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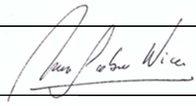
G. M. Nicora		18/11/2020
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G. A. Badi		19/11/2020
E. E. Ávila		19/11/2020

Volcanic Alert System by Lightning Detection Using the WWLLN - Ash Cloud Monitor

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ABSTRACT

Electrical discharges are observed in many volcanic eruptions and they have often been used as indicators of such eruptions. Volcanic lightning is remarkably similar to those produced during thunderstorms and is called analogous to thunderstorm-like plume lightning. The WWLLN developed a program called "Ash Cloud Monitor" (ACM), in which alerts are issued for possible volcanic eruptions when lightning strokes are detected around a volcano. The ACM tool has demonstrated to be a very effective technique to be aware of volcanic eruptions. However, most of the alerts released by ACM belong to false alarms of volcanic activity, because, in general, the detected lightning is produced by thunderstorms near the volcano.

In order to assess and improve the ACM to detect volcanic eruptions, reducing false alert emissions and improving the quick interpretation of them, we develop a web platform called Georayos-VolcanoAr with a new structure and a modified algorithm, with respect to the algorithm used by ACM, for the classification of alerts. The new algorithm considers an alert system with 3 levels: Red - Yellow - Green, with the Red alert being the highest level and decreasing towards Green. The Red alert was assigned to those volcanoes where only recorded lightning within a radius of 20 km or the lightning detected within a radius of 20 km is at least twice as much as that detected up to 100 km from the vent.

The study focused on 32 volcanoes located in the Andes, close to the Argentine-Chilean border, and analyzed the results reported by the ACM network in terms of a climatological study of the lightning activity, thunderstorm days and predominant winds in that region. This analysis serves as a basis for a general recognition of the study zone in order to improve the interpretation of the distribution and generation of false alerts; as well as to help decision makers, among others, to have a reference that allows them to issue the warning.

Keywords: WWLLN, Ashfall, Volcanic Lightning, Andes, Monitoring

1. Introduction

Throughout history, volcanoes have been and will continue to be the object of wonder and fear for human beings. The presence of active volcanic structures creates an imminent hazard for society, its economy, life in general and air traffic (Webley and Mastin, 2009). Volcanic products, such as pyroclastic flows or lahars generated during an eruption are high hazard and an impact phenomenon. Due to their characteristics, they have proximal effects, that means they reach the immediate areas of the volcano. Although in the immediate vicinity of the volcanic centers in Argentina and Chile there are generally rural areas of low population density, the material expelled by the eruption into the atmosphere can cause a significant danger in regions far away from the volcano, reaching urban areas with a higher population density and causing a long-term negative impact on their health, economy and air

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transportation (Connor et al., 2001; Spence et al., 2005; Pavolonis et al., 2006; Elissondo et al., 2016a, among others).

In southern South America, the Andes acts as a natural limit between the countries of Argentina and Chile. Within this region around 500 volcanic structures are recognized**,** almost a hundred of which have been classified as active or potentially active (Caselli and Velez, 2011; Elissondo et al., 2016a; Lara and Calderon, 2015). Geological and historical evidence show great variability of eruptive style in the region. As a general scheme we can distinguish a compositional gradation of the erupted magmas from North to South in the Andes mountain range sector under study. Towards the North the volcanoes reach great heights, with compositions, mainly andesitic to dacitic. Few records historical activity during the Holocene, being the Láscar the volcano with a recurrent activity (Petrinovic et al., 2017) with eruptive styles that varies from effusive to explosive eruption with generation of pyroclastic flows and ashfall. Due to the fact that these volcanoes are far from populated areas, the main hazard associated with their eruptions is the eventual tephra fall (Petrinovic, 2004). Towards the South, beyond the volcanic gap in the Pampean flat-slab segment, the historical records show an eruptive activity of the Strombolian, Vulcanian and Plinian types. The composition of the magmas involved in this sector of the volcanic arc varies from those rich in silica with predominant explosive eruptions in the north to andesitic to basaltic in the south (Sruoga and Schonwandt, 2004). However, some eruptions on the South have included rhyolitic magmas too. Four major eruptions have been recorded during the last century in this region, that of the Quizapú Volcano (1932), Hudson (1991), Chaitén (2008), Puyehue - Cordón Caulle (2011) and Calbuco (2015) (*Observatorio Argentino de Vigilancia Volcánica* - OAVV, Elissondo et al., 2016). The risk in this sector is increased by the existence of nearby towns with greater urban development (Sruoga and Schonwandt, 2004).

In this scenario, it is of great relevance not only to develop detailed protocols and maps of volcanic hazards in the proximity of the eruption center, but also to improve the tools for early detection of volcanic eruptions and remote monitoring of volcanic clouds; mainly for those most isolated worldwide volcanoes.

Many studies show a large variety of eruptions that have a historical record and present considerable electrical activity associated with the generation of a volcanic plume released during the explosive stage of the eruption (McNutt and Williams, 2010; Muller, 2011; Houghton et al., 2013; Shevtsov et al., 2016). Thomas et al. (2010), have classified electrical activity that occurs during a volcanic eruption into three groups: vent discharges, near-vent lightning and analogous to thunderstorm-like plume lightning. The first ones are small short-term discharges (less than one millisecond) that are generated in the early stages of the eruption, while analogous to thunderstorm-like plume lightning is a large discharge that can easily reach 20 km in length and is generated once the volcanic plume has been established. As it is generated in the volcanic plume, when carried by the surrounding winds, electric discharges can move with it (Thomas et al., 2007; Behnke et al., 2013; McNutt and Thomas, 2015). The analogous to thunderstorm-like plume lightning are the most useful in terms of providing early warning, due to the frequency and intensity of the produced discharges.

Like in the thunderstorm, the lightning stroke associated an eruption emits electromagnetic radiation over a wide wavelength range; in particular, the radiation emitted at very low frequencies (VLF 3-30KHz) can travel long distances with a relatively weak attenuation. This allows the lightning to be detected and recorded remotely. The same happens with the electrical discharges produced during thunderstorms; for this reason, the detection networks created to locate these types of discharges are also useful to detect the strokes from a volcanic plume. Based on the VLF radiation emitted by lightning, the World Wide Lightning Location Network (WWLLN), is a real-time, world-wide, ground network that detects preferentially strong lightning strokes (Dowden et al., 2008).

The WWLLN currently operates with more than 80 sensors spread around the world and records the *sferics* that are transmitted in the VLF band. The WWLLN developed a program called "Ash Cloud Monitor" (ACM hereafter), in which alerts are issued for possible volcanic eruptions when lightning strokes are detected around a volcano (http://wwlln.net/volcanoMonitor.html).

Some studies have shown the effectiveness of the ACM program in detecting the spatial and temporal evolution of the volcanic eruption lightning activity as well as the plume displacement in the atmosphere. For instance, Nicora et al. (2013), analyzed the discharges that occurred during the eruption of the Puyehue-Cordón Caulle (2011) volcanic complex as registered by the WWLLN. They observed a good spatial correlation between them and the generated volcanic plume. Besides, during this eruptive event, they found that the alert issued by the ACM network was 30 minutes before the one given by the National Service of Geology and Mining (SERNAGEOMIN) - Southern Andes Volcanological Observatory (OVDAS). Van Eaton et al. (2016), took into account lightning strokes registered by the WWLLN, satellite images and field observations to determine the relationship between lightning and the dynamics of the volcanic plume during the development of the two eruptive events of the Calbuco volcano (2015). They found that changes in electrical activity would be related to the dynamics of the eruptive event, mainly with the variation of the mass eruption rate (MER) and the height reached by the volcanic plume. Finally, Hargie et al. (2019), studied the electrical activity and the plume movement during the eruption of the Kelud volcano (2014), in order to find a relationship between the electrical activity location and the dynamics of the plume. Also, they observed that the electrical activity was linked to changes in the MER and that most energetic discharges were found in the vicinity of the volcano, even when the ash cloud extended large distances from it.

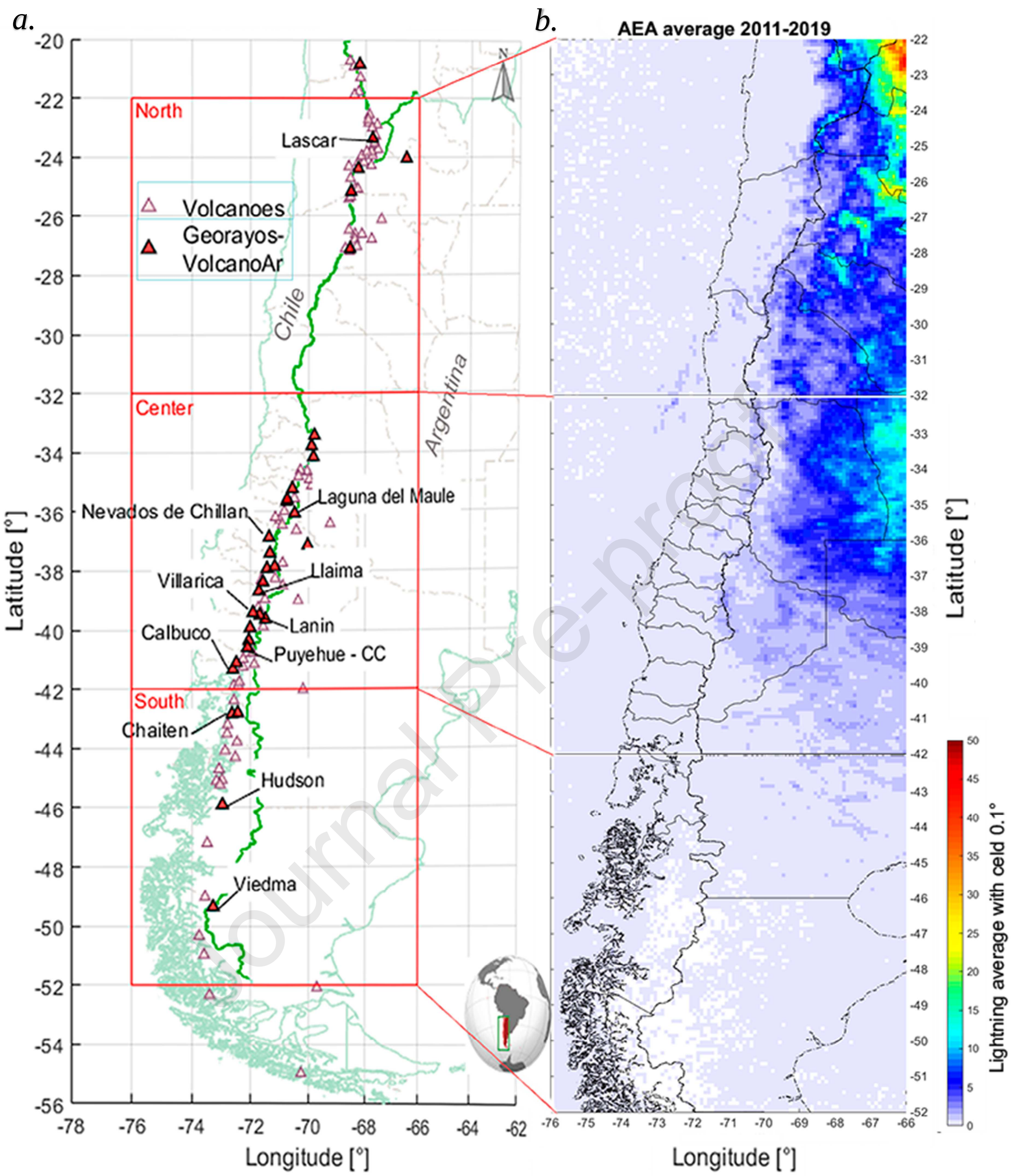
The ACM tool has demonstrated to be a very effective technique to be aware of possible volcanic eruptions. However, most of the alerts released by ACM belong to false alarms of volcanic activity, because, in general, the detected lightning are produced by thunderstorms near the volcano and not by eruption as expected. Thus, the major problem with this tool lies in the difficulty of discriminating between the lightning produced by storms and volcanic eruptions. Studies are still underway to extend the knowledge that allows us to differentiate between them (Behnke and McNutt, 2014; Muller, 2011).

In this work we focus on 32 volcanoes located in the Andes, close to the Argentine-Chilean border, and analyze the results reported by the ACM network in terms of a climatological study of the lightning activity, thunderstorm days (TD) and predominant winds in that region. The study serves as a basis for a general recognition of the study zone in order to improve interpretation of the distribution and generation of false alerts. We develop a web platform called Georayos-VolcanoAr with a new structure and a modified algorithm, with respect to the algorithm used by ACM, for the classification of alerts. The platform displays the alert status of each monitored volcano georeferenced on a map, as well as the evolution in time of these alerts. We present the results obtained during the first phase of testing, which enable us to evaluate the first steps to be taken in future in Georayos-VolcanoAr.

The goal of our work is to assess and improve the available technique (ACM) to detect possible volcanic eruptions, reducing false alert emissions and improving the quick interpretation of them in the region under study. In this way, the given information can be manipulated by the decision maker and by the interested user. While it would be ideal to eliminate the totality of false alerts, we know that it is important during this process that early detection should not be lost in the event of explosive eruption.

2. Study area

The study area covers the Andes which involves the Argentine-Chilean border. The area extends from 22° to 52° South latitude and from 66° to 76° West longitude. A total number of 107 volcanoes are registered for the selected region in the Smithsonian Institute's Global Volcanic Program (GVP) database (https://volcano.si.edu/). Figure 1-a displays the volcanoes sites; it is possible to observe that they are located mainly in the Argentinean-Chilean border and in the Chilean territory.



The study area was divided into three sectors with different features in terms of the lightning activity. These sectors are (Figure 1-a): North sector between 22° and up to 32° South latitude; Central sector between 32° and 42° South latitude and South sector between 42° and 52° South **Figure 1:** a- Location of volcanoes inside the study area. The sectors North, Center and South are marked by red squares. The triangles mark the location of all volcanoes and black triangles highlight the volcanoes used by the platform Georayos-VolcanoAr. b- Atmospheric Electrical Activity (AEA) average inside each region between 2011 and 2019 taking a 0.1° x 0.1° cell.

latitude. The same longitude range was maintained for the subareas (from 66° to 76° west longitude).

The most active volcanoes and those that pose the greatest risk to society are mainly in the Central sector. In this area, there are three volcanoes that erupted with a Volcanic Explosive Index (VEI is a relative measure of the explosiveness of volcanic eruptions proposed by Newhall and Self, 1982) greater than 2 in the last decade. These are the Planchón-Peteroa (2011), Puyehue-Cordón Caulle (2011) and Calbuco (2015). Currently, there are three volcanic centers with yellow technical alerts in this region, the second lowest level of a four-level scale used by SERNAGEOMIN to quantify volcanic alerts. Among those three volcanic centers, Nevados de Chillán deserved special recognition by its recurrent explosions with ash columns of moderate height. On the other hand, the North sector has fewer volcanoes than the Central sector. Only one volcano has sporadically emitted ash and gas into the atmosphere in recent years (Láscar, 2015), although the volcanoes in this region have a moderate to high volcanic risk level for society (SERNAGEOMIN reports; Elissondo et al., 2016a). Finally, the South sector has the fewest volcanoes compared to the other sectors, to date the Cerro Hudson volcano was the only volcano that has shown low level activity in the last ten years; it is currently active but stable (SERNAGEOMIN reports).

3. Dataset

3.1 Meteorological

For the atmospheric electrical activity (AEA) and thunderstorm days (TD) analysis, the database for the years 2011 to 2019 was provided by the WWLLN. A thunderstorm day is defined as the day on which the WWLLN detects at least one lightning in a given cell (Nicora, 2014). The WWLLN currently has about 80 active sensors around the globe, the efficiency of the network is estimated in 10%, mainly detecting the most energetic cloud-ground (CG) discharges with currents larger than 40 kA (Van Eaton et al., 2020). The data provided by the WWLLN give the date and time of the detection of the stroke according to the Universal Time Coordinated (UTC), the location in latitude and longitude of said stroke and the number of sensors that were used to determine the stroke location. This data is provided as a single daily file in which all strokes detected globally on that day are recorded.

The wind condition in the study region is quite relevant because it provides information of possible displacement of the volcanic plume released during the eruption. Given the lack of information of the wind speed and direction in situ area, in real time, the wind data from the National Center for Environmental Prediction (NCEP)/ National Center for Atmospheric

Research (NCAR) reanalysis numerical model was used. The provided information corresponds to the Monthly Mean Subset data available online from the Research Data Archive at the National Center for Atmospheric Research for the years 2013 to 2019. These data consist of the monthly average of the latitudinal and longitudinal component of the wind (in m/s) for 17 levels of altitude in millibars (1000,925,850,700,600,500,400,300,250,200,150,100,70,50,30,20 and 10 mbar), and it has worldwide coverage with a resolution of 2.5° latitude and 2.5° longitude (approximately 278.3 km by 278.3 km).

3.2 Ash Cloud Monitor network

The ACM network as a part of the WWLLN continually monitors a total of 1825 volcanoes worldwide. Every minute the network records all the electrical discharges that occurred in the last hour within an area of 20 km radius from the vent of each volcano (internal lightning) as well as in a ring between 20 km and 100 km radius measured from the volcano vent (external lightning) (http://wwlln.net/volcanoMonitor.html). Every time the network detects that the number of internal lightning is greater than the number of external lightning, it sends an email alert to previously registered users. The information displays the name of the volcano, the number of internal and external lightning that were recorded in the last hour and what were the most recent strokes that triggered the alert.

The information is represented on a static table in the ACM web page, where all the monitored volcanos, geographic coordinates of them, the region, the type of volcano, the number of internal and external lightning and the link with a compatible file with Google Earth® which has a space distribution of all the registered electric discharge.

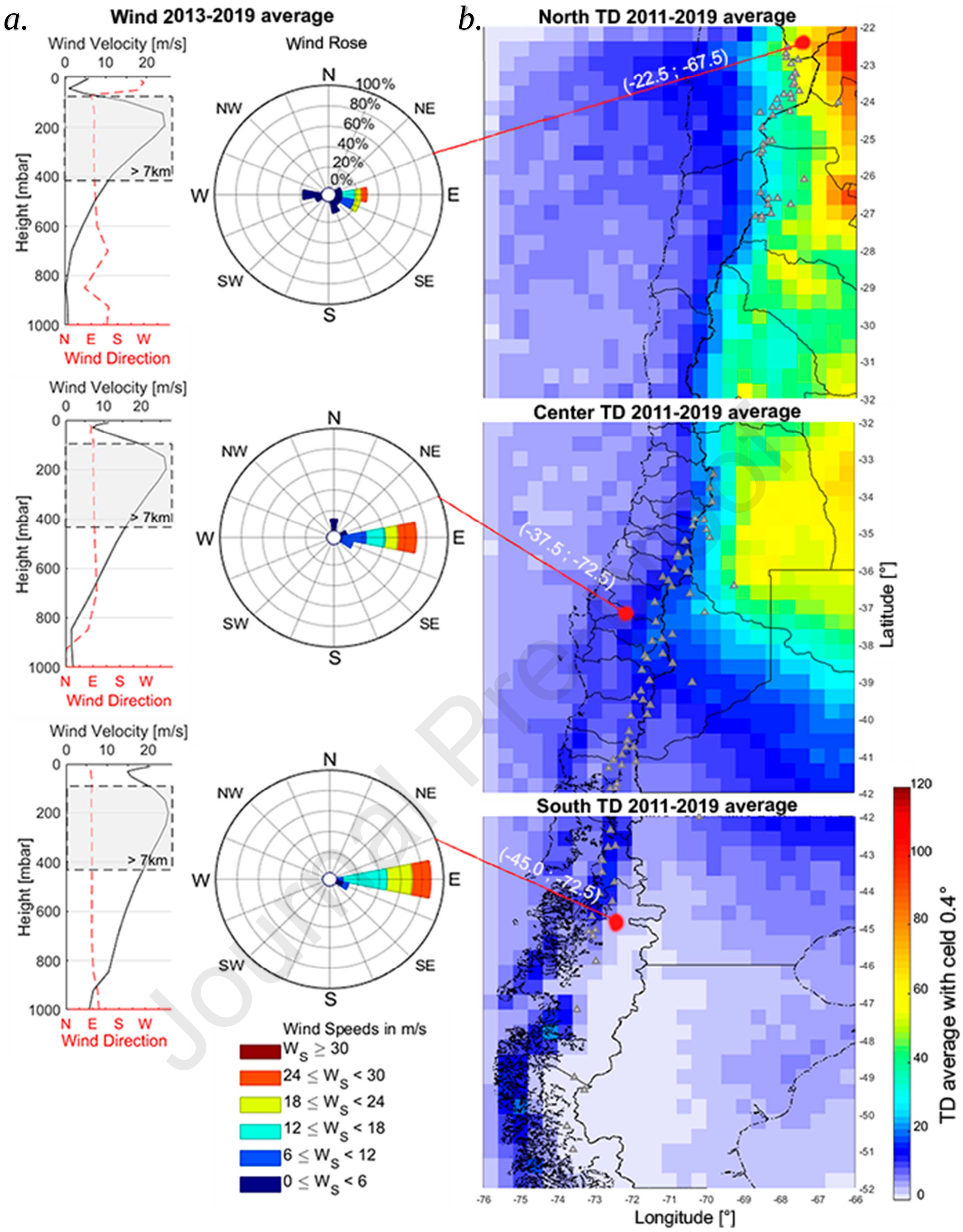
The number of internal and external lightning are uploaded every minute on this table but they are not recorded into a file, this information is only available in real time. An archive data with the total number of internal and external lightning detected is provided by ACM every day. That is, if a volcano had more internal than external lightning during a part of the day and sent an alert by email, but later during that day, the external lightning increased up to the point of surpassing the internal ones, only the final state will be keep in the file data, without any register that some alert had been sent.

As described in the section 5, we used the archive data for the ACM web diagnosis for the study of previous years (2011-2019); but for our platform, we did an own minute by minute registration of the internal and external lightning data shown by the ACM on its web page for the volcanoes selected.

3.3 Volcanic Network Information

The Smithsonian Institution's Global Volcanism Program (GVP) provides in its web page information on the eruptive history of each volcano including the VEI for each eruptive process

Figure 2: a- Wind rose (right) and vertical profile (left) for the 2013-2019 average wind direction and velocity at the representative point (red point) of the NCEP/NCAR grid data. b- Thunderstorm Days (TD) average inside each region between 2011 and 2019. The gray triangles mark the volcanoes location and the red points mark the representative spot in which we take the wind information represented in 2-a.



197 The National Geology and Mining Service (SERNAGEOMIN) monitors volcanic activity in Chile, expanding the coverage and quality of monitoring, the delivery of timely information to government authorities and communities, contributing, through the National Emergency Office of the Ministry of the Interior (ONEMI), to the reduction of the risk associated with volcanic activity.

202 The Argentine Geological Mining Service (SEGEMAR) has begun in recent years to monitor volcanic activity in Argentina with the collaboration of SERNAGEOMIN for bordering volcanoes. For its part, the National Comprehensive Risk Management System (SINAGIR) is responsible

for actions to reduce and manage risk at the national level. Each province has its own Civil Protection Infrastructure and in turns is invited to join SINAGIR.

4. Meteorological framework

The lightning generated in volcanic plumes is similar to thunderstorm lightning (McNutt and Thomas, 2015; Thomas et al., 2010; Behnke et al., 2013; Nicora, 2014; Baissac, 2017; Baissac et al., 2018). In order to make more effective the early detection of eruption using lightning locations, it is crucial to know the meteorological conditions within the interesting area. For this purpose, we performed a baseline study regarding AEA, TD and the average wind speed and direction, for each sector in the study area.

The characterization of the electrical activity in each sector was performed based on the average of the strokes detected between the years 2011 and 2019 with a spatial resolution of 0.1° x 0.1°, which is equivalent to an area of around 123 km^2. To guarantee that the analyzed lightning is of meteorological origin, the strokes generated during the Puyehue - Cordón Caulle (2011) and Calbuco (2015) eruptions were discarded.

The TD were calculated using the database for the years 2011 to 2019 provided by the WWLLN and a 0.4° grid was taken. The TD data assigned to each grid cell is the annual average of the storm days detected by WWLLN in the period of time considered (Nicora, 2014).

The electrical activity in a given sector is parameterized with the number of lightning per cell between 2011 and 2019. Figure 1-b displays the characteristics of the AEA in the study region. The highest lightning number per cell is produced in the Northeast sector of the North sector, reaching values close to 35 lightning per cell. The electrical activity decreases toward the South sector, with values of 15 per cell in the Central sector and with values less than 2 per cell in the South sector. The larger values are found within the Argentine territory and lightning activity close to the volcanoes under study is substantially lower, with values of lightning number per cell of 20, 5 and less than 2 for each of the North, Central and South sectors respectively.

Figure 2-b shows a map with the TD distribution within the study region, we notice a behavior similar to that of the electrical activity in the North and Central sectors, but towards the west of the Argentine-Chilean border of the South sector, the TD value increases. On the eastern flank of the mountain range in the North sector, the annual average of TD varies between 110 and 36 per year. On the western slope, however, it does not exceed 18 TD per year. In the Central sector these values decrease, with maximums around 65 and minimums of around 7 TD on the East. In the south-western sector of the Central sector, there is an increase in the TD which continues towards the southern sector mainly located in the coastal sector of Chile; all this sector reaches values close to 18 TD per year. However, the lightning number per cell does not

have an increase in these sectors, which would indicate that although there are more TD, these days do not have a large number of lightning. This behavior of the TD in the Southwestern sector of the Central sector and the West of the South sector was shown in Garreaud et al. (2014).

In general, the results show that the percentage of days with thunderstorms is about 5% in a year around the active volcanoes; which suggests there is a low probability of a simultaneous temporal and spatial coincidence between a volcanic eruption and a thunderstorm. This result suggests that the technique of early detection of eruptions through the detection of associated electrical activity could be suitable.

In order to characterize the wind in the region between the years 2013-2019, we took as representative point of the wind data grid which is nearest to the volcano region for each sector (North, Central and South) as shown in Figure 2-a and b. This is because the grid of National Center for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) is very large and few grid points are close to the volcanic zone. On each point we calculate the 2013-2019 average of the direction and velocity of the wind for each level. Figure 2-a displays the wind rose and vertical profile, performed with these data for the 17-high level.

The results of the analysis of the NCEP/NCAR data mostly indicate the presence of winds with a predominantly east-southeast direction without large variation between levels. However, in the North sector, the wind direction shows some components of other direction as to the Southeast and West. The West component has a low speed (less than 6 m/s) and corresponds to high altitude (see Figure 2-a-left). Generally, the volcanic plumes with lightning have a bigger height than 450 mbar (more than 7 km). Observing the variation of wind direction and velocity in function of height we noticed that the sectors have not relevant variation in wind direction for heights above to 500 mbar, with a strong tendency to the East and reaching maximum speed value for these levels (> 500 mbar).

The knowledge of frequency of thunderstorms and typical lightning activity around the volcano's sites is crucial to differentiate between the lightning produced by storms and volcanic eruptions. Also, the knowledge of the prevailing winds in the area is useful in terms of the mobility of the material released during an eruption. All this information is essential for decision makers.

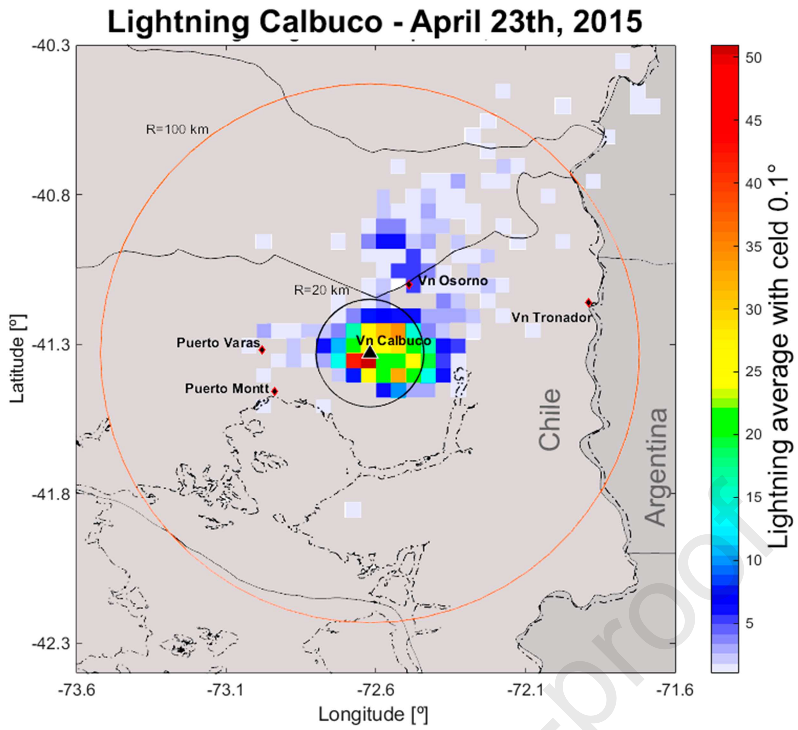
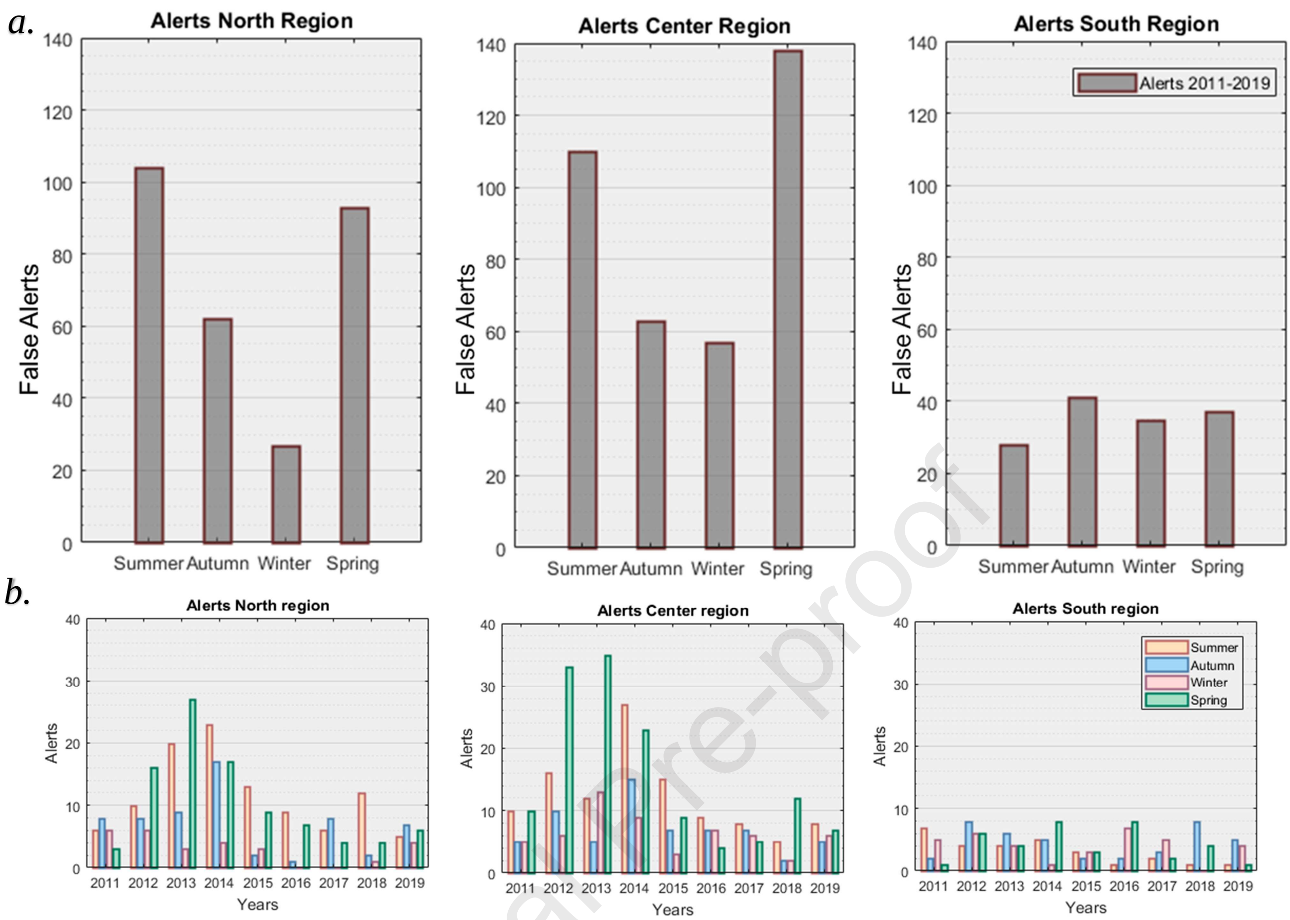


Figure 3: Example of the lightning registered during the Calbuco volcano eruption on April 23, 2015 using WWLLN data in a 0.1 grid. The black ring represents a distance from the vent of 20 km and the orange ring one of 100 km.

5. WWLLN – Ash Cloud Monitor Diagnosis

In order to improve the functioning of the WWLLN-ACM network, it will be very useful to analyze the false alerts emitted by this system. We performed a study of all false alerts that were issued between the years 2011 - 2019, in each one of the pre-established sectors (North, Center and South). A false alert occurs when the ACM issued an alert, but it did not belong to an eruption; probably it was generated by meteorological events that occurred near a volcano.

In order to verify if the alerts correspond to an eruption, initially it was determined which alerts in the archive data were false alerts and which were not. The eruption information was obtained from the Global Volcano Program (GVP) database (http://volcano.si.edu/). According to this, 17 eruptions were registered for the study area between 2011 and 2019, of which just three had a VEI of between 3 and 5. Based on the analysis of alerts, we found a total of 803 alerts reported by the network during the period examined. As we mentioned previously, during this interval of time 17 volcanoes had eruptive activity according to the GVP, but Nicora et al. (2013) and Van Eaton et al. (2016), only found evidence of electrical activity in two volcanoes; these were the eruption of Puyehue - Cordón Caulle (2011) and Calbuco (2015), the latter exemplified in Figure 3. Of the total alerts reported by ACM, 8 alerts are related to both



eruptions with confirmed lightning. For this reason, the other alerts issued by the network were considered as false alerts.

Figure 4: a- False Alerts of Ash Cloud Monitor (ACM) network between 2011 and 2019 in the North, Center and South sector for each season. b- False Alerts of ACM for year in each region between 2011 and 2019.

Regarding all the false alerts in the three sectors, we found that 36% were registered in the North sector, 46% in the Center sector and the remaining 18% in the South sector (Figure 4-a). Although lightning in the North sector is more common, the largest number of volcanoes in the Central sector generates an increase in the number of false alerts. Figure 4-b displays the analysis of the seasonal variability of the false alerts within every sector. The Center and North sectors show that the false alerts are more frequent during spring and summer seasons; accordingly, with the seasons when more thunderstorms occur. In the South sector, false alerts appear to be equally distributed throughout the year; in this sector the TD are very low.

In average the ACM submits more than 90 alerts per year warning about possible volcanic activity in the region under study. Definitely, this technique needs to be improved in order to be more reliable.

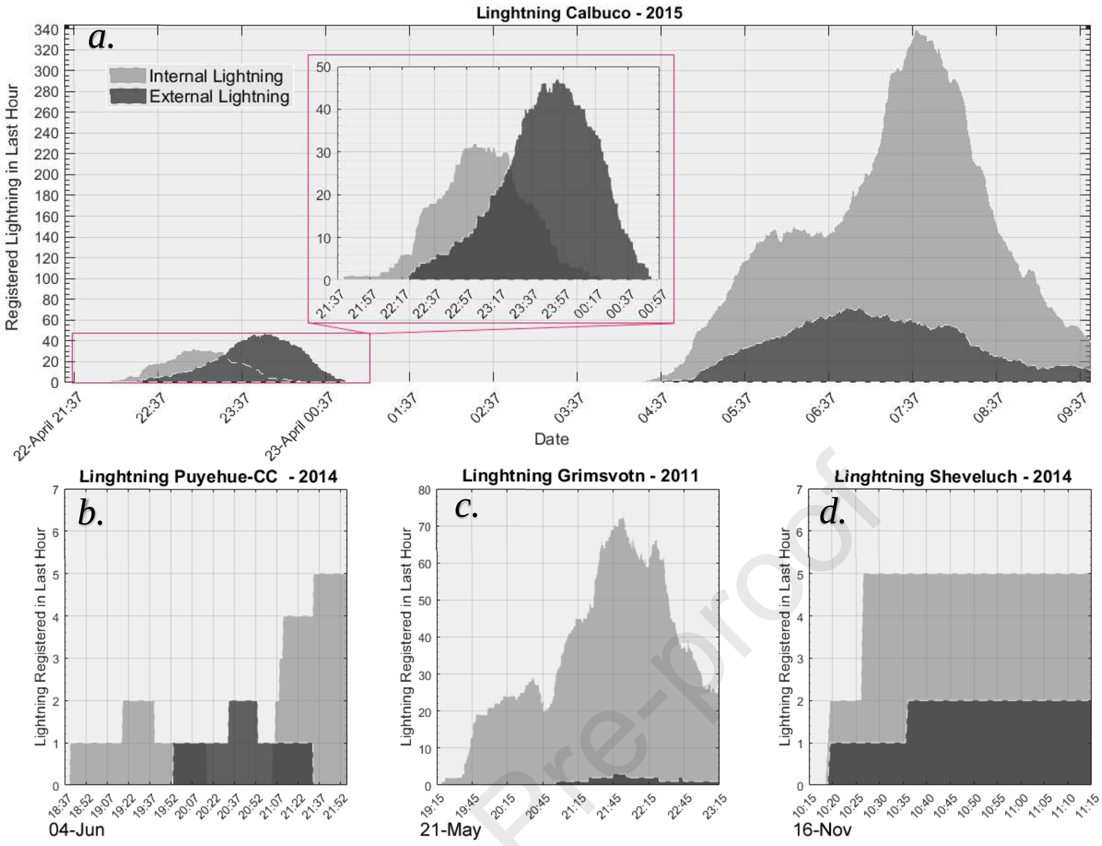


Figure 5: Temporal evolution of internal (< 20 km) and external (between 20 km and 100 km) lightning registered at (a) Calbuco volcano on April, 2015; (b) Puyehue-Cordon Caulle volcanic complex on June, 2011; (c) Grimsvötn volcano on May, 2011 and (d) Shiveluch volcano on November, 2014.

6. Platform Georayos-VolcanoAr

As mentioned previously, the objective of this work is to evaluate and improve the existing technique used by the ACM to detect possible volcanic eruptions. For this reason, we created the Georayos-VolcanoAr platform, as a tool designed to reduce the number of false alerts received by the decision maker and improve the quick interpretation of these alerts.

6.1 Platform Description and Methodology

6.1.1 *Georayos-VolcanoAr description*

Georayos-VolcanoAr is a web platform which started its development at the beginning of 2019, with the purpose of making the information offered by the ACM to be more operational and intuitive. Based on this objective, the volcanoes of interest are filtered in the Georayos-VolcanoAr web platform and classified according to the electrical activity recorded in each one.

Alert	Condition
Green Alert	Inter. Lightning = 0 or Inter. Lightning ≤ ½ Extern. Lightning
Yellow Alert	Inter. Lightning < 2 & Inter. Lightning ≥ ½ Extern. Lightning
Red Alert	Inter. Lightning ≠ 0 and Extern. Lightning = 0 or Inter. Lightning ≥ 2 Extern. Lightning

Table 1: *Conditions of classification algorithm*

Condition designated for the alerts used by the classification algorithm in the Georayos-VolcanoAr. Internal and external lightning refers to registered lightning within 20 km radius area and between 20 km and 100 km radius area respectively measured from the volcano vent.

The difference with the ACM, which shows the electrical activity of all the volcanoes of the world in a static table, the Georayos-VolcanoAr platform only shows the information of certain volcanoes located in the area under study on an interactive map. These are represented by a color icon according to the alert stage assigned.

The possible assigned stages of alert are Red-Yellow-Green. The alert status is shown in real time and is updated every minute. The alert classification system is based on an algorithm which assigns a state of alert to each volcano according to the relationship that exists between the internal and external lightning registered by the ACM. The algorithm also filters volcanoes of the region we want to monitor, as detailed in the following section.

In order to improve Georayos-VolcanoAr interaction with other risk platforms, when a volcano registers a Red alert, it is automatically registered in a special section of CAP (Common Alerting Protocol, Botterell, 2006). These alerts can also be shown on the same web page in case that registered users want to use it, or can be sent as a notification by email.

Other information is available within the platform, such as the evolution of the alert for each volcano and the lightning data used by the platform.

6.1.2 *Algorithm*

The volcanoes and alerts shown on the platform are the product of the application of a classification algorithm. This algorithm first filters the worlds volcanoes monitored by the ACM, with the purpose of keeping only the volcanoes of interest within the region under study. After this, each of the filtered volcanoes are classified each minute according to the number of internal (< 20 km from the vent) and external (between 20 km and 100 km from the vent) lightning.

The list of volcanoes of interest to be filtered are manually introduced. Of the total of volcanoes, those which involve more risk for the territory are selected. These are selected according to their Specific Volcanic Risk and Specific Risk Ranking data provided by SERNAGEOMIN in Chile and by Elissondo et al. (2016a) in Argentina. In this way, we monitor active volcanoes which, even being stable, imply a high risk to society in case of eruption. Also considering that the discarded volcanoes have a low eruption probability, the alerts coming from this group of volcanoes, would be, in principle, taken as false alerts by Georayos-VolcanoAr and therefore will not be sent.

The filtered volcanoes are assigned a state of alert which can be Red, Yellow or Green alert. This depends on the relationship between the amount of internal and external lightning registered on each of the volcanoes, following the conditions detailed in Table 1. The Red alert is the maximum level of alert, and indicates the possible occurrence of an eruption with the presence of particulate matter and gas in the atmosphere, the scale decreases gradually towards the Green alert.

The relationship between internal and external electrical discharges used to trigger an alert, was chosen taking into account the meteorology and the electrical activity behavior during different confirmed eruptions. In this way, we define a Red alert when lightning have been registered only in the internal ring or, if the external ring also registers lightning, we take a Red alert when the registered lightning on the internal ring are the double or more of the registered on the external ring. The Green alert is started when there is no lightning detection in the inner ring of the volcano, or when the discharges registered in the vicinity of the volcano are less than half of the discharges recorded on the external ring. Finally, the Yellow alert considers the transition conditions between these two alerts, when it is not sufficiently clear if the discharges could be due to an eruption.

The analysis of the electrical activity produced by the different eruptions was developed taking into account the Puyehue-Cordon Caulle (2011), Grimsvötn (2011), Shiveluch (2014) and Calbuco (2015) eruptions, shown in Figure 5. In these eruptions, we observe that the electrical activity at the beginning is generated near the volcano and later, when the volcanic plume is carried by the atmospheric winds, the lightning are more distal, and are register on the outer ring. Taking into account the first hours of the eruption, in all cases when internal and external lightning are present, the amount of internal lightning is much bigger than the external ones. The minimal relationship is shown in the Shiveluch eruption where the recorded amount internal lightning are double of external lightning (Figure 5-d). That is why we choose this relationship between internal and external lightning which diminishes the false alerts, but does not considerably modify the detection time in case that the alert is really generated by an eruption.

6.2 Results

To evaluate the Georayos-VolcanoAr platform, a preliminary analysis of the emitted alerts was performed. A period of 102 days was taken and was corroborated if during this period some eruption had taken place which could have generated lightning. As there were no eruptions with

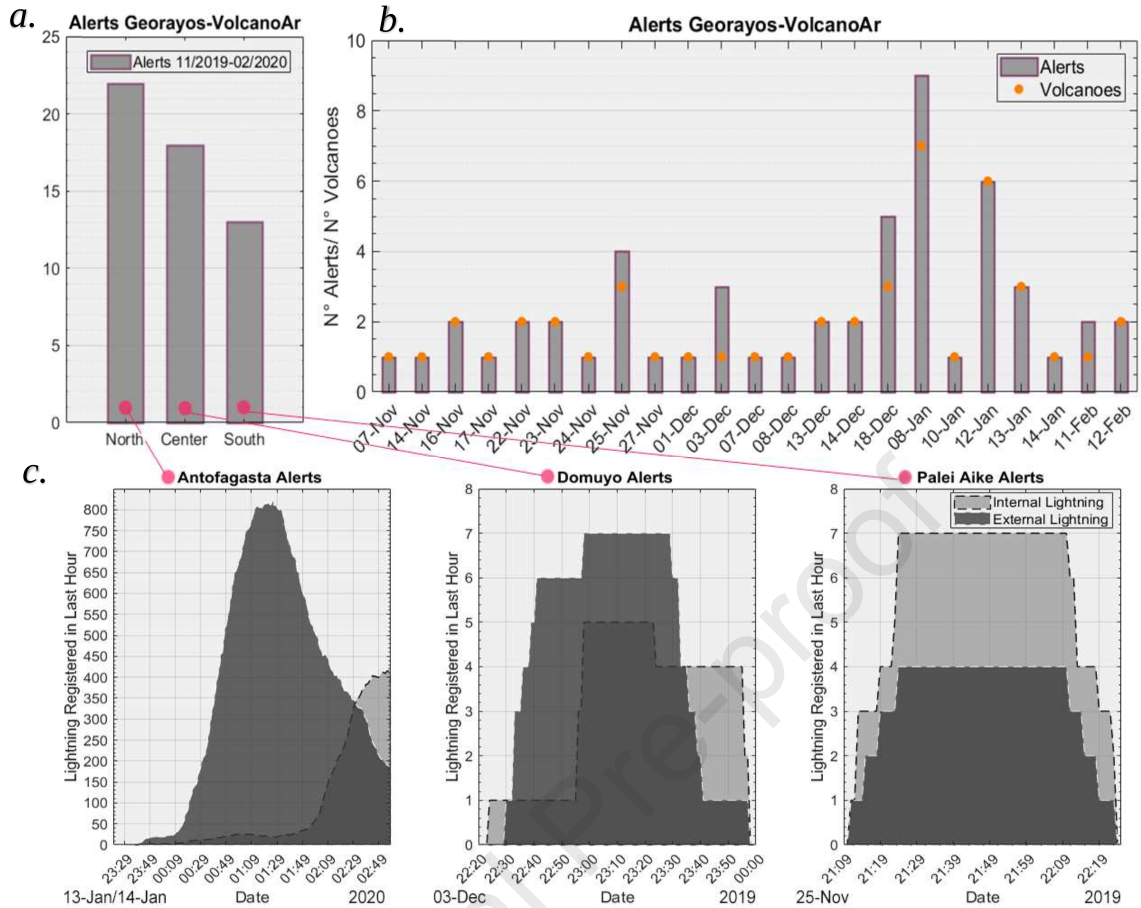


Figure 6: a- All alerts issued by Georayos-VolcanoAr in North, Center and South sector between 04-Nov-2019 and 14-Feb-2020. b- Detail of the days with alerts registered (bars) and the number of volcanoes that has emitted alerts in the same day (orange dots). c- Example of the temporal evolution of internal and external lightning registered for three volcanoes by the Georayos-VolcanoAr.

lightning associated; the alerts were taken as false alerts. Afterwards, in order to evaluate the effectiveness of the platform with respect to the ACM, we compared the emitted alerts by both during the same period of time, using the ACM methodology when the archive data was stored.

To do the preliminary analysis of the false alerts sent by Georayos-VolcanoAr, we took the registered data from 04-Nov-2019 up to 14-Feb-2020. A total of 102 days have been recorded, of which at least one Red alert has been sent about some volcano on 23 of those days. The Red alerts have been sent by 28 of the 32 volcanoes monitored volcanoes during the period under consideration. With respect to the total of false alerts sent in each sector shown in Figure 6-a, we can observe that the number decreases from the North to South sector, according to the AEA present in each of these regions as shown in Figure 1.

Examining more accurately, we find that most of the days we have had a Red alert sent by only one volcano, but on several days, we found alerts sent by two up to almost seven different volcanoes. This is important because it happens in some sectors where volcanoes are near between them (as in Center sector), and a neighboring storm can trigger a Red alert on all volcanoes of the same area.

The continuous registration of the alerts that Georayos-VolcanoAr, allows to analyze in more detail the temporal evolution of the alerts in each volcano. For all the Red alerts that have been registered by the platform, we have made a temporal evolution analysis of the internal lightning as well as the external ones which generated such alerts. An example of this for three cases in each region is shown in Figure 6-c. We find two patterns present in a Red alert emission. The first case shows a log that begins with a greater number of external lightning than internal and later they increase internal lightning until the Red alert is sent. The second case shows a greater number of internal lightning than the external ones and afterwards the relationship is reversed, increasing the number of external lightning as time passes by.

We have noticed that, in the North and Central sector, half of the alerts sent and registered showed a behavior as in the first case, while in the South region around 90% show this behavior. As described beforehand, the lightning observed in a volcanic eruption start with an electrical activity near the vent and then they can be registered in sectors further away from it. The time evolution of lightning triggering the Red alert does not belong to a volcanic eruption but to the development of a storm whose electrical activity moves away from the volcano.

With the rest of the sent Red alerts, the time evolution of lightning belongs to the second case. Generally, the alerts which develop in this way, pass from Red alert to Yellow in a short lapse of time. This type of behavior is also typical of the storm development generated very near the volcano and which later involves sectors far away from it.

We could distinguish a third pattern (or particular case from the second one) in the evolution of the Red alert similar to the second case, but where the internal discharges surpass the external ones the whole time or simply there are only internal discharges, without register of external discharges. Although it does not occur frequently, it is extremely difficult to identify if the discharges were generated by storms or by an eruption due to the similarity of both behaviors.

With the purpose of comparing the false alerts generated by ACM and Georayos-VolcanoAr, we consider the methodology used by ACM or for archive data, detailed in section 3.2, for each volcano that has emitted a Red alert according to the platform. Following the method of ACM, Georayos-VolcanoAr keeping as Red alerts a total of 4 alerts during the 102 evaluated days. During this period, the ACM has a register of 18 false alerts.

Comparing the false alerts issued by the platform with those emitted by the ACM during the same period, we observed a reduction of almost 75% in the false alerts received by the decision maker from Georayos-VolcanoAr. Considering the sectors, we notice that the number of false alerts in the North and Central sector has reduced considerably, and that during this period the platform has not registered false alerts for the South sector, always considering the method of archive data of the ACM.

6.3 Discussion

During the test period, between 04-Nov-2019 and 14-Feb-2020, we registered each minute the state of alert for all the monitored volcanoes by the platform Georayos-VolcanoAr. From this information, we observe that the number of false alerts is related with the atmospheric electrical activity. In the North sector of the area under study we found a higher number of false alerts than in the Central and South. This happens in spite that the number of volcanoes located in the North sector is less than in the Central one. As suggested, the study of AEA and TD, the use of the detection of electric discharges as a tool for the early detection of volcanic eruptions is more precise towards the Southern section.

By analyzing the evolution of the alert developments issued by several volcanoes, we were able to recognize three patterns that trigger a false Red alert. In the first case, we saw that lightning are first recorded on the outer area and then, as time passes, the record on the inner area increases until the Red alert is issued. In order to disregard this type of warning in the future, we must take into account the recording of lightning during a time interval prior to the time when the Red alert is triggered and thus distinguish this type of behavior. That could reduce the false alerts sent by the platform by more than half.

In the second case, the discharges are registered in the inner area at the beginning, but then it can happen that the discharge registers in the external one increase reaching large values. This case, and the third particular case, are the most complex to correct considering only the record of lightning. Eliminating this type of false alert, in a similar way to that proposed for the first case, would produce a significant delay in the issuance of the Red alert that would be counterproductive. Currently, with the incorporation of the GOES-16 and GOES-17 geostationary satellites, satellite information is available with a delay of 10 minutes (https://www.goes.noaa.gov/). The interactive map of the web platform helps decision makers, among others, to have a quick reference of the sector that issues the alert and to corroborate through satellite images or any other tool they have at their disposal.

When compare Georayos-VolcanoAr with the ACM we have an estimate of the false alerts sent by each system. In this sense, we observed a decrease in the number of false alerts issued compared to the Ash Cloud Monitor, but we must take into account that the number of alerts sent by day is greater than those that are finally saved as archive data.

It should be noted there are eruptions that do not generate electrical discharges, they are usually eruptions with low-energy eruptive columns that do not reach more than 7km in height. These eruptions could not be detected by the platform. On the other hand, the volcanic electric activity is not always generated at the beginning of the eruption; this can happen sometimes later on, as in the case of the second pulse of the Calbuco volcano, where the electric activity took place minutes after the start (Van Eaton, 2020). In these cases, the early warning of the onset of the eruption is lost, but even so, the warning is useful to announce the presence of volcanic products at higher atmospheric altitudes at that time. These are tool limitations due to the characteristics of the natural phenomenon, which have to be considered at the time of using it.

7. Concluding remarks

The study area in this work covers the Chilean and Argentinean Andes; it extends from 22° to 52° South latitude and from 66° to 76° West longitude and covering the volcanoes that are recognized as involve more risk.

From the study of the atmospheric electrical activity and thunderstorm days, we note that the use of the detection of electric discharges as a tool for the early detection of volcanic eruptions may be applicable in this region, being more precise towards the Southern sector.

We performed the Georayos-VolcanoAr platform which has an algorithm for the classification of volcanic alerts that considers the highest risk volcanoes located in the study area. Based on the number of lightning recorded in an internal area of 20 km radius and an external area of 20 km up to 100 km radius, according to the Ash Cloud Monitor, we assign to these volcanoes one of the three alert levels that we established: Red, Yellow or Green. During the trial period, between 04-Nov-2019 and 14-Feb-2020 we recorded the alert status data for all volcanoes monitored by the Georayos-VolcanoAr platform for each minute. From this information, we observed a decrease in the number of false alerts issued compared to the Ash Cloud Monitor.

The Georayos-VolcanoAr platform, allowed to have essential information that could be used to improve the algorithm. Having a record of how alerts occur in each volcano helps the development of a system that discriminates between meteorological and volcanic electrical discharges with greater precision. Once the potential use of the current results has been identified, the interested Agencies will be able to use them. As a future development of the web platform, we suggest attaching to the current map a layer with satellite images or products to have useful information on the same platform and accelerate its interpretation.

This study serves as a basis for a general recognition of the study zone in order to improve the interpretation of the distribution and generation of false alerts; as well as to help decision makers, among others, to have a reference that allows them to issue the warning.

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Highlights

- The detection of electric discharges as a tool for detection of volcanic eruptions and ashfall is more precise towards the Southern sector of the study area.
- Georayos-VolcanoAr is a web platform designed to improve the alerts received by the decision maker and their quick interpretation.
- We observed a decrease in the number of false alerts issued compared to the Ash Cloud Monitor.
- Georayos-VolcanoAr helps the development of a system that discriminates between meteorological and volcanic lightning with greater precision.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: