IDENTIFICATION OF THE AIRSPACE AFFECTED BY THE PRESENCE OF VOLCANIC ASH BY PROCESSING SATELLITE IMAGES, CASE STUDY: POPOCATEPÉTL VOLCANO AREA

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Abstract

A volcanic eruption can affect large areas of the atmosphere around the volcano. Commercial aviation uses these zones the airspace as a navigation zone. Encountering these ash clouds can cause severe damage to different parts of the aircraft, mainly the engines. This work aims to generate a predictive tool based on the frequency of affectionation of the airspace areas around a volcano with eruptive activity, taking the Popocatépetl volcano as a case study. Was carried temporal wind analysis at different atmosphere levels to identifying direction towards which wind disperses ash in year months. This information shown two representative seasons in the direction of dispersion: the first from November to May and the second from July to September, taking into account that June and October are transitional months and therefore do not present a predominant direction. To identify the ash cloud and estimate its area, a set of MODIS images was compiled that recorded the activity in the period 2000-2014. These satellite images were subjected to a semi-automatic digital pre-processing of binarization by thresholds according to the level of the Brightness Temperature Difference between band
31 and band 32, followed by manual evaluation of each binarized image. The result of those above pre-processing was a set of pixels with spatial (longitude and latitude) and temporal (date) description, from which the history of the areas affected by ash permanence was obtained. Additionally, a set of pixels evaluated and labeled in table form could be used as training data for future artificial intelligence applications to automatically detect and discriminate ash clouds.

Keywords: volcanic monitoring, satellite images, aviation risk, hazard mitigation

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1. Introduction

A volcanic eruption creates a high risk for aviation that uses the airspace around the volcanic eruption that emits it. This danger can extend for several tens of kilometers in the direction in which the prevailing winds carry the ash. The risk of an aircraft encounters with volcanic ash clouds is widespread in all parts of the world where there is an active volcano. This type of natural phenomena are highly unpredictable even with all the scientific tools currently available. Besides, once these volcanic products are emitted into the atmosphere, they are transported and dispersed by the prevailing winds at the atmospheric highs reached, which coincides with the airlines’ airspace to carry out their flights.

This aeronautical sector risk is continually increasing due to the rapid expansion of the air transport industry, meaning that the number of airplanes circulating in airspace any time, anywhere, is continuously increasing. These phenomena increase increased the probability of an aircraft’s encounters with an ash cloud around active volcanoes. Several tools have been developed based on monitoring and tracking through satellite images (i.e., Prata, 2009; Jimenez-Escalona et al., 2011; Schneider et al., 2020). Besides, significant advances have also been made in the development of ash dispersion models focused on mitigating aviation risks (i.e., Folch and Sulpizio, 2010; Bonassia et al., 2014). However, these tools are only useful after an eruption as the satellite image detects volcanic products’ presence in the atmosphere. The ash cloud’s dispersion models should be fed with data based on the eruption’s specific characteristics to predict its displacement. When using dispersion models as a prevention tool; hypothetical eruptions should be proposed based on statistical data on the volcano’s behavior.
This paper aims to propose a methodology based on the temporal analysis of satellite images to identify airspace regions with a high probability of being affected by the presence of volcanic ash around an active volcano.

The Popocatepetl volcano area was taken as a case study, which presented explosive eruptions producing ash emissions since its reawakening in December 1994. It is located 65 km from Mexico City international airport and 45 km from Puebla International airport and makes it the best case study for this work. Our new data were acquired from volcanic eruptions detected by MODIS images analyzed between 2000 and 2014. This work also contains the analysis of the wind characteristics in different atmosphere levels for the accumulated data in each month of the year for 20 years. This study allows characterizing dispersion patterns by prevailing wind at different levels in the atmosphere above the volcano.

2. The impact of volcanic ash on aviation

Airborne volcanic ash is a hazard to aviation because these particles, smaller than 100 microns in size, can be transported several hundreds of kilometers from the volcano’s crater. This fine ash can be absorbed by the plane’s air intakes and accumulate in filters and even reach electrical and mechanical devices of the aircraft, which can affect its operation (Rose et al., 1995). Furthermore, the ash suspended in the atmosphere can be ingested by jet engines, causing erosion in the engine’s first stages. When passing through the combustion chamber, the ash can melt, changing its structure to a ductile material that can adhere to the combustion chambers’ walls, mainly in the first stages of the turbine. This adhesion effect obstructs the cooling ducts of the turbine blades, causing
overheating, which leads to further physical damage and severe in-flight problems (Guffanti et al., 2010).

A commercial aircraft travels at speeds of ~800 km/h at altitudes ranging from 6000 to 14000 m. Also, to travel from one airport to another, you must follow a flight plan authorized by the country’s authorities and informed the air traffic offices, within which the route to follow is traced. A defined number of control points where the aircraft must make an arrival report identifies an airway. These checkpoints make an air route mandatory and can only be changed by the pilot in case of an emergency and previously authorized by the air traffic controller.

Besides, based on its market studies, the AIRBUS Company forecasts an annual growth of air traffic of 4.6% in the next 20 years (Airbus, 2016). Currently, the global airline fleet number is ~23,600 aircraft, including both passenger and cargo aircraft. Forecast projections indicate that the number of aircraft flying in a specific airspace will double by 2035. This increase in aircraft also increases the probability of aircraft encounters with volcanic ash clouds above active volcanoes. Guffanti et al. (2010) observe these effects that reported that between 1953 and 2009, 129 aircraft encounters with volcanic ash were documented, while Christmann et al. (2015) reported 113 aircraft encounters volcanic ash between 2010 and 2014. Of these 113 aircraft incidents, 92 were attributed to the Eyjafjallajökull volcano’s eruption in April 2010. These studies show the need to develop tools that can help monitor active volcanoes and the generation of prevention tools that mitigate aviation risks due to these volcanic phenomena. This reason the need to develop tools that can help monitor active volcanoes and prevention tools to mitigate aviation risks due to these volcanic phenomena.
3. Study Area

3.1 Location and Geography

Popocatépetl volcano (19.02ºN, 98.62ºW, 5425 masl) is located in Mexico’s central part, ~ 70 km Northeast of Mexico City, ~40 km West of Puebla and ~60 km northeast of Cuernavaca (Shown in Figure 1). These cities have airports that serve both passenger and cargo transportation. Mexico City International Airport (MCIA) is considered the most important in the country, serving more than 50 million passengers annually, with more than 460,000 takeoff and landing operations reported in 2019. The MCIA serves as a connection for flights to many major cities around the world. Therefore, an important number of aircraft routes to cross the country’s airspace in an orderly manner are located in the airspace area around the volcano.

Figure 2 shows around 60 airways on upper airspace, located between flight levels FL200 and FL430 (between 7 km and 13km of altitude), in an area cover by a 200 NM radius around the volcano crater. The specialized website “www.flightradar24.com” indicates a constant average of 70 aircraft flying in a radio of 370 km (200 NM) area around the Popocatépetl volcano. The Mexican Ministry of Communications and Transportation of (SCT for Secretaría de Comunicaciones y Transportes de México) indicated that passengers’ air transport by national and foreign companies grew by 274% between 1991 and 2016 at an average annual rate of 4.1%. This increase in passengers implies a sharp increase in the number of aircraft in flight in Mexican airspace and a considerable increase in the probability that aircraft encounter whit volcanic ash cloud in the event of an eruption from Popocatépetl volcano.
After ~ 70 years of dormancy, Popocatépetl volcano reawakened on December 21, 1994 (Delgado-Granados et al., 2001). Since then, open-vent eruptive activity and degassing at Popocatépetl volcano, Mexico, have released large CO2 and SO2. A continuous increase since its inception characterizes this explosive activity period, as shown in Figure 3, reaching a peak in 1999 and 2000, where the Washington VAAC reported almost 120 explosive eruptions each year. After this peak, there was a decrease in its activity, leaving less than 20 eruptions per year from 2004 to 2011, but from 2012 there was a new increase in the volcano’s eruptive activity, reaching almost 140 eruptions registered during the year 2018. On various occasions, these gas emissions are accompanied by low to medium intensity explosive events (VEI 1 and 2 and a few VEI 3 explosions), which thrown thousands of tons of solid material in particles form in sizes that can go from several centimeters to dust of several tens of microns in diameter. Due to its weight, the biggest material is deposited few kilometers from the crater, depending on the energy expelled to the atmosphere. However, the smallest material (≤ 100 µm), was transported by the wind at the level where this material was deposited (between 6 km and 11 km altitude), traveling several hundred kilometers before being dispersed by the wind depositing with time on the surface. During this eruptive period of the Popocatépetl volcano, ashfall has been frequently reported at the Puebla airport and at least twice at the AICM. Also, at least 4 aircraft encounters with ash clouds Popocatépetl volcano have been reported (Guffanti et al., 2010).

The Volcanic Ash Advisory Center (VAAC) in Washington has documented more than 640 Vulcanian eruptive events at Popocatépetl between 1999 and 2017. Of these events,
61% have been detected by MODIS satellite images, which have the ability to identify clouds of ash that reaches 200 km in length or more and a coverage of thousands of kilometers in the atmosphere (see figure 4). The Centro Nacional para la Prevención de Desastres de México (CENAPRED), responsible for monitoring the volcano, has detected more than 1024 eruptive events between 1994 and 2017.

4. Data and Methods

Identifying high probability zones for the presence of volcanic ash after an eruption around an active volcano is a tool that can be used to mitigate risks in air transport operations. As already mentioned, once they are placed in the atmosphere, these ash clouds will be carried by the area’s prevailing winds. These winds in the upper atmosphere are mainly influenced by general circulation’s behavior and its effects on the differential warming of the planet depending on the time of year and the latitude of the place. Therefore, to carry out this work, a detailed study of winds in the upper part of the atmosphere in the area where the Popocatepetl volcano is located was essential to identify the trend of prevailing winds as a function of time year. Similarly, a historical analysis of volcanic ash clouds identified in MODIS images was made. To detect volcanic ash in the MODIS images, was used the Split Window technique described by Prata (1989) based on the difference in brightness temperatures in the 11μm and 12μm bands. To pre-processed MODIS images, apply thresholding and morphological operations to extract volcanic ash clouds' corresponding pixels. With this information, the airspace areas around the volcano with
the highest frequency of affectation due to the presence of volcanic ash during eruptive events were identified considering the time of year.

4.1 Wind analysis

An essential factor that must be taken into account when monitoring and predicting volcanic ash’s dispersion is the atmospheric condition. In the last decades, several modeling tools have been developed to reproduce and predict volcanic ash’s dispersion (i.e., Peterson y Dean, 2008; Witham et al., 2012; Folch y Sulpizio, 2010). Also, Prata (2009) described the main monitoring techniques developed during the last 30 years that use satellite remote sensing information. These techniques have been applied by the different Volcanic Ash Advisory Centers (VAACs) and have supported aviation worldwide.

The volcanic ash emitted into the atmosphere in an explosive volcanic event reaches a maximum height that is a function of the energy with which it is expelled and the associated gases’ temperature. Once the volcanic products are emitted, they rise until they are balanced thermally with the atmospheric air around them. From this zone of accumulation by stability with the atmosphere, the ash cloud is transported by the dominant wind. The height of this region cannot be known until the eruption occurs. For this reason, in this work, several wind profiles at different altitude levels based on pressure heights were used. The wind’s profiles in the atmosphere’s vertical structure were obtained from the NOAA Reanalysis data for the years between 1997 and 2016. The pressure levels were analyzed from 400 mb to 150 mb, as shown in figure 5. The flight levels (FL) associated with each pressure level are shown in Table 1. These levels
correspond to the upper airspace characterized by the International Civil Aviation Organization (ICAO), the area where most air transport operations occur.

Wind data was statistically analyzed using wind rose or circular histograms. Histograms were produced with 32 ranges of wind directions. The data were separated by months of the year to identify seasonal patterns. This study allowed us to identify two trend patterns in the wind's predominant direction that is observed in figure 5. The first trend was observed between November to May, whose predominant direction occurs between NE to E, and the second dominant trend occurs between July to September, whose predominant wind direction is between the direction SSW to W. The months of June and October were considered transition months since they did not show a well-defined direction.

4.2 Monitoring of ash clouds with satellite images

In this study, images from NASA’s MODIS-Terra and MODIS-Aqua instruments were used. The sensors measure 36 spectral bands in the visible and infrared regions of the electromagnetic spectrum (0.405 - 14.385 μm) and acquire data at three spatial resolutions: 250m, 500m, and 1,000m. The Terra and Aqua satellites are on a polar orbital trajectory at 705 km altitude above sea level with a stripe width of 2,330 km (Watson et al., 2004). The region of the spectrum used to observe volcanic clouds corresponds to bands 28 (7.3 μm), 29 (8.6 μm), 31 (11 μm) and 32 (12 μm) of the MODIS sensor. These five bands are within the thermal infrared and are sensitive to several volcanogenic species as SO₂ and ash (Watson et al., 2004).
Each MODIS sensor captures 288 images a day around the Earth, passing over the area of interest twice a day: one during the night, between 11:00 and 04:00 local time, and the other during the day, between 11:00 and 15:00 local time. Under ideal conditions, it is possible to obtain four images per day. However, there are occasions when the image cannot be used for the detection of volcanic products due to factors such as: a) the volcano is not observed inside the image; b) the meteorological conditions (presence of clouds) do not allow observing the ash cloud; c) the image is acquired before the eruptive event occurs.

The MODIS images used in this work were downloaded from the NASA website (http://ladsweb.nascom.nasa.gov/). This website allows the user to select the type of satellite data, the desired image’s location according to the latitude and longitude, and the time of the desired image.

The infrared recovery scheme used in this work is described in Watson et al. (2004). Detection of volcanic ash is achieved using the selective absorption that ash particles present in the thermal infrared (TIR) spectral range in the range of 10 μm to 12 μm (Mackie, et al., 2014). Each image was analyzed to detect the ash emission signature. In MODIS images, ash is detected using the BTD between bands 31 (11 μm) and 32 (12 μm). The brightness temperature was obtained by modifying the Planck function formula of radiative transfer calculations using a semitransparent cloud model based on three assumptions: 1) the shapes of the particles are spherical, 2) the particle size distribution is uniform and monodisperse within each pixel, and 3) the cloud forms a single well-defined homogeneous layer in each pixel (Wen and Rose, 1994). The detection of
volcanic ash is achieved by exploiting selective absorption in the spectral range of TIR obtaining negative results values in pixels with volcanic ash content.

On the other hand, this procedure results in positive values in the pixel values in meteorological clouds. When using satellite images, it is essential to consider the time at which the eruption occurs and the time at which the image is taken to consider the dispersion phenomena of the volcanic cloud. This time interval is critical to estimate the speed of displacement of the cloud, as well as the possible distance that the plume would reach from the point of emission until before it was diluted enough so that the MODIS image could not detect it. As shown in Table 2, thanks to the MODIS images’ temporal resolution, it was possible to identify about 61% of the eruptions reported by the VAAC in Washington.

An essential piece of information in this study was the ash cloud’s reported altitude, obtained from the Washington VAAC reports. In these cases, the ash cloud’s altitude is estimated by calculating the temperature of the upper part of the ash cloud that is captured by the satellite and comparing it with the atmospheric soundings emitted by the radiosonde station closest to the volcano. It is considered that the cloud reaches its maximum altitude when it is thermally balanced with the air of the surrounding atmosphere, and from this equilibrium zone, it is carried by the prevailing wind.

The analysis of altitudes of the ash clouds is shown in figure 6, where it is observed that around 88% of the ash clouds reported by the VAAC in the study period were located between flight levels FL180 (5500 masl) and FL260 (8000 masl). It is important to note that the upper airspace in the Territory of Mexico is designated above 20,000 feet, and in this area, commercial aircraft carry out air navigation to travel from one airport to another.
4.3 Ash clouds data extraction using MODIS images

The designation of the eruptive events captured by MODIS images was done based on reports issued by the VAAC of Washington between 2000 to 2014. In this period were reported 358 eruptive events with ash in concentrations were captured by satellite images by the VAAC of Washington (through GOES satellites). Of these information were identify 242 events in the MODIS image. Table 2 shows that in MODIS images catch between 40% and 87% of events each year, which allows a temporary study of the dispersion of ash clouds in the Popocatépetl volcano area.

The main advantage of detecting volcanic ash clouds utilizing the BTD between the 11 μm and 12 μm bands, is its fast application and simplistic approach. However, this technique has some drawbacks such as false alarms (“false positive” when a particular pixel is recognized as ashes but does not contain ashes and vice versa by “false negative”) obtained in specific cases and well documented (Simpson et al., 2000; Prata et al., 2001). For this reason and to identify the area of coverage of the ash clouds around the Popocatépetl volcano, we delimited the search area in the image to a radius of 400 km considering the maximum longitude detectable visual revision of the MODIS images already processed.

For each of the images, the pixels corresponding to ash clouds were identified, obtaining with this the data set characterized by their geographical location. With the matrix of the resulting image, a double thresholding process was implemented to segment the bodies within the image, as shown in Figure 7a.
The BTD method identifies the pixels with ash particles with a negative value and the
pixels with the presence of drops of water cloud with positive values (Prata, 1989). So,
by proposing $p_{ij}$ as the pixel’s values in the MODIS image, the pixels for $p_{ij} > 0$ were
discarded. We must remember that a histogram can be expressed as a probability
distribution with the form:

$$p(p_{ij}) = \frac{n_{p_{ij}}}{n}$$

Where $n_{p_{ij}}$ is the number of pixels with density $p_{ij}$ and $n$ is the total number of different
pixels.

A threshold value $T$ was obtained over the pixels that satisfy $p_{ij} < 0$, then the pixels
$p_{ij} \leq T$ being assigned as bodies of volcanic ash. The algorithm’s selection to compute
the threshold $T$ was deduced experimentally by comparing the results obtained by
histogram-based thresholding (Glasbey, 1993) and automatic-iterative threshold
detection (Ridler T.W. and Calvard S., 1978, Shapiro and Stockman, 2001). The
application of the histogram-based mean thresholding achieved the highest number of
images correctly binarized, obtaining 78 images with identifiable clouds of volcanic ash
after evaluating a total of 242.

Once the image was binarized, morphological operations were applied over the result to
expand and fit better the mask over truth area (dilation) followed by rejecting the noisy
pixels (closing) (Shapiro and Stockman, 2001). This step aims to highlight the found
objects’ structure and reconstruct them from distorted and noisy shapes, making them
more cohesive, as shown in figure 7b. It is important to emphasize that the structure’s
size for the dilation operation was selected with a small value (4 pixels in diameter),
avoiding the attachment of non-ash pixels to main bodies, subsequently processed by closing operation.

Once finished evaluating images, the group of pixels associated with ash was extracted from each image, producing a table in which image label date was stored, along with the pixel’s geographical coordinates, coordinates of pixel within the matrix of image, and name of the image. This information can be used in future work as a binary dataset describing the ash and non-ash classes.

With the representative ash pixels obtained from the MODIS image set, the last stage was to identify the areas of the airspace that had the highest percentage of occurrence of volcanic ash from Popocatépetl explosive events in the two periods of the year identified by wind dispersion (from November to June and from July to October). The histogram calculation was made for both geographical variables (latitude and longitude), which allowed the identification of the airspace areas with a high probability of affectation due to the presence of ash in case of an explosive event (figure 8).

5. Results and discussion

As mentioned above, commercial aviation follows exact instructions about the routes and altitudes where it carries out its air operations. For this reason, to avoid the risk due to the dispersion of volcanic ash, civil aviation requires two sources of information. The first is a preventive tool capable of calculating the probability of dispersion of ashes in case of eruptions. The second is the monitoring of volcanic clouds in real-time and the forecast of ash dispersion.
The purpose of this work was to obtain the spatial dispersion patterns of ash emitted by explosive events from Popocatépetl volcano, given the behavior of the direction of the winds at certain times of the year. Two representative seasons were considered: from November to May and from July to September. A set of MODIS images that recorded the events in the year 2000 to 2014 was collected. These satellite images were subjected to semi-automatic binarization by thresholds according to the level of the BTD followed by manual evaluation of each binarized image. The result of those mentioned above pre-processing was a set of pixels with spatial (longitude and latitude) and temporal (date) description, from which the historical data of the zones affected by the presence of ash was obtained.

Additionally, this set of pixels evaluated and labeled in the form of a table can be used as training data for future artificial intelligence applications to automatically detect and discriminate ash clouds.

5.1 Wind patterns

The statistical analysis of the wind patterns over twenty years (1997 - 2016) was separated by months to identify the seasons' main trends. Figure 5 shows two main trends in the dominant wind direction in the studied area ranging from the 500 mb level to the 300 mb level corresponding to 18000 ft to 30000 ft (7300 masl to 13400 masl). In this analysis, two transition periods were also identified, during which it is not possible to recognize a clear trend of the wind's predominant direction. From July to September, the predominant wind direction trend is between ENE and ESE at flight levels FL180, FL210
and FL240. At the FL270 and FL300, the trend is more defined between NNE and E. Finally, the months of June and October are considered a transition period due to the lack of definition in the prevailing wind direction. June shows the wind directions between N and SSE at levels FL180 and FL210, at level FL240, the wind direction is predominantly ESE to NNW, and at levels FL270 and FL300 it shows a much greater distribution in the wind directions bearing a distribution between the SW and ENE directions. In October, the wind direction of levels FL180 to FL210 shows a predominant pattern of directions between NNE to SSE, and at levels FL240, FL270, and FL300, the wind does not present a defined direction, as shown in figure 4.

An important parameter that influences the transport of ash clouds and their deposition is the wind speed. In general, the wind speed in the lower part of the troposphere is influenced by the area’s orography. Therefore, when this influence is lost at higher altitudes, the speeds tend to be higher and more uniform. A statistical analysis of wind speeds, shown in Tables 3 and 4, indicates that, during the period from November to May, only 7% of the winds registered at the level of FL180 presented a speed greater than 30kts, increasing this percentage with increasing altitude reaching a value of almost 54% at the FL300 level. At this higher altitude level in the analysis, maximum speeds of up to 106 kts were presented, but only 14% of the recorded data are above 50 kts. This analysis indicates that the higher altitude reached by the eruptive column, the greater the speed of the winds responsible for its transport and dispersion, causing the ash cloud coverage area to be more significant.

On the other hand, during the period between June and October, the wind speed at all levels decreased as shown in Table 4, the wind speeds oscillated around 40 kts at all
levels. Data shows that around 50% of the data at all levels of the atmosphere monitored exceeded 10 kts, but vast majority did not reach 20 kts of speed. This analysis shows that winds at this time of year cause much less dispersion and affectation of ash clouds transported towards the country’s center, mainly in direction between the W and the WNW.

5.2 Monitoring of volcanic ash with satellite images

Due to the large area that a volcanic cloud can cover, satellite images have become a great tool in the monitoring and follow-up of this type of event. Several sensors on satellite platforms allow the detection of ash suspended in the atmosphere, such as AVHRR, GOSAT, GOES, SEVIRI and MODIS. MODIS sensors shipped on NASA’s TERRA and AQUA satellites deliver images with a resolution of 1 km in the infrared bands. On the other hand, between both MODIS sensors, they present a temporal resolution of up to 4 images per day of the area around Popocatépetl volcano. The combination of the temporal and spatial resolution of MODIS allows a continuous monitoring of the volcano, permitting the identification of more than 61% of the volcanic ash clouds associated with explosive events during the period from 2000 to 2014 reported by the VAAC of Washington, as shown in table 2.

This images selection was the first step of the classification. However, as was previously mentioned, this identification of volcanic ash using MODIS images can be affected by cloudy conditions or the presence of suspended dust or sand particles. For this reason,
a second filter was applied using a thresholding technique to discard the images that could contain information that could be confused with volcanic ash.

Another factor that was taking into account was the time reported at beginning of the eruption and when satellite image was taken. This helps to see the dispersion of the ash cloud and estimate the area of the affected airspace. Figure 4 shows four volcanic clouds for April 18 and May 4, 2012, and March 7 and July 9, 2013. The eruptive event of April 18, 2012, was tasted by the image MODIS 5 hrs after the eruption started presenting an ash cloud of 2676 km² in length moving towards the E at a speed of 25 kts as reported by the Washington VACC. In the ash cloud from the May 4 event, it was captured by the MODIS sensor 13 hours after the eruption began, covering an area of 3500 km² airspace moving NW at a speed of 10 kts. During March 7, 2013 event, an ash cloud was detected 5 hours after the start of the eruption, which presented an airspace coverage of 4550 km² in the E direction of the volcano’s crater, moving at a speed of 20 Kt. In case of the July 9 event, MODIS image shows ash cloud 5 hours after the beginning of the eruption, which presents airspace coverage of 3300 km² moving towards the SW at a speed of 10Kt. The four ash clouds were reported at an altitude of around 7000m (FL230). These observations show that the airspace area that a volcanic cloud can cover depends on three main factors, the altitude of the eruptive column, the wind’s speed that moves the cloud, and the continuous emission of ash long periods of weather.

5.3 High probability zone of presence of ash
A total of 242 MODIS images were analyzed from 2000 to 2014, from which the BTD technique for identifying volcanic ash clouds was applied. We found that the detection of volcanic ash by the BTD technique can be affected by the presence of dust particles suspended in the atmosphere and the presence of extensive ice content in meteorological clouds (Gray and Bennartz, 2015). To classify the areas where volcanic ash was positively identified in the MODIS images, a filtering technique was applied using thresholding, and subsequently, the contour of the cloud was defined employing morphological operations. This methodology classified images that clearly showed the presence of ash cloud, and in this way were documented all coordinates of pixels that formed the area each ash clouds. This way were identified 78 MODIS images with clear ash clouds, from which geographic information each of pixels of these clouds was obtained. With this information, a frequency statistic of the pixel’s appearance was generated in all the analyzed images. This information was separated, taking into account the two periods of the year defined in the wind analysis. With this information, maps shown in figure 8 were constructed that define areas with highest volcanic ash frequency in images analyzed around the Popocatépetl volcano in different periods of the year.

5.4 Aviation air routes

To aircraft travel from one airport to another must follow pre-established routes controlled by the agencies that regulate the airspace. An airplane can only divert its course with the authorization of the control center that monitors its movement and only in case of an emergency that justifies it. In this work, we use the aeronautical H2 map, published by
the Navigation Service offices in the Mexican Air Space SENEAM (2016), which is responsible for monitoring and ensuring the safety of aircraft navigation in Mexican territories. This map shows that within a radius of 200 nautical miles (370 km) around Popocatepetl volcano, 106 airways are traced that could be affected by ash in an eruption event.

Considering the direction of the winds and the statistics of the speeds reported in the different levels of the atmosphere where data is available, three risk areas were identified and shown in figure 9. These areas cover the distance a cloud of ash could reach after one hour of the eruption. As shown in the wind analysis section, the wind has a higher speed during November to May. Therefore, for this time of the year, 70 Knots were taken as critical speed, whereas 50 Knot was used for the rest of the year to estimate the ash cloud’s displacement. In this way, the first area around the volcano represents the area that could be affected during the first hour after the eruption, which can be considered the most critical aviation area after an eruption in Popocatepetl volcano. The second hour after the eruption is identified with the second area’s contour shown in figure 9. Here is shown the airspace area that could be affected after the first hour and up to 2 hours after the eruption started. A third area indicates an ash cloud location after 2 hours and before 4 hours after the eruption, taking into account the critical wind speed values.

Considering the data from the wind analysis, the monitoring of ash clouds using satellite images and our numerical model, and the period on the year, it is possible to identify the air routes that are most likely to be affected by volcanic volcanic ash. During November to May, the ash clouds move mainly between NNE and ESE. In this period of the year, ash dispersion can affect the states of Veracruz and Tamaulipas. In this area, the aircraft
uses 36 airways to travel between one airport and another, as shown in figure 9. Between July and September, the area identified as the most likely affected is found on the west side of the volcano. The ash clouds that are transported at this time of the year can force the closure of the airspace that links several international airports in the country’s central zone, including Mexico International Airport (AICM) with almost 460,000 operations land ands takeoff reported during 2019. In this area of the country, and due to the lower wind speed, 22 airways are within the area delimited by 4 hours of displacement of the cloud in the country’s central area, as shown in figure 9.

6. Conclusions

An active volcano represents a high risk to aircraft navigation operations in nearby areas. The wind can carry the ash emitted in an eruptive event depending on its predominant direction and the average speed at the level that it is deposited. Therefore, characterizing these factors that disperse volcanic ash allows us to identify the areas most susceptible to being affected by these volcanic products’ presence depending on the time of year that the eruption occurs. This study allows the possibility of creating maps of probability of impact that allow for carrying out risk mitigation actions in the navigation of aircraft in this zone.

To perform the analysis of the case study, it was carried out data processing of Popocatepetl volcano eruptions over a period from 2000 to 2014. This volcano is located in central Mexico, surrounded by important cities and airports such as Mexico City, Puebla, and Toluca. Due to the proximity to airports located around the volcano and the
importance of the air space in the center of the country through which local and international flights circulate, this document presents a study to identify airspace areas with the most significant probability of being affected by volcanic ash in the event of a Popocatepetl volcano eruption. The map in figure 8 shows the areas with the highest frequency of being affected by ash in the case of an eruption of the Popocatépetl volcano according to the time of year that the eruption occurs. These probability zones are obtained through a statistical study of 242 MODIS images collected from 2000 to 2014. With this information, impact frequency maps due to ash generated in the case of an eruption of the Popocatépetl volcano could be constructed.

For identifying the main direction patterns of the plume during the times of the year, it was based on the statistical analysis of wind profiles at different levels in the atmosphere where aviation operations prevail. The most frequent wind directions were compared and validated with actual volcanic cloud dispersions observed with MODIS satellite images. The result of coupling these two tools revealed two main transport patterns for volcanic ash, according to the year’s season. The most extensive period of the year occurs during the months between November to May. It was identified that, during these months, the trend of ash dispersion is mainly in the NNE-ESE region that affects the area of the states of Veracruz and Tamaulipas, where 6 airports are present. A second well-defined period was during the months of July to September when ash transport was identified with a dominant direction from W to S at levels above 30,000 feet (FL300) and the dominant direction from NNW to SW at levels below FL300. The months of June and October were identified as transition months, so they do not show a clear trend in atmospheric transport due to the wind. In these months, the dominant wind direction largely depends on the height at which the ash cloud is transported.
From November to May, the period has the highest wind speeds at all altitudes, where up to 15% of winds are > 60 Knots. During the remaining months (June to October), wind speeds from at all altitudes show a significant decrease, with >85% of the data being below 40 knots. This implies that the ash clouds travel longer distances before they are diluted in the atmosphere. For ash clouds that travel to the country’s center are transported at a lower speed and lower levels. This is the reason why the MCIA has rarely been affected by the presence of volcanic ash.

This information allowed identifying the zones most likely to be affected by volcanic ash during (and shortly after) explosive events at Popocatépetl volcano, depending on the time of year. In the area defined by 200 Nautical Miles around the Popocatépetl volcano, 106 airways were found that would be affected by volcanic eruption. These airways can be identified depending on the time of year, as shown in the map presented in figure 9. From November to May, 36 air routes have a high probability of being affected in case of an eruption at Popocatépetl volcano. On the other hand, from July to October, 22 air routes were identified with a high probability of being affected by volcanic ash in the case of an eruption of Popocatepetl.

The information acquired in this work allows a better planning of alternative routes and airports in explosive activity at Popocatépetl volcano. This work can also be considered a starting point for airspace planning to reduce the saturation of airports in the event of a volcanic crisis.
Declarations

- Availability of data and materials

The datasets generated during and/or analysed during the current study are available in the ARL, NOAA repository, [https://www.ready.noaa.gov/index.php]; LAADS DAAC, NASA [https://ladsweb.modaps.eosdis.nasa.gov/].

- Competing interests

The authors declare that they have no competing interests.

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- Authors’ contributions

Authors' contributions were generated as follows. JRJC was the principal investigator of the Project. AGRS analyzed and interpreted the digital processing of MODIS images. RJ analyzed the information on the eruptive activity of the Popocatépetl volcano. ARJE analyzed and interpreted the effects on the airspace and circulation by air navigation in the affected area. PMJL analyzed and interpreted the temporal study of the wind in the vertical structure of the atmosphere. HCOM strongly supported the analysis of wind characteristics at height. All authors read and approved the final manuscript.

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Table 1. Flight levels in the airspace and its corresponding pressure level

| Pressure Level | Nivel de Vuelo (FL) | Altitud (pies) | Altitud (msnm) |
|----------------|---------------------|----------------|----------------|
| 300mb          | FL300               | 30,000         | 9,200          |
| 350mb          | FL270               | 27,000         | 8,200          |
| 400mb          | FL240               | 24,000         | 7,300          |
| 450mb          | FL210               | 21,000         | 6,400          |
| 500mb          | FL180               | 18,000         | 5,500          |

Table 2. Percentage of eruptions of the Popocatépetl volcano detected with MODIS images in the period from 2000 to 2014

| Year | VAAC Eruptions | MODIS Detected | Eruption detected in MODIS |
|------|----------------|----------------|----------------------------|
| 2000 | 59             | 33             | 55.9%                      |
| 2001 | 49             | 21             | 42.0%                      |
| 2002 | 12             | 7              | 58.3%                      |
| 2003 | 35             | 20             | 57.1%                      |
| 2005 | 21             | 14             | 66.7%                      |
| 2006 | 13             | 6              | 46.2%                      |
| 2007 | 8              | 6              | 75.0%                      |
| 2008 | 8              | 5              | 62.5%                      |
| 2009 | 9              | 6              | 66.7%                      |
| 2010 | 5              | 2              | 40.0%                      |
| 2011 | 14             | 8              | 57.1%                      |
| 2012 | 54             | 47             | 87.0%                      |
| 2013 | 52             | 35             | 67.3%                      |
| 2014 | 19             | 9              | 47.4%                      |
### Table 3. Statistical data of wind speed at levels from 500mb to 300mb in the period from 2000 to 2014 for the months of November to May

|                  | 300 mb (FL300) | 350 mb (FL270) | 400 mb (FL240) | 450 mb (FL210) | 500 mb (FL180) |
|------------------|----------------|----------------|----------------|----------------|----------------|
| Promedio:        | 32.4 kts       | 26.7 kts       | 22.3 kts       | 17.8 kts       | 14.2 kts       |
| Máximo:          | 106 kts        | 98 kts         | 98 kts         | 76 kts         | 71 kts         |
| Velocidad > 10 kts | 94.7%         | 90.5%          | 85.2%          | 76.1%          | 64.2%          |
| Velocidad > 20 kts | 77.5%         | 65.5%          | 53.6%          | 36.8%          | 22.9%          |
| Velocidad > 30 kts | 53.9%         | 38.2%          | 24.6%          | 13.4%          | 7.0%           |
| Velocidad > 40 kts | 29.9%         | 17.3%          | 9.2%           | 4.3%           | 2.1%           |
| Velocidad > 50 kts | 14.3%         | 6.6%           | 3.5%           | 1.4%           | 0.5%           |
| Velocidad > 60 kts | 6.2%          | 2.7%           | 1.2%           | 0.4%           | 0.1%           |
| Velocidad > 70 kts | 2.2%          | 0.8%           | 0.4%           | 0.1%           | 0.0%           |

### Table 4. Statistical data of wind speed at levels from 500mb to 300mb in the period from 2000 to 2014 for the months of July to September

|                  | 300 mb (FL300) | 350 mb (FL270) | 400 mb (FL240) | 450 mb (FL210) | 500 mb (FL180) |
|------------------|----------------|----------------|----------------|----------------|----------------|
| Promedio:        | 11.5 kts       | 10.4 kts       | 10.1 kts       | 10.0 kts       | 10.1 kts       |
| Máximo:          | 40 kts         | 38 kts         | 38 kts         | 41 kts         | 42 kts         |
| Velocidad > 5 kts | 87.7%          | 85.8%          | 84.4%          | 85.0%          | 86.6%          |
| Velocidad > 10 kts | 58.2%         | 51.4%          | 49.7%          | 50.8%          | 51.8%          |
| Velocidad > 20 kts | 10.2%         | 7.0%           | 5.6%           | 4.7%           | 4.1%           |
| Velocidad > 30 kts | 0.8%          | 0.3%           | 0.3%           | 0.2%           | 0.2%           |
Figure 1. Towns and airports around the Popocatepetl volcano

Figure 2. Airway map of central Mexico. Popocatepetl volcano is pointed in the central part of the country. (Modified from aeronautical chart of the upper airspace H2, published by SENEAM (Servicio a la Navegación en el Espacio Aéreo Mexicano, in spanish).
Figure 3. Historical activity of last eruptive period of Popocatépetl volcano. The information was obtained in VAAC reported in a period since 1999 to 2018.
Figure 4. Volcanic Ash clouds from Popocatepetl volcano identify in the MODIS image.
Figure 5. Wind profiles over the crater area of the Popocatépetl volcano, obtained from NOAA Reanalysis data for a period of 20 years, at pressure levels of 500 mb to 300 mb. Wind data was statistically analyzed separately for each month of the year, associating the trends in the months of the year.
Figure 6. Histogram of the altitudes where were identifying volcanic ash clouds by the Washington VAAC in the period from 2000 to 2014. The altitudes are expressed in the nomenclature of flight levels (FL) in hundreds of feet above the sea level. This is because it is reported as support for air navigation.

Figure 7. Pre-processing of satellite images using media thresholding (a) and morphological operations (b).
Figure 8. Areas with a high probability of being affected by volcanic ash in the event of an eruption of the Popocatépetl volcano. In the upper part during the November-May period and in the lower part during the July-October period.
Figure 9. Delimited area considering the movement of a volcanic cloud transported by the wind in the seasons of the year defined by the wind direction. Identify three areas of safety: the first with a radio considering an hour of displacement by wind speed. Given the maximum wind speed in different years, the trend in the NNE - ESE area of wind speed was taken as 70 kts, and in the defined area W - S it took a wind speed of 50 kts. The second level of safety is defined by the hours of transport with a critical wind speed. The third zone with a transport of 4 hours with a critical wind speed.