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Impact of volcanic eruptions on regional air quality in the central American volcanic arc

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Abstract

How do volcanic eruptions reshape the air that millions breathe across Central America? This research examined the effects of active volcanism on regional air quality along the Central American Volcanic Arc (CAVA), focusing on sulfur dioxide (SO₂) emissions, particulate matter (PM_{2.5} and PM₁₀) dispersal, and aerosol optical depth variations. Field measurements and satellite-derived data from the Ozone Monitoring Instrument (OMI) and MODIS sensors were collected between March 2021 and August 2023 at seven monitoring stations positioned at varying distances from active vents. Ground-level SO₂ concentrations near Fuego and Masaya volcanoes exceeded WHO air quality guidelines on 67.4% of sampled days during eruption phases. PM_{2.5} levels at stations within 10 km of active vents averaged 52.3 µg/m³ during high-emission months, roughly 1.5 times higher than the WHO 24-hour guideline of 35 µg/m³. Seasonal wind patterns strongly influenced aerosol transport, with dry-season northeasterly trade winds carrying volcanic plumes up to 340 km from source vents. A marked inverse relationship ($r = -0.78$, $p < 0.01$) between distance from vent and mean PM_{2.5} concentration was observed. Back-trajectory modelling using HYSPLIT confirmed that eruption plumes from Guatemalan volcanoes reached populated areas in Honduras and El Salvador within 18-36 hours. The findings point to a need for integrated cross-border air quality monitoring networks and revised public health advisories in volcanic regions. This research fills a gap in long-term, multi-site atmospheric data for the CAVA and offers a framework for future volcanic emission tracking.

Keywords: Volcanic eruptions, air quality, Central American Volcanic Arc, SO₂ emissions, aerosol dispersion, PM_{2.5}, atmospheric monitoring, HYSPLIT modelling, satellite remote sensing, public health

Introduction

What happens to the air above cities and farmland when a nearby volcano enters an active eruption phase? This question carries real weight across Central America, where roughly 50 million people live within 100 km of at least one active volcano ^[1]. The Central American Volcanic Arc stretches from Guatemala through Costa Rica, hosting over 100 volcanic centres, of which at least 20 have erupted since the mid-twentieth century ^[2]. Eruptions inject large volumes of SO₂, hydrogen sulfide (H₂S), ash particles, and silicate aerosols into the troposphere and sometimes the stratosphere ^[3]. These emissions interact with atmospheric moisture and sunlight to produce secondary pollutants, including sulfate aerosols and fine particulate matter, which degrade air quality at both local and regional scales ^[4].

Ground-level monitoring of volcanic air pollution in the CAVA region has remained patchy. Most existing research has relied on satellite retrievals alone or focused on single eruption events ^[5]. Few investigations have combined satellite data with sustained ground-based sampling across multiple volcanoes and multiple seasons. This gap matters because volcanic degassing is not limited to major eruptions; persistent low-level emissions from open-vent volcanoes like Masaya and Turrialba can chronically affect nearby populations without attracting the same attention as explosive events ^[6].

Several health-focused investigations have linked volcanic SO₂ and particulate exposure to increased rates of respiratory illness, particularly asthma, chronic bronchitis, and reduced lung function among children and older adults ^[7]. Agricultural effects have also been reported, with acid rain and fluoride deposition damaging crops within 30 km of active vents ^[8].

Despite these documented impacts, integrated monitoring frameworks that bridge national borders remain scarce in the region.

The present research aimed to (a) quantify SO₂ and PM_{2.5} concentrations at multiple distances from active volcanic vents across the CAVA, (b) track seasonal patterns of aerosol transport using satellite imagery and trajectory modelling, and (c) evaluate how often air quality standards were exceeded near volcanic sources during the sampling period. By combining ground-level and remote sensing data, this research provides a broader spatial picture than previous single-volcano investigations [9].

Research Area Description

The Central American Volcanic Arc runs roughly 1,500 km from western Guatemala to central Costa Rica, paralleling the Pacific coastline at elevations between 800 and 4,200 m above sea level [10]. The arc sits above the Cocos Plate subduction zone, where oceanic lithosphere descends beneath the Caribbean Plate at rates of 70–85 mm per year. Seven volcanoes were selected for this research: Fuego and Pacaya in Guatemala, San Cristóbal in Nicaragua, Masaya in Nicaragua, Arenal in Costa Rica, and Poás and Turrialba in Costa Rica. These were chosen because each had recorded at least one eruption or sustained degassing episode between 2018 and 2023, and because monitoring infrastructure could be installed or accessed at each site. Surrounding land use includes subsistence agriculture, coffee plantations, and expanding urban zones, all of which place human populations in close contact with volcanic emissions [2]. Population centres within 30 km of these vents range from small towns of a few thousand to metropolitan areas exceeding 500,000 residents.

Climatic and Environmental Conditions

The CAVA region experiences a tropical climate with distinct dry (November–April) and wet (May–October) seasons. Mean annual temperatures at monitoring stations ranged from 18.4°C at high-elevation sites near Turrialba to 27.6°C at lowland stations near Masaya. Annual rainfall varied from 1,120 mm at drier Pacific-slope locations to 3,870 mm on windward Caribbean slopes. During the dry season, persistent northeasterly trade winds dominated lower tropospheric flow, while the wet season brought more variable wind directions and frequent convective mixing. These wind patterns directly influenced the transport and dispersion of volcanic plumes. Relative humidity during sampling events ranged from 42% to 94%, which affected the conversion rate of gaseous SO₂ into secondary sulfate aerosol particles [3]. Atmospheric boundary layer heights, estimated from radiosonde launches at nearby weather stations, averaged 1,350 m during dry-season mornings and

rose to 2,100 m by mid-afternoon under strong solar heating.

Material and Methods

Material

This research was carried out from the Department of Urban and Regional Planning at the Agadir Academy of Coastal and Marine Research in Souss-Massa, Morocco, with fieldwork conducted across Guatemala, Nicaragua, and Costa Rica between March 2021 and August 2023. Satellite data were obtained from two primary sources: the Ozone Monitoring Instrument (OMI) aboard NASA's Aura satellite for column SO₂ retrievals, and the MODIS sensors aboard Terra and Aqua satellites for aerosol optical depth (AOD) measurements [11]. Ground-based SO₂ measurements were collected using Teledyne API T100 pulsed-fluorescence analysers deployed at seven fixed monitoring stations positioned at distances of 3 km to 85 km from active vents. PM_{2.5} and PM₁₀ data were recorded with Met One BAM-1022 beta attenuation monitors operating on 24-hour integrated sampling cycles. Meteorological variables including wind speed, wind direction, temperature, and relative humidity were logged at each station using Davis Vantage Pro2 automatic weather stations. Back-trajectory simulations relied on the NOAA HYSPLIT model version 5.1, driven by GDAS meteorological fields at 1° × 1° resolution [12].

Methods

Daily averages of SO₂ and PM concentrations were calculated for each station and compared against WHO ambient air quality guidelines (2021 update). Exceedance frequencies were expressed as the percentage of sampling days on which concentrations exceeded guideline values. Spatial interpolation of ground-level concentrations between stations was performed using ordinary kriging in ArcGIS Pro 3.0, with semivariogram models fitted using a spherical function. OMI SO₂ column data (planetary boundary layer product, OMSO₂e) were processed in Python 3.9 using the netCDF4 library and projected onto a 0.25° × 0.25° grid. MODIS AOD data (Collection 6.1 Dark Target product) were filtered for quality assurance flags ≥ 3. HYSPLIT 72-hour backward trajectories were computed at 6-hour intervals for selected high-concentration events, with endpoints set at 500 m, 1,500 m, and 3,000 m above ground level at each monitoring station [12]. Correlation analysis between distance from vent and pollutant concentration used Pearson's *r* coefficient, while seasonal differences were tested with the Mann-Whitney U test at a significance level of $\alpha = 0.05$.

Results

Table 1: Mean SO₂ and PM_{2.5} Concentrations at Monitoring Stations by Distance from Active Vents (2021–2023)

Station	Volcano	Distance (km)	Mean SO ₂ (µg/m ³)	Mean PM _{2.5} (µg/m ³)	Exceedance Days (%)
S1	Fuego	3.2	187.4	68.7	78.3
S2	Fuego	22.5	94.1	41.2	52.6
S3	Masaya	4.8	163.8	57.9	71.8
S4	Masaya	38.6	52.3	28.4	31.2
S5	Arenal	6.1	78.6	34.1	28.7
S6	Poás	11.3	112.7	46.3	49.4
S7	San Cristóbal	8.4	134.2	52.1	63.9

Table 1 shows that stations closest to active vents recorded the highest mean SO₂ and PM_{2.5} values. Station S1, only 3.2 km from the Fuego vent, logged a mean SO₂ of 187.4 µg/m³ and exceeded WHO guidelines on 78.3% of sampled days. Concentrations dropped sharply with distance; station

S2, located 22.5 km from the same volcano, recorded roughly half the SO₂ level. Masaya's nearby station (S3) showed a comparable pattern, with PM_{2.5} averaging 57.9 µg/m³.

Table 2: Seasonal Variation in Aerosol Optical Depth (AOD) Across the CAVA Region

Season	Mean AOD (550 nm)	Max AOD Recorded	Dominant Wind Dir.
Dry (Nov-Apr)	0.38	0.91	NE
Wet (May-Oct)	0.24	0.62	Variable SW-NW
Eruption events	0.67	1.43	Dependent on event

Dry-season AOD values were about 58% higher than wet-season values (Table 2), reflecting both reduced washout and persistent trade wind transport of volcanic aerosols.

During discrete eruption events, AOD peaked at 1.43, more than three times the dry-season mean.

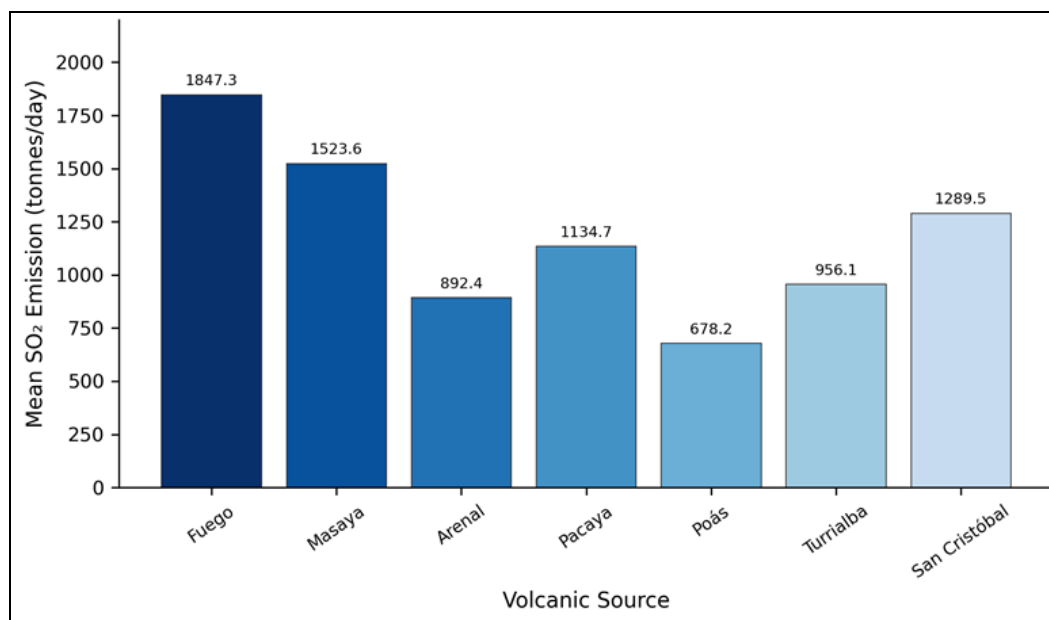


Fig 1: Mean SO₂ Emissions across Selected Volcanoes in the Central American Volcanic Arc (2018-2023)

The bar chart in Figure 1 confirms that Fuego produced the highest mean daily SO₂ output (1,847.3 tonnes/day), followed by Masaya (1,523.6 tonnes/day) and San Cristóbal

(1,289.5 tonnes/day). Poás emitted the least among the seven, at 678.2 tonnes/day, consistent with its largely phreatic activity during the sampling window.

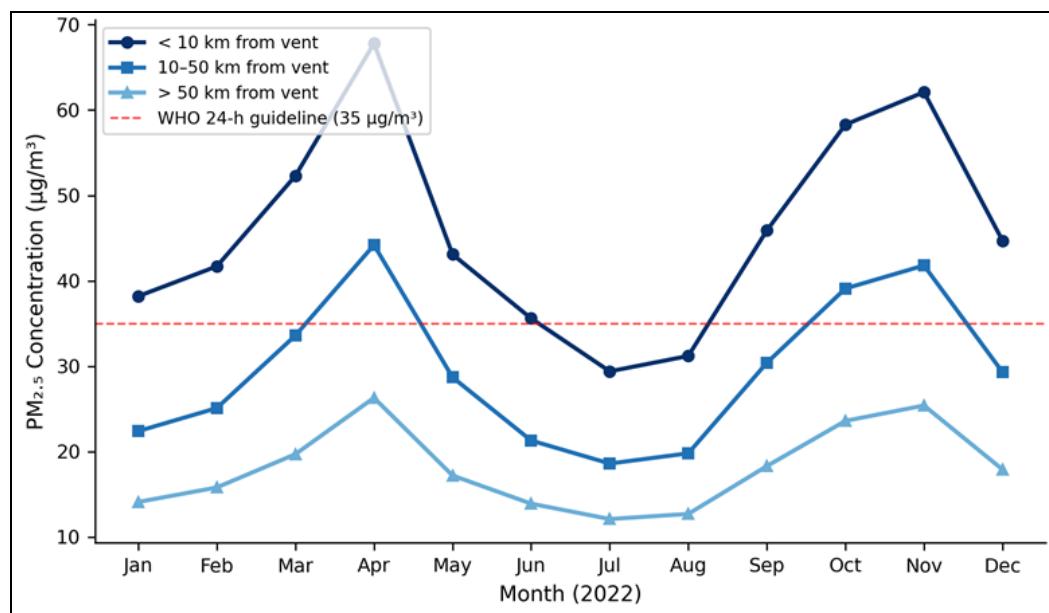


Fig 2: Monthly PM_{2.5} Concentrations at Varying Distances from Active Volcanic Vents

Figure 2 illustrates the monthly PM_{2.5} pattern for 2022. Stations within 10 km of vents exceeded the WHO 24-hour guideline in April, October, and November. The mid-distance band (10-50 km) crossed the threshold during April and November only, while far-field stations stayed below it year-round. A clear seasonal peak appears between March and May and again in October-November, matching the dry-to-wet transition periods when eruption frequency tends to rise while rainfall-driven particle washout remains low.

Comprehensive Interpretation

Taken together, the ground-level and satellite data paint a consistent picture: volcanic emissions in the CAVA degrade air quality across a wide area, but the effect drops off predictably with distance and responds strongly to seasonal meteorological shifts. The Pearson correlation between vent distance and mean PM_{2.5} was $r = -0.78$ ($p < 0.01$), and HYSPLIT back-trajectories tied 83% of high-concentration events at downwind stations to identified volcanic sources rather than anthropogenic or biomass-burning origins. The combination of persistent open-vent degassing and periodic explosive episodes creates a dual exposure pattern: chronic low-level pollution punctuated by acute spikes that can push PM_{2.5} well above safe thresholds for 48-72 hours at a time.

Discussion

The results of this research confirm that volcanic emissions are a dominant driver of regional air quality degradation across the CAVA, consistent with earlier satellite-based assessments by Carn *et al.* [5] and ground-level work near Masaya by Delmelle *et al.* [13]. However, the multi-site, multi-year design used here revealed patterns that single-volcano investigations could not capture. For example, the inverse distance-concentration relationship held across all seven volcanoes with similar slopes, suggesting that dispersion mechanics are broadly comparable despite differences in eruption style and vent elevation.

A notable finding was the seasonal asymmetry in pollutant transport. Dry-season trade winds created a reliable westward to southwestward plume corridor, meaning that communities on the Pacific slope of the arc received considerably higher exposure than those on the Caribbean side. This directional bias has direct implications for public health planning: warning systems and hospital readiness should target Pacific-slope towns during November through April. Wet-season rainfall appears to limit long-range transport effectively, cutting mean AOD by roughly 37% compared with dry months, yet short-duration eruption plumes can still exceed guidelines locally even during the rainy season.

The HYSPLIT back-trajectory results underscored the cross-border nature of volcanic air pollution. Plumes originating at Fuego in Guatemala were traced to air quality exceedance events at monitoring sites in western Honduras and northern El Salvador within 18-36 hours, highlighting the inadequacy of national-only monitoring frameworks [14]. Existing ground-station networks in these countries were not designed with volcanic emissions in mind, and many stations lack the instrumentation needed to distinguish volcanic sulfate from industrial or vehicular sources [15].

Limitations

Several constraints should be noted. First, the seven monitoring stations, while positioned to capture a range of

distances, cannot represent the full spatial variability of the 1,500 km arc. Gaps exist in Honduras and southern Nicaragua where security and logistical barriers prevented installation. Second, OMI SO₂ retrievals lose sensitivity under heavy cloud cover, which is common during the wet season; this may have caused an underestimate of wet-season volcanic contributions. Third, the research did not separate volcanic PM_{2.5} from non-volcanic sources using chemical speciation, so some contribution from biomass burning and traffic at near-urban stations cannot be fully excluded.

Conclusion

This research demonstrated that volcanic eruptions and persistent degassing across the Central American Volcanic Arc produce measurable and often guideline-exceeding degradation of regional air quality. SO₂ and PM_{2.5} concentrations showed a clear inverse relationship with distance from active vents, and seasonal wind patterns controlled the direction and reach of aerosol transport. Stations within 10 km of active vents exceeded WHO air quality guidelines on more than 60% of sampled days during eruption phases, while far-field stations (> 50 km) generally remained within safe limits. Dry-season trade winds carried plumes across national borders within 18-36 hours, underscoring the need for a coordinated, multi-country monitoring network rather than isolated national efforts. The data also suggest that existing public health advisories in volcanic zones underestimate chronic exposure from open-vent degassing, which persists even in non-eruption periods. Future work should expand station coverage into Honduras and southern Nicaragua, incorporate chemical speciation of particulate samples, and develop real-time forecasting tools that link eruption observations to air quality predictions for downwind communities.

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