolated people were also reported in smaller towns around Bariloche. In Villa Tráful, the municipality managed to provide inhabitants of the opposite side of the lake who remained in their homes with food and water.

15 Between 5 and 9 June the towns of the Línea Sur remained isolated due to the closure of the routes due to poor visibility. In addition to the closure of the routes, drivers avoided using vehicles to prevent damage due to ash, including clogging of air filters. Between 7 and 9 June, a wind storm exacerbated the situation hindering the supply of vital products and the arrival of aids from the national and provincial government. Around Ingeniero Jacobacci, families and indigenous communities were isolated, suffered water shortages and were forced to remain in their houses due ash storms caused by strong winds. Road traffic was forbidden and people were recommended to stay at home, and to go out only in case of emergencies using goggles and masks.

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8 Impact on infrastructures and lifelines

8.1 Electric system

The electric supply was damaged since the start of the eruption in almost all localities affected by ash fall, causing cascading problems to water supply, trade and educational and administrative activities. Supply failures had different causes, including ash accumulation on the network, damage to substations, power plant failures due to falling of both trees and poles and lightning. As a consequence, energy companies had to schedule additional interruptions for cleaning and maintenance purposes. In Villa La Angostura, blackouts began during the first week of the eruption and lasted for one month. On 8 June, widespread ash fall mixed with rainwater caused cut-offs due to wet ash deposition on the insulating lining.

According to the director of Villa La Angostura EPEN (Provincial Agency for Energy of Neuquén), during the first days of the eruption, services were restored only in strategic areas, such as hospitals, fire-fighter stations and crisis committee meeting sites. Continuous power outages lasted until 24 June (with 40 % of the town without power), followed by sporadic events after June.

Causes of energy cut-offs in Villa La Angostura included failures of the power plant, transformer stations and insulation of the power lines, particularly during days of falling ash and rain (e.g. 8 and 9 June). The EPEN scheduled power cuts for cleaning low voltage lines, and simple protection measures with PVC pipes solved problems due to the adhesion of ash on the conductors of the electrical system.

In Bariloche, cuts in the electricity supply were also recorded from the beginning of the eruption, including the Alicurá-Bariloche high-voltage 132 kV power plant. Reported power cut-offs were more frequent during the first and second week of the eruption, later occurring sporadically. On 6 June, the ash fall mixed with rain caused cuts in the transformer station of Bariloche (La Paloma). In the morning of 7 June, a massive blackout of more than 12 h was reported in town.

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In the Línea Sur, power failures were also reported. On 8 June, a heavy windstorm hit the area causing power outages caused by accumulation of remobilized ash on high-voltage masts. After the first week of the eruption electric cuts were sporadic. In Villa Traful, problems on the power supply were reported since the first ash fall episodes on 5 June.

8.2 Water and drainage systems

Tephra fall also affected the water supply at various locations. In areas where the water intakes are in open courses, the service was interrupted due to the high amount of suspended material. At sites where the sockets were located on the lake, tephra clogged pumps and filters, and temporary water shortages occurred during maintenance operations, such as replacing pumps. In some cases, cuts in water service were directly related to power outages.

In Villa La Angostura the media reported water cuts since the beginning of the eruption and, by 9 June, water service was interrupted in the neighbourhoods located at higher elevations. The EPAS (Provincial Agency for Water and Sanitation) replaced pumps and performed maintenance and cleaning operations of the water intakes and, from 20 June, the service was restored in most of the town, except in Puerto Manzano (port in Villa La Angostura), where the intakes are on the surface of the lake. Intakes located in the rivers Bonito (south of town) and Correntoso (north of town) were closed due to the high amount of floating and suspended material. EPAS conducted monitoring of drinking water quality and found no toxicity. In Bariloche, where most intakes are located on the lake and to a lesser extent in streams and springs, the increase of suspended material required an increase in maintenance. On 9 June, a breakdown of the system occurred, and the municipality distributed drinking water to the population. Supply disruptions were also reported for the neighbourhoods at higher elevations that depend on intakes in springs or streams. The Provincial Department of Water performed analyses to warrant drinking-water qualities. In the Línea Sur, problems with water supply were related to electricity breakdown. In Villa Traful water supply was also

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disrupted because 90 % of drinking water comes from streams, leading to increase turbidity and temporary closure of water intakes, to avoid abrasion and clogging. In San Martín de Los Andes, the Provincial Department of Water suspended water intake in the river Quilquihue and the storage tanks were used for supply.

5 In Villa La Angostura and Bariloche, obstruction of urban drainage systems occurred during rainy days because water-indurated ash deposited on the streets. Municipality teams used dedicated machinery to remove the ash. At the beginning of the eruption Villa La Angostura received assistance from other municipalities because they had no proper machineries and staff to clean the roads.

10 8.3 Roof collapse

Collapse of roofs happened in Villa la Angostura, Bariloche and Brazo Rincon (northern limit of Nahuel Huapi Lake) but with no associated injuries or casualties. On 8 June, a whole restaurant collapsed in the area of Paso Samoré, partially due to poor construction (i.e. thin roofs, wooden structure; Fig. 4d). In Bariloche, roof collapses were
15 mainly reported in the poorest neighbourhoods, such as “El Alto Bariloche”. After 14 days from the beginning of the eruption, 147 houses made of metal and wood were significantly affected. The ceiling of a school also collapsed, but it was not clear if this occurred due to the accumulation of ash.

9 Impact on animals

20 9.1 Livestock

The Cordón Caulle eruption intensified the crisis that had been affecting the livestock sector since 2007 due to persistent drought. This resulted in loss of animals, low birth rate and high predation. A few days after the beginning of the eruption, ash had already covered grass and water pools causing a shortage of water and forage for the
25 animals. Ash re-suspension also disoriented animals that could not feed anymore.

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The most affected departments in the Province of Neuquén were those located between the Cordillera and the extra-Andean Patagonia. The total number of animals at the moment of the eruption, including sheep, goats and cattle, was 149 000. Given that livestock producers depend on the forest to feed their animals and that many producers
5 had no reserves, the mortality rate for animals was high due to lack of food and was estimated at 22 % (number of animals; Anselmi et al., 2012). The southwest departments of Río Negro Province (INTA-EEA, 2011) were the most impacted in terms of number of producers and of animals affected (total of 1400 farmers who raise sheep, cows and goats). The decrease in the production of wool and the loss of animals varied
10 according to the amount of accumulated ash (Fig. 5a). The areas with the largest impact were those suffering ash accumulation thicker than 3 cm, where accessibility to forage was low. The northern departments of Chubut Province were also affected with ash accumulation between 0.3–4 cm (INTA-EEA Chubut, 2011).

Reported problems to livestock included eye irritation, difficulties in breathing and
15 digestion. In many places, an accelerated aging of the flocks by the wear of the teeth of animals was observed (Giraudó and Villagra, 2011). These factors contributed to the reduction in the income of producers, most of whom depended on complementary feeding for animals provided by National, Municipal governments and INTA (National Institute of Agricultural Technology). Animals ingested large amounts of ash in areas
20 where the grass was covered. The ash accumulation and passage through the digestive tract of animals produced alterations of different types. The presence of ash was detected in the digestive tract in sheep and by observed changes in the colour of the mucosa or inner wall of the digestive organs (Robles, 2011). In the case of sheep, the change in diet, generated by the ash fall, plus supplementation with forage and
25 implemented grains, possibly triggered early outbreaks of enterotoxemia (enteric and septicaemia disease caused by different types of *Clostridium perfringens* and its toxins). Cases of diarrhoea and sudden death were reported for cattle, but it is not clear whether they were due to direct action of the ash or to an infectious disease. For horses, colics and subsequent death were reported (Robles, 2011).

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The insecticidal effect of the Cordón Caulle ash removed much of herbivorous insects, such as grasshoppers, which feed on the vegetation of wet meadows, the main forage resource in the Patagonian steppe. In addition, it affected the bee populations in areas southwest of Río Negro and west of Neuquén, where a total of 1200 hives belonging to smallholders were estimated at the time of the eruption. A bee mortality of more than 70% was reported (Huerta, 2011). It also decreased the abundance of wasp known as “Yellow Jacket” (“Chaqueta amarilla”, *Vespula spp.*) in several locations in the mountainous area of Río Negro and Neuquén.

10 Impact on vegetation

A report by botanical experts and researchers from UNC and CONICET (Javier Puntieri and Javier Grosfeld, in Ubeda et al., 2011) emphasizes that “it is a benefit that the eruption occurred at that time of the year when most of the plants have very low metabolic activity”. They also stated that the germination of some species for the following spring could be compromised depending on the accumulation of ash and its dispersal. According to the experts, the greatest damage would have been on pastures in steppe area, but tephra could also break fruit buds and the branches of large trees in the forest areas (Fig. 5b).

INTA (Gaitan et al., 2011) conducted seasonal and inter-annual vegetation monitoring from MODIS image data to detect the effects of ash. The EVI (Enhanced Vegetation Index) is used to characterize bio-physical/biochemical states and processes from vegetated surfaces (Huete et al., 2002). Analyses were performed for 3 types of vegetation: forests, steppes and wet-meadows. They concluded that the ash had a negative initial impact on all the 3 types of vegetation, proportional to the thickness of ash fall. Gaitan et al. (2011) classified the Neuquén and Río Negro province surface in 10 classes according to the total tephra deposit thickness (from class 1: no ash, to class 10: 15–30 cm). In December 2011, forest sectors closest to the volcano kept EVI values between 30 and 35% below average. The steppes showed initial impact

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proportional to the amount of ash deposited and in December 2011, even though they had partially recovered, they were between 27% (class 2) and 37% (class 6) below the mean for the period 2000–2010. For wet-meadows (“mallines”), the recovery appeared to be associated to geographical location in relation to the level of annual precipitations, varying between 800 and 300 mm from west to east. Those located in the wettest area regained their activity, while wet-meadows located further east were still with values up to 50% below average.

To assess the impact on steppes, two studies were conducted. The first considered a transect along National Route 23 between Bariloche and Onelli and the second an experiment in the Precordillera (Ghermandi and Gonzalez, 2012). They confirmed a general delay in growth, mainly in wet-meadows and steppes, expressed in lower forage biomass per unit area (Siffredi et al., 2011). The second study was carried out on grasslands located 30 km east of Bariloche, where 20 forest clearings, representing sites of biodiversity and safe sites for the reproduction of the matrix species (grass and shrubs; Ghermandi and Gonzalez, 2012), were randomly selected. Species richness was lower after the eruption (24 vs. 17%), as it was the percentage of annual species (37.5 vs. 6%). They concluded that for the study area the impact on vegetation will be important and lasting, because the estimated value of accumulated ash on forest clearings of one hectare of pasture is high, coupled with the semi-arid climate of the region.

11 Impact on health

11.1 General well being

Although no official study is available, most locations reported increased medical visits for respiratory difficulties, eye problems and stress. At the hospital of Villa la Angostura, although no serious cases were treated, cases of gastritis (possibly related to lack of electricity and food preservation) and conditions related to stress (contractures, various

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pains, high blood pressure) were also reported. In San Martín de Los Andes, hospital visits for cases of eye irritation increased. On 8 June, the hospital in Cipolletti reported that 80% of consultations were for bronchospasm, asthma attack and eye irritation. The hospital of Roca reported cases of inquiries for respiratory problems. In Villa La Angostura, Bariloche and San Martín de los Andes, the media also reported psychological impact. The population was alarmed because the lack of information during the first days of the eruption.

Even though cristobalite was reported for the products of the 2008 Chaitén eruption (Reich et al., 1999; Horwell et al., 2010), it was not detected through X-ray diffraction of CC ash (Daga et al., 2014). Wilson et al. (2013) reported a low total amount of cristobalite in the CC ash deposit (0.21 ± 0.42 wt.%).

11.2 Air quality

Since July 2011, a SEGEMAR team for the control of air quality performed measurements of concentration of suspended particulate materials (PM_{10} ; equivalent aerodynamic diameter $\leq 10 \mu\text{m}$) at various locations (Villa La Angostura, Piedra del Aguila, Ingeniero Jacobacci and San Martín de Los Andes). Due to instrumental limitations, no concentrations of particles smaller than $2.5 \mu\text{m}$ in diameter, SO_2 and NO_x were measured. Values established by law 24.585 (Argentine Environmental law on standard air quality, water and soil levels) were taken as reference, indicating maximum levels of PM_{10} of $150 \mu\text{g m}^{-3}$ for a 24 h exposure and $50 \mu\text{g m}^{-3}$ for an exposure of one year. Systematic monitoring of PM_{10} was carried out for 10 months starting in September 2011 in Villa La Angostura and Ingeniero Jacobacci. The aim of this study was to assess the medium-term effects of ash fall. Two time periods were considered: the first one included determinations carried out one month after the eruption onset and for a short time (less than or equal to one week) and the second included determinations carried out between September 2011 and July 2012.

As an example, PM_{10} concentrations are presented in Fig. 6a and b for Villa La Angostura, representing measurements taken in July 2011 in the hospital and school

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CPEM68 (Centro Provincial de Enseñanza Media no. 68). In the hospital, the daily exposure limit ($150 \mu\text{g m}^{-3}$) was exceeded only once and outside of the building. For School 68 there is a correlation between outdoor and indoor concentrations, and in both cases the tolerance limit for daily exposure was largely overcome. Indoor, the concentration values decreased below the daily exposure limit ($150 \mu\text{g m}^{-3}$), but lay above the level of $50 \mu\text{g m}^{-3}$. Conversely, PM_{10} concentration for school 356 in Ingeniero Jacobacci, measured outside and inside of the building (Fig. 6c), shows that the air quality inside the school was higher, and only the value of 3 July exceeded the limit of $150 \mu\text{g m}^{-3}$. Outside, for days 3, 4, 5 and 6 July 2011, standard PM_{10} concentrations exceeded the limit of $150 \mu\text{g m}^{-3}$ for a 24 h exposure.

PM_{10} values measured between September 2011 and July 2012 are also presented in Fig. 7 for Villa La Angostura and Ingeniero Jacobacci in combination with wind and rain data. In both cities, the level of breathable aerosols was very high from September 2011 to January 2012 (high to moderate risk to health); values were above the annual limit in most of the stations, with some of them surpassing the daily limit. In Ingeniero Jacobacci, the PM_{10} concentrations were more than the double than in Villa La Angostura. This could be related to both the significantly finer grain size characteristic of Ingeniero Jacobacci (Bonadonna et al., 2015b), higher wind and lower rain fall (Fig. 7e and f).

12 Crisis management

12.1 Towns

Municipalities affected by ash falls organized emergency committees including Civil Defense, Fire Fighters, Police and Health departments among others. The municipalities of Cordilleran localities were informed about the increased seismic activity weeks before the start of the eruption, by the SERNAGEOMIN (Geological Survey of Chile) and SEGEMAR (Geological Survey of Argentina). Consequently, in Villa La Angostura,

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an emergency committee was formed 72 h before the onset of the event including local authorities, Civil Defence, Army personnel and civilian volunteers. Masks and 400 000 L of drinking water were prepared. In the remaining localities (Bariloche, Villa Traful, San Martín and Junín de Los Andes), emergency committees were organized during ash fall. Civil Defence conducted various press releases to inform the population, detailing a series of recommendations on how to deal with ash fall.

When problems in the supply of electricity and water arised, responsible agencies standardized services. Bodies responsible for electricity (EPEN Neuquén and CEB-Edersa Río Negro) conducted scheduled outages, maintenance, replacements and cleaning of lines, transformers and power plants. In all localities water analyses were regularly performed and in the most affected areas replacements of pumps, filter cleaning and water harvesting were scheduled where water intakes were located in streams. Distribution of potable water, masks, food and medicine was also orgainized.

Volunteer groups were organized to clean roofs (Villa La Angostura), streets (Bariloche, Ingeniero Jacobacci) and seal buildings openings (Ingeniero Jacobacci). In Villa La Angostura, Bariloche and Ingeniero Jacobacci, municipalities conducted street-cleaning operations, evacuating the removed ash by private trucks to municipal quarries. Removal of ash in Villa la Angostura was organized by the emergency committee. Over a million and a half cubic meters of volcanic ash and lapilli were removed in the eight months between 2011 and late April 2012 (Fig. 5c). In Villa Traful, cleaning operations continued until October.

During the first week of the eruption, most municipalities declared a state of emergency. In Villa La Angostura, funds designated for other purposes were used for emergency management, including funds from Government, Province and/or donations. In Villa La Angostura, Villa Traful, Bariloche and Jacobacci, aid was sent to the isolated rural inhabitants including drinking water, livestock grazing, firewood and masks. In the remaining municipalities affected by ash fall, emergency committees were assembled for communicating recommendations to the population and for scheduling the suspension of classes and public activities.

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Civil Defence personnel, army, and fire management volunteers cleaned the channels in order to prevent the formation of lahars (Fig. 5d). During the first weeks of the eruption, Civil Defense removed trees and temporary sediment that formed in streams in the area of Villa La Angostura. Between August and November, additional cleaning tasks in these streams were performed, including the replacement of bridges to avoid potential floods caused by their obstructions. In Villa La Angostura, a group of experts formed by Civil Defence personnel and mountaineers performed a daily to weekly monitoring of the stability of the snowpack with interbedded ash.

12.2 Provincial governments

12.2.1 Neuquén

The government of Neuquén sent to an official request to the National Parliament to declare a “state of economic and social emergency and environmental disaster”. A local declaration of “disaster area and emergency” was also signed with local entrepreneurs for San Martín de los Andes, which would result in tax benefits and credit to sustain employment. The Social Security Institute of Neuquén sent two trucks with 23 000 L of water and 13 000 masks for distribution in Villa La Angostura, Villa Traful, Bariloche and San Martín de los Andes.

12.2.2 Río Negro and Chubut

The government of Río Negro signed the declaration of Agricultural, Economic and Tourism Disaster for localities of the “Línea Sur” and the economic and tourism declaration of emergency for the departments of Pilcaniyeu and Bariloche. Aid sent by the central Government was delivered, including a contribution of 1 million pesos for the municipality of Bariloche, another 500 000 pesos for Jacobacci and 150 000 pesos for Pilcaniyeu, Comallo and Maquinchao. Potable water and forage were distributed. The Provincial Civil Defense adopted preventive measures in all locations and worked

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(Kalnay et al., 1996) for the period 2000–2015, providing 4-daily wind profiles. No relevant seasonal pattern was observed below 20 km a.s.l. (Fig. 8 and Appendix B).

1000 eruptions were simulated following the long-lasting eruption range scenario of Biass et al. (2014). For each simulation, eruption dates and durations were stochastically sampled within the predefined ranges in order to retrieve the corresponding wind profiles. The median and sigma values of a Gaussian total grain-size distribution were sampled (Table 8), and aggregation is accounted for using the method of Bonadonna et al. (2002) (see Biass et al. (2014) for more details). The entire eruption duration was split into 6 h-long intervals, for which a plume height was sampled and converted into an erupted mass using the formulation of mass eruption rate of Degruyter and Bonadonna (2012). ESPs were assumed constant over 6 h long periods, and each 6 h period was sent separately to the TEPHRA2 model. The final accumulation consists of the sum of these separate periods.

Results are presented in various forms (Fig. 8). First, we compiled maps contouring the probability of exceeding a given tephra accumulation. Figure 8a shows the geographical distribution of probabilities to exceed an accumulation of 10 kg m^{-2} , which indicates damage to vegetation (hazard map for 1 and 100 kg m^{-2} are shown in Appendix B for disruption of airport operation and collapse of the weakest roofs, respectively; see Figs. B1 and B2); exceeding probabilities of tephra accumulation are also shown as hazard curves for selected towns (Anticura and Riñinahue in Chile and San Martín de Los Andes, Villa Traful, Villa La Angostura and Bariloche in Argentina; Fig. 8b). Probabilities $> 60\%$ of reaching 10 kg m^{-2} are shown only for the Chilean area and are $< 60\%$ for the Argentinean area (Fig. 8a and b). Only the towns of Anticura (Chile) and Villa La Angostura (Argentina) reach accumulations $> 100 \text{ kg m}^{-2}$, while the lowest accumulations are shown by San Martín de Los Andes and Bariloche ($< 20 \text{ kg m}^{-2}$; Fig. 8b). Second, probability maps were converted into probabilistic iso-mass maps, which show the typical tephra accumulation given a probability of occurrence of the hazard (e.g. Biass et al., 2013). Figure 8c shows the probability of occurrence of 1, 10, 50 and 90% for the tephra accumulation of 100 kg m^{-2} compared to

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the accumulation of 100 kg m^{-2} observed for the climactic phase of the eruption (4–5 June), suggesting that this phase is within 1% of all the possible atmospheric conditions recorded in the last 15 years. In fact, the most common wind direction is towards east, i.e. median values of 90° from north (Fig. 8d). The median value of 90° from north is constant for all months, i.e. there is no significant seasonal variability of wind direction (Fig. 8d). The dispersion that characterized the whole month of June 2011 was anomalous with respect to the general trend as it swept from SE to NE with only a few days being dispersed directly E (i.e. 20% of the time: 11, 14, 15, 23 and 28 June; Table 2).

10 14 Discussion

The orientation of the Southern Andes volcanic arc, the persistence of westerly winds and the location of human settlements on both sides of the Andean Cordillera, imply a largely different impact of explosive eruptions on Chilean and Argentine settlements. In general, Chilean settlements are exposed to proximal phenomena (coarse tephra fallout, PDCs, lava flows, lahars) while Argentine settlements are often affected by significant lapilli and ash fallout dispersed over very large areas.

The 2011 Cordón Caulle eruption produced multiple types of impact in different areas as discussed in the previous sections. Table 9 summarizes the principal types of recorded impact, the affected areas, beginning and duration of impact, deposit thickness and mean grain size. The map in Fig. 9 shows the distribution of the different impact types associated with each locality. In this paper, the different types of impacts were identified and described in a qualitative way. As there is no quantification of the impact, the parameters used for comparing the impact at different areas is the number of different impacts recorded. From these data, it can be observed that the localities with a thickness of tephra higher than 2 cm suffered a larger variety of impacts than those with less than 2 cm of tephra thickness (Fig. 9a). These areas experienced disruption to transport systems (aviation, ground transportation, navigation), cut-offs of electric and

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water supply, suspension of activities in urban areas, health problems, agricultural and livestock disruptions, vegetation damage, animal death, floods and lahars. The impact not only varied according to the thickness (and distance from vent), but also according to the amount of population and degree of development of urbanization. For instance, Bariloche, with a relatively small ash thickness compared to Villa La Angostura (Table 6), recorded a variety of impact typologies (Table 7) due to the higher population density and urbanization. In medial areas, with a deposit thickness of 3 to 1 cm along the plume axis, several types of impact were experienced, including roads closure, cuts of electric and water supply, suspension of activities in urban areas, health problems, agricultural and livestock disruptions, vegetation damage and animal death. In distal areas (1 cm or less of ash), the impact recorded included agricultural and livestock disruptions, interruption of transport systems (closure of airports and roads) and suspension of activities during days of ash fall or re-suspension. It is important to note that the thickness reported in the media was higher than the measured thickness, except for Paso Samoré section, where the measured thickness was higher (Table 6). Besides the thickness, grain-size is a very important factor conditioning the type of impact. Figure 9b shows the impact map with the median diameter ($Md\phi$, with $\phi = -\log_2 D$, where D is the particle diameter in millimeters) for Unit I (Bonadonna et al., 2015b) and the Table 9 summarizes the $Md\phi$ interval for each impact. The large amount of dispersed ash also extended the impact to distal areas. In areas with $Md\phi$ values higher than 2ϕ ($< 250 \mu\text{m}$) the impact consisted of a large variety of problems related with fine ash suspension (including road closure due to low visibility, cuts of electric and water supply, suspension of activities in urban areas, health problems, agricultural and livestock disruptions, air traffic disruption and closure of airports). Additional problems related to the coarser grain size of the fallout material were recognized in areas with $Md\phi$ values lower than 2ϕ : ground transportation, navigation due to sedimentation of lapilli on the lakes, roof collapse, vegetation damage, animal death, floods and lahars. The fine ash (PM_{10}) concentration measured during eruption in Ingeniero Jacobacci and Villa La Angostura is consistent with the $Md\phi$ values estimated (Fig. 7). PM_{10} values

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at Ingeniero Jacobacci ($Md\phi$ 5.42) were more than twice than in Villa La Angostura ($Md\phi$ 0.22).

Impact at proximal sites was possibly increased by the emplacement of the fine ash deposits related to the final, lower intensity phases of the eruption. For example, the occurrence of fine ash on top of the sequence was responsible for the high efficient rainfall runoff and downstream sedimentation producing floods and lahar events in Villa la Angostura and along the national road 231 between the Argentine-Chilean pass and Villa La Angostura. This effect has been largely described for several mid- to low-intensity eruptions also at Vesuvius, Italy (Cioni et al., 2008).

Interesting data and similarities emerge from the analysis of available information on impact related to other three large-scale, well-documented eruptions occurred in the last 100 years in the southern Andes: Quizapu (Kittl, 1933; Hildreth and Drake, 1992), Hudson (Naranjo et al., 1993; Scasso et al., 1994), Chaitén (Lara, 2009; Alfano et al., 2011; Major and Lara, 2013). It is interesting to note that the regions downwind or very close to the different erupting volcanoes suffered very similar impacts (e.g. health problems, damage to vegetation, death of animals, roof collapse, air traffic disruptions, roads closure, lahars and flooding), suggesting that a detailed collection of all the data on impact immediately after an eruption can help the development of contingency plans.

14.1 The 1932 Quizapu eruption

The Quizapu eruption of 10 April 1932 is the largest Andean eruption of the XX Century (tephra volume of 4 km^3 Dense Rock Equivalent, DRE; Hildreth and Drake, 1992). Although the eruption generated no casualties or injuries, it had a large economic impact even for the less developed societal and economic organization of the time. Similarly to CC, in proximal areas (Chile) lahars were reported; a dam break also generated damage downstream Río Maule (Hildreth and Drake, 1992). In Argentina, tephra fallout strongly affected the economy of the southern portion of Mendoza, La Pampa and Buenos Aires provinces, mainly based on subsistence horticultural farming, as a con-

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sequence of burial of cultivated and grass lands, and impact in urban areas (Mikkan, 2012). The impact of the eruption included a high mortality of farm animals, due to grass and water scarcity related to increased stream water turbidity. As a long-term effect, Abraham and Prieto (1993) remarked the intense desertification of south Mendoza as a consequence of the eruption.

14.2 The 1991 Hudson eruption

The eruption of Hudson volcano in August 1991 is considered the second largest eruption in magnitude in the XX Century for the Southern Andes. With a total volume of 2.7 km^3 (DRE), the eruption covered with tephra a great surface of Santa Cruz and Chubut provinces (Argentina), and fallout was reported as far as 1000 km in Malvinas (Falkland Is.) (Naranjo et al., 1993; Scasso et al., 1994). The impact of this eruption, very similar to that described for the CC eruption, included big economic losses in Patagonia, mainly from the impact on livestock and crops, air traffic disruption and water contamination. As in CC, Wilson et al. (2010, 2012) also reported interruptions and

disruptions in electricity and water supply, accumulation of pumice in lakes over a long period of time, abrasion and weathering of machinery and electrical devices. An important psychological-social impact in the population was also recorded, together with farm and towns abandonment (in Puerto Ibañez, Chile, spontaneous evacuation of people was gradual, reporting a decrease of 30 % from a starting population of 4000). Desertification of the extra Andean Patagonia was an important long-term effect of the eruption that needs to be within a comprehensive long-term land-use planning. The eruption affected different types of farms, including pastoral farms with sheep and cattle and horticultural farms (Wilson et al., 2010, 2012). Similarly to the CC eruption, a massive loss of sheep (1 million) and cattle (about a thousand) in Argentina and Chile was estimated, due to burial of vegetation from ash, water contamination and animal poor health conditions. As in the case of CC eruption, Wilson et al. (2010, 2012) also reported animals with gastrointestinal affections, teeth abrasion, blindness, immobilization and dehydration. Impact on vegetation varied according to the thickness

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of the ash deposit. It has been reported that 2 to 5 years after the eruption vegetation recovered in the Cordillera and in the steppe. In some cases, mostly in horticultural farms, activity was strongly affected by remobilized ash, and recovery was accelerated after the tephra was mixed with the soils (Wilson et al., 2010, 2012). In the Chilean Cordillera, with the highest thickness of tephra, vegetation recovery was slower in spite of the high humidity. Pastures were completely lost where tephra thickness was more than 10 cm. Finally, a strong effect on post-eruptive resilience of the impacted territories was also related to the remobilization of ash, which started generating ash storms that extended for several months the problems related to the syn-eruptive phase.

14.3 The 2008 Chaitén eruption

The eruption of Chaitén volcano began in May 2008 and represents the most similar case to the CC eruption, in terms of magma composition and eruption intensity, magnitude and duration. Also in this case, however, the general problems related to the eruption were still not very different from those described for the largest eruptions of Quizapu and Hudson. Tephra was dispersed eastward from the volcano, affecting a wide area of Argentina with an estimated tephra volume of about 1 km^3 (Alfano et al., 2011). Chaitén town (4600 inhabitants, 10 km south of the volcano) was evacuated immediately before the eruption (Lara, 2009; Major and Lara, 2013). Tephra dispersal affected commercial airline traffic and disrupted activities in downwind communities. Also flooding, sediment transport and erosion affected Chaitén, disrupting aquaculture and tourism, among other activities.

In proximal areas, PDCs, tephra fallout and lahars heavily damaged approximately 480 km^2 of forest (Swanson et al., 2013). Within days of the heaviest tephra fall, small rainstorms produced an extraordinary sedimentation response in the Chaitén river basin, with an initial lahar followed closely by two surges of muddy floodwater. One of the main factors contributing to the high runoff capacity and the rapid downstream sedimentation appears to be the thick impermeable fine ash cover mantling the whole basin and the steepness of the basin slopes (Pierson et al., 2013). Lahars and floods

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Rainfall during the volcanic eruption can have both a positive and negative effect on impact: on one hand it can cause electric shortage, water clogging, flooding and lahar, but on another hand it helps to reduce ash resuspension and lower PM₁₀ values.

- 5 5. Impact on health: even though there are not official data on health, the hospitals reported increased medical visits for respiratory issues, eye problems and stress. A SEGEMAR team for the control of air quality performed measurements of PM₁₀ in Villa La Angostura and Ingeniero Jacobacci between September 2011 and July 2012. In both cities, the level of breathable aerosols from September 2011 to January 2012 was above the annual limit (50 µg m⁻³) in most of the stations (high to moderate risk to health), with some of them surpassing also the daily limit (150 µg m⁻³).
- 10 6. Impact on animals: ash covered agricultural lands (grass and water pools) causing a shortage of water and forage for the animals. The CC 2011 eruption intensified the crisis that had been affecting the livestock sector since 2007 due to persistent drought. This resulted in loss of animals, low birth rates and high predation. The ash impact on fish populations was variable; the microorganisms were the most affected among the aquatic biota. Native fish populations were mostly affected in terms of displacement of young members from the most affected coastal areas to the open waters with lower concentration of ash but less protected. The insecticidal effect of the Cordón Caulle ash removed much of herbivorous insects and affected both the bee and wasp populations.
- 15 7. Impact on vegetation: the eruption occurred at the beginning of the winter when most plants had very low metabolic activity, but the germination of some species for the following spring was compromised depending on the accumulation of ash and its distribution. In the Cordillera area thick deposit of fine tephra in forest canopy caused breakage on large trees and bowing on small trees, even if the exotic trees like pines were the most impacted. In the “Patagonia extra-Andina”

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observations made between September and October 2011 confirmed a delay in growth, mainly in wet-meadows and steppes, expressed in lower forage biomass per unit area. In the steppe the recovery of wet-meadows appeared to be associated with the level of precipitation.

- 5 8. Probabilistic analysis of atmospheric and eruptive conditions have shown that the main direction of dispersal is directly towards east of the volcano and that the climactic phase of the CC 2011 eruption has a < 1% probability of occurrence. San Martin de Los Andes and Bariloche share similar probabilities of tephra accumulation, even though Bariloche was more affected during the 2011 CC eruption. However, considering the high density of active volcanoes between Chile and Argentina (i.e. 112 volcanoes erupted in the Holocene), a large number of communities distributed along the border have a high potential to be affected in a similar manner regardless of the prevailing wind direction.
- 10 9. The comparison with the impact of the most recent volcanic crises in the southern Andes (i.e. Quizapu, 1932; Hudson, 1991; Chaiten, 2008) suggests that similar problems are related to eruptions with similar dynamics although with variable magnitude and geographic region. This is possibly mainly due to the similar economic and social development of the central-southern areas of Argentina, where wide portions of the territory are dedicated to tourism, pasture and farming, and human settlements are sparse and of medium size. This suggests that a detailed collection of data on impact immediately following the eruption can represent a useful tool to increase preparedness and to compile emergency management plans for future eruptions in the Andean region.
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Appendix A: Additional references used to describe eruption impact

A1 Sect. 3: Chronology

- Diario Andino Digital Villa La Angostura: <http://www.diarioandino.com.ar>, last access: November 2014.
- 5 Diario de Río Negro: <http://www.rionegro.com.ar>, last access: November 2014.
- Diario La Angostura Digital: <http://www.laangosturadigital.com.ar>, last access: November 2014.
- Diario La Mañana del Neuquén: <http://www.lmneuquen.com.ar>, last access: November 2014.
- 10 Diario La Nación: <http://www.lanacion.com.ar>, last access: November 2014.
- Diario Página 12: <http://www.pagina12.com.ar>, last access: November 2014.

A2 Sects. 4, 5, 6, 7 and 8: Evacuation, Impact on transport systems, Tourism, Impact on communities, Impact on infrastructures and lifelines

- Abumohor, J. A. and Díaz C. E.: Informe técnico consolidado. Actividad volcánica Complejo Puyehue-Cordón Caulle desde Junio a Octubre 2011. Sección de Análisis y estudios, ONEMI, Santiago, Chile, 50 pp., 2011.
- 15 Barbier, J. L.: Erupción del Volcán Puyehue-Cordón Caulle en la República de Chile, 4 de junio del 2011, in: Seminario Regional “Alianzas entre el sector público y privado para la gestión del riesgo de desastres: Continuidad de gobierno y continuidad de operaciones ante situaciones de desastres”, Lima, Perú, 7–8 June 2012, SP/SR-CGCORRD/Di No. 7–12, 2012.
- 20 Diario Andino Digital Villa La Angostura: <http://www.diarioandino.com.ar>, last access: November 2014.
- Diario de Río Negro: <http://www.rionegro.com.ar>, last access: November 2014.
- 25 Diario La Angostura Digital: <http://www.laangosturadigital.com.ar>, last access: November 2014.

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- Diario La Mañana del Neuquén: <http://www.lmneuquen.com.ar>, last access: November 2014.
- Diario La Nación: <http://www.lanacion.com.ar>, last access: November 2014.
- Diario Página 12: <http://www.pagina12.com.ar>, last access: November 2014.

5 A3 Sect. 9: Impact on animals

- Anselmi, F., Valot, N., and Spinelli, G.: Diagnóstico y Propuestas de diversificación productiva departamento Los Lagos, CLER (Comité Local de Emergencia Rural, Departamento Los Lagos), 33 pp., available at: <http://www.diarioandino.com.ar/diario/wp-content/uploads/2012/05/DIAGN%C3%93STICO.doc-1.pdf>, last access: 3 December 2012.
- 10 Buteler, M., Stadler, T., López García, G. P., Lassa, M. S., Trombotto Liaudat, D., D’Adamo, P., and Fernandez-Arhex, V.: Propiedades insecticidas de la ceniza del complejo volcánico Puyehue-Cordón Caulle y su posible impacto ambiental, *Rev. Soc. Entomol. Argent.*, 70, 149–156, 2011.
- 15 Corley, J., Masciocchi, M., and Pereira, A. J.: Una “buena” del volcán: lun verano sin chaquetas!, INTA-EEA Bariloche Publicaciones Regionales, *Revista Presencia*, 59, 5–8, 2012.
- Giraud, C. and Villagra, S.: Informe: la producción ganadera después de la ceniza. INTA EEA Bariloche, 4 pp., available at: <http://inta.gob.ar/documentos/la-produccion-ganadera-despues-de-la-ceniza> (last access: 3 December 2012), 2011.
- 20 Huerta, G.: ¿Cómo afectó la ceniza volcánica a las abejas y la actividad apícola?, INTA-EEA Bariloche Publicaciones Regionales, *Revista Presencia*, 57, 26–28, 2011.
- INBIOMA-CONICET-COMAHUE: Puyehue: la recuperación total de los lagos tardará un año más, edited by: Balseiro, E. and Cussac, V., available at: <http://www.conicet.gov.ar/puyehue-la-recuperacion-total-de-los-lagos-tardara-un-ano-mas> (last access: 25 1 March 2013), 2012.
- INTA-EEA (Estaciones Experimentales Bariloche y Valle Inferior): Estado de situación y recomendaciones para el sector ganadero de la Patago-

5424

- Tuffen, H., James, M. R., Castro, J. M., and Schipper, C. I.: Exceptional mobility of an advancing rhyolitic obsidian flow at Cordón Caulle volcano in Chile, *Nat. Commun.*, 4, 2709, doi:10.1038/ncomms3709, 2013.
- Wilson, T. M., Cole, J. W., Stewart, C., Johnston, D. M., and Cronin, S. J.: Assessment of Long-term Impact and Recovery of the 1991 Hudson Eruption to Agriculture and Rural Communities, Patagonia, South America, GNS Science Report 2009/66, GNS Science, New Zealand, 100 pp., 2010.
- Wilson, T. M., Cole, J. W., Cronin, S., Stewart, C., and Johnston, D.: Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery, *Nat. Hazards*, 57, 185–212, doi:10.1007/s11069-010-9604-8, 2011a.
- Wilson, T. M., Cole, J. W., Stewart, C., Cronin, S., and Johnston, D.: Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. *B. Volcanol.*, 73, 223–239, doi:10.1007/s00445-010-0396-1, 2011b.
- Wilson, T., Cole, J., Johnston, D., Cronin, S., Stewart, C., and Dantas, A.: Short and long-term evacuation of people and livestock during a volcanic crisis: lessons from the 1991 eruption of Volcán Hudson, Chile, *J. Appl. Volcanol.*, 1, 11 pp., 2012.
- Wilson, T., Stewart, C., Bickerton, H., Baxter, P., Outes, V., Villarosa, G., and Rovere, E.: Impacts of the June 2011 Puyehue-Cordón Caulle volcanic complex eruption on urban infrastructure, agriculture and public health, GNS Science Report 2012/20, GNS Science, New Zealand, 88 pp., 2013.

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Table 1. Pre-eruptive activity of the CVPCC from June 2010 to June 2011. The table includes Alert Level and type, number and location of earthquakes. Magnitude corresponds to ML: Local Magnitude, except indication in brackets that corresponds to MD: Duration Magnitude; eq h^{-1} : earthquakes per hour; VT: Volcano Tectonic; LP: Long Period; HB: Hibrid; LOFZ: Liquiñe-Ofqui Fault Zone, CC: Cordón Caulle. Taken from SERNAGEOMIN-OVDAS, 2010–2012.

Month	Alert Level	Period	# of Events	Type	Magnitude (ML)	Location and Depth (km)
June 2010	1. Green		41	VT	< 2.3 (MD)	Related to LOFZ
July 2010	1. Green		12	VT	< 1.8 (MD)	Related to LOFZ
August 2010	1. Green		125	VT		Related to LOFZ
	1. Green	10–15	68	VT	< 2 (MD)	C. Nevada-Puyehue < 10 km
September 2010	1. Green		46	VT	< 2 (MD)	10–11
	1. Green		4	LP		
October 2010	1. Green		67	VT	< 2 (MD)	C. Nevada, \leq 11 km
	1. Green		2	LP		
November 2010	1. Green		121	VT	< 2 (MD)	Cordón Caulle, \leq 10–11
	1. Green		1	LP		
December 2010	1. Green		39	VT	< 2 (MD)	C. Nevada-Puyehue, \leq 10–11
January 2011	1. Green		49	VT	< 2.1 (MD)	C. Nevada-Puyehue, \leq 10
February 2011	1. Green		85	VT	< 2.1 (MD)	C. Nevada-Puyehue-LOFZ, \leq 10
	1. Green		2	LP		
March 2011	1. Green		70	VT	< 2.7 (MD)	C C-C. Nevada, \leq 9
April 2011	2. Green	19 Apr 2011	1	VT	3.4	C. Nevada-C C., 5 km
			187	Swarm		C. Nevada-C C., 4–6
	2. Green	26 Apr 2011				
	3. Yellow	27 Apr 2011	185	Swarm HB	< 3	CVPCC, 4–6
			1	HB	3.9	CVPCC, 4
3. Yellow	29 Apr 2011	56	1	Swarm VT	< 2.4	C. Nevada-C C., 4–6
				VT	3.1	C. Nevada-C C., 4, 8
3. Yellow	1 to 30	1050	214	VT		
				HB		
May 2011	3. Yellow	4 May 2011		HB	3.6	CC, 3.5
		8 May 2011		HB	3.1	SW C. Nevada caldera, 3.4
	3. Yellow	9 May 2011	1	HB	3.3	4.8
		17 May 2011		HB	4.2	CC, 8
	3. Yellow	1 to 17	20 eq in 2 h		< 3	
			364	VT		
3. Yellow	30 May 2011	37	6	HB		
				LP		
3. Yellow	31 May 2011	1	1	Swarm HB		
				HB	3.4	C. Nevada, 2.3
3. Yellow	31 May 2011	1	25	HB	3.3	C C, 3
				Swarm HB		
June 2011	3. Yellow	2 Jun 2011	750 (20 eq h^{-1})	Swarm HB LP		SE C C, 2–5
			1	HB	3.8	3.7
	4. Yellow	3 Jun 2011	140 (25 eq h^{-1})	HB LP		SE CC, 2–5
			1450 (60 eq h^{-1})	HB LP	130 $\text{eq} > 2$	SE CC, 2–5
	5. Red	4 Jun 2011	230 eq h^{-1}	Swarm HB LP	12 > 4/50 > 3, Max 4.4	C C., 1–4

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Table 5. Different types of impacts in urban areas and relative duration, as reported in the media (see references in Appendix A). ****: first month; ***: first two weeks; **: first week; *: sporadic.

	Villa La Angostura	Bariloche	Ingeniero Jacobacci-Línea Sur	Villa Traful	San Martín de Los Andes	Río Negro Valley	Piedra del Aguila	Chubut	Río Negro, Atlantic Coast	La Pampa
Disruption of electric supply	X****	X***	X**	X**	X**					X**
Water supply	X****	X***	X**	X**	X**					
Obstructions of drainage systems	X**	X**	X							
Disruption of communications	X***	X***	X***	X**						X**
Disruption of road traffic	X**		X***	X**						
Roof collapse	X***	X***								
Disruption of Navigation	X***	X***		X*						
Isolation of towns and people	X***	X***	X***	X**						
Saturation of gas stations, supermarkets and drugstores	X**	X**	X**							
Suspension of school and administrative activity	X***	X***	X****	X**	X**	X**	X**	X**	X**	X**

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Table 6. Distance from vent and population of towns and settlements affected by tephra fallout.

Towns/Settlements	Province	Distance from vent (km)	Population (number of inhabitants)
Villa La Angostura	Neuquén	48	11 063
Villa Traful	Neuquén	65	417
San Martín de Los Andes	Neuquén	79	28 599
Junín de Los Andes	Neuquén	111	13 086
Piedra del Aguila	Neuquén	184	3689
Neuquén	Neuquén	390	231 780
Zapala	Neuquén	254	32 355
San Carlos de Bariloche	Río Negro	98	112 887
Pilcaniyeu	Río Negro (Línea Sur)	136	757
Comallo	Río Negro (Línea Sur)	168	1497
Clemente Onelli	Río Negro (Línea Sur)	194	114
Ingeniero Jacobacci	Río Negro (Línea Sur)	237	6261
Maquinchao	Río Negro (Línea Sur)	300	2494
Los Menucos	Río Negro (Línea Sur)	344	5187
Cona Niyeyu	Río Negro	461	217
Río Colorado	Río Negro	711	13 828
San Antonio Oeste	Río Negro	609	21 643
Sierra Grande	Río Negro	582	7641
Viedma	Río Negro	773	53 618
General Roca	Río Negro	426	90 607
Cipolletti	Río Negro	397	85 161
Gastre	Chubut	310	602
Gan Gan	Chubut	390	661
Telsen	Chubut	482	544
Dolavon	Chubut	617	3307
Gaiman	Chubut	631	6627
Rawson	Chubut	660	31 787
Trelew	Chubut	642	99 430
Puerto Madryn	Chubut	642	81 995
Puerto Pirámides	Chubut	693	565

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Figure 4. (a) Airplane covered with volcanic ash in Bariloche airport (photo Reuters); (b) Lake Espejo covered with lapilli-size pumice; (c) view of the main street from Villa La Angostura town covered with ash and lapilli, few days after the eruptive climactic phase (Photo Diario de Río Negro, 15 June: <http://www.rionegro.com.ar/diario/>); (d) and (c) collapsed tin roof of a restaurant in the area of Paso Samoré.

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Figure 5. (a) Sheep in the field covered with ash near Ingeniero Jacobacci (photo Diario de Río Negro, <http://www.rionegro.com.ar/diario/>); (b) Villa La Angostura Forest covered with tephra in June 2011; (c) over a million cubic meters of volcanic ash and lapilli were stocked in an old quarry; (d) army and fire management volunteers cleaning the channels in order to prevent the danger of formation of lahars (photo <http://www.minutoneuquen.com>).

5446

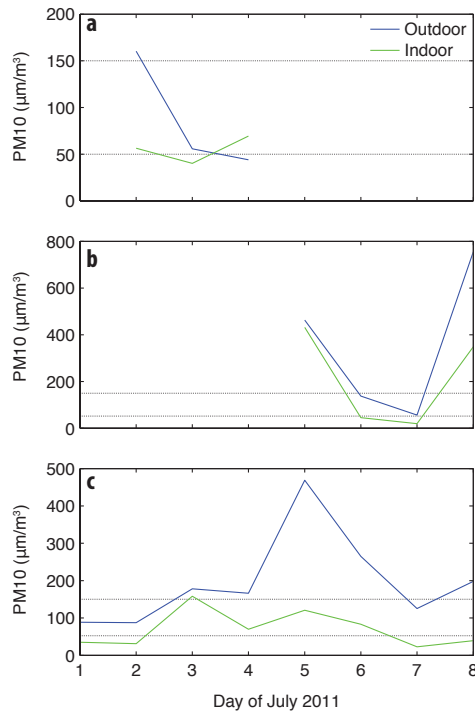


Figure 6. PM₁₀ concentration measured indoor and outdoor for Villa La Angostura and Ingeniero Jacobacci during the beginning of July 2011. **(a)** Villa La Angostura hospital; **(b)** Villa La Angostura CPEM 68 School; **(c)** Ingeniero Jacobacci School 356. The horizontal lines indicate maximum levels for a 24 h exposure ($150 \mu\text{m m}^{-3}$) and for an exposure of one year ($50 \mu\text{g m}^{-3}$).

5447

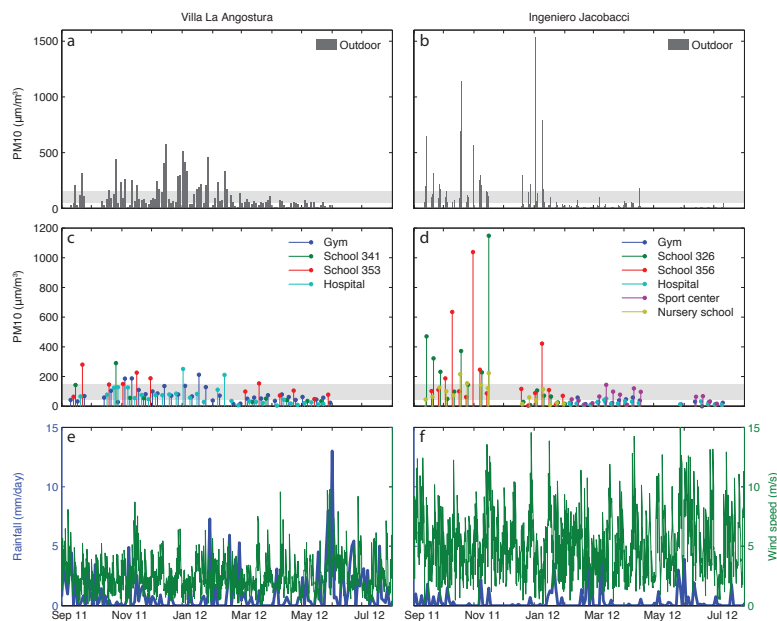


Figure 7. PM₁₀ concentrations between September 2011 and July 2012 for **(a)** Villa La Angostura (fixed station outdoor), **(b)** Ingeniero Jacobacci (fixed station outdoor), **(c)** Villa La Angostura (indoor measurements) and **(d)** Ingeniero Jacobacci (indoor measurements). Shaded area indicates maximum levels for a 24 h exposure ($150 \mu\text{m m}^{-3}$) and for an exposure of one year ($50 \mu\text{g m}^{-3}$). Daily rainfall and wind speed averaged over 6 h obtained from the NOAA NCEP/NCAR Reanalysis database are also shown for **(e)** Villa La Angostura and **(f)** Ingeniero Jacobacci.

5448

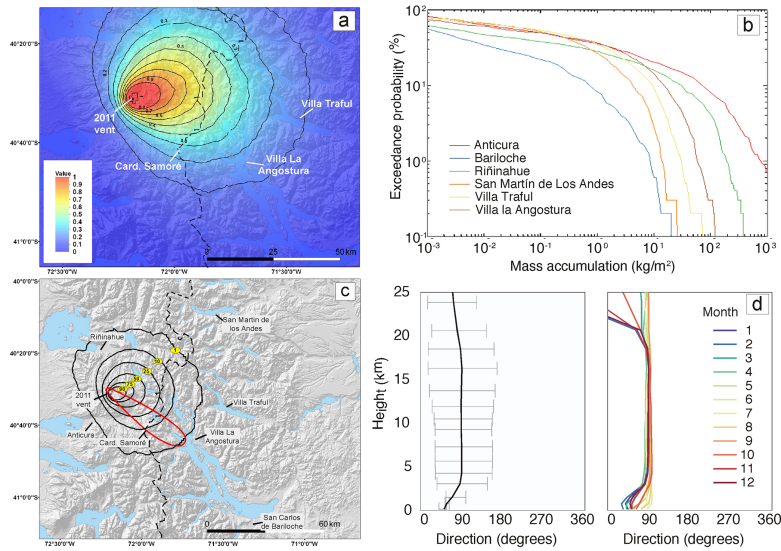


Figure 8. (a) Map showing the spatial distribution of the probability of reaching a tephra accumulation of 10 kg m⁻²; (b) hazard curves showing the exceeding probability for the towns of Anticura and Riñinahue in Chile and San Martín de Los Andes, Villa Traful, Villa La Angostura and Bariloche in Argentina; (c) location of the 100 kg m⁻² isomass contours as inferred from the probabilistic modelling for probabilities of occurrence of 1, 10, 50 and 90 % resulting from an eruption of similar intensity of the 2011 CC climactic phase (see also Table 8); the red isoline shows the 100 kg m⁻² isomass line for the 2011 CC climactic phase as compiled by Bonadonna et al. (2015) as a comparison; (d) statistical analysis of the wind direction based on the NOAA NCEP/NCAR Reanalysis database for the period 2000–2015 (left plots shows the median value and standard deviation, while the right plot shows the median value for each month; see main text for more details).

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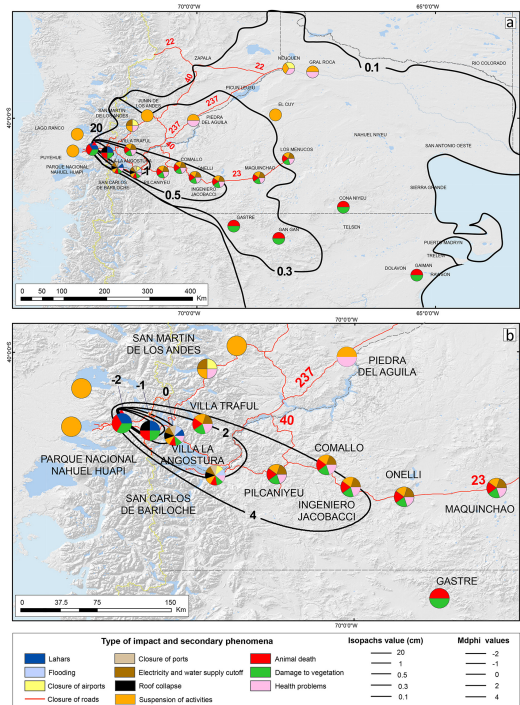


Figure 9. Distribution of the different impact types and secondary phenomena (indicated in the pie charts) associated with various localities in Argentina (southeast Río Negro, South Neuquén and north of Chubut Provinces) and Chile (Lago Ranco and Puyehue areas). (a) Isopach lines of Unit I are shown as solid lines from 20 to 0.5 cm (from Pistolessi et al., 2015); isolines of 0.3 and 0.1 cm are associated with the whole deposit observed by Gáitan et al. (2011). (b) Solid lines represent the Median diameter (Mdphi) for the Unit I (Bonadonna et al., 2015b).

5450

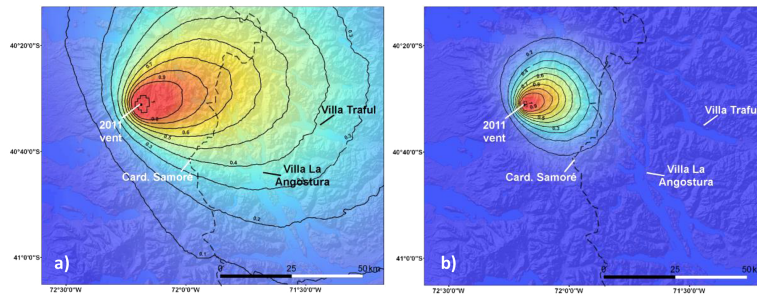


Figure B1. Hazard maps showing the spatial distribution of the probability of reaching a tephra accumulation of (a) 1 and (b) 100 kg m⁻² (see also Fig. 8 of main text).

5451

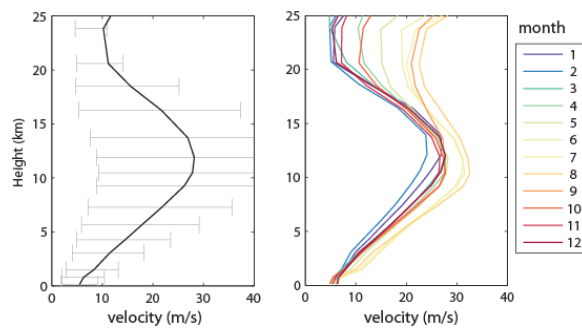


Figure B2. Statistical analysis of the wind velocity based on the NOAA NCEP/NCAR Reanalysis database for the period 2000–2015: (a) median value and standard deviation and (b) median value for each month; see Fig. 8 of main text for analysis of wind direction.

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