Use of Unmanned Aerial Vehicles to Monitor Air Quality in Areas with Poor Accessibility. Case Study: the Orinoquía Natural Region, Colombia

Uso de vehículos aéreos no tripulados para monitorear la calidad del aire en áreas con poca accesibilidad. Caso de estudio: región de la Orinoquía, Colombia

*Carlos Alberto Echeverri Londoño**
Universidad de Medellín, Colombia
carelo1967@hotmail.com
http://orcid.org/0000-0001-8849-6896

Gabriel Jaime Maya Vasco
Universidad de Medellín, Colombia
gjmaya@udemedellin.edu.co
http://orcid.org/0000-0003-3922-3239

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Abstract

The concentrations of some atmospheric pollutants, including some considered greenhouse gases, were measured at different altitudes in the lower troposphere of the Orinoquía region (Colombia). Several sensors attached to an unmanned aerial vehicle (UAV) were used. The sensor system can capture the spatiotemporal variations of some atmospheric pollutants and meteorological variables. Vertical distribution patterns of pollutant concentrations monitored in the lower troposphere were mainly correlated with the temperature gradients, relative humidity, and solar radiation. CO_2 concentrations ranged from 72.3 to 646.5 ppm, for a mean value of 130.1 ppm.

Keywords: unmanned aerial vehicles, air quality, air pollutants.

Resumen

Se miden las concentraciones de algunos contaminantes atmosféricos, entre ellos algunos considerados como gases de efecto invernadero, a diferentes alturas en la troposfera baja de la Orinoquía (Colombia). Se emplearon varios de sensores acoplados a un vehículo aéreo no tripulado (UAV). El sistema de sensores puede capturar las variaciones espaciotemporales de algunos contaminantes atmosféricos y variables meteorológicas. Los patrones de distribución vertical de las concentraciones de los contaminantes monitoreados en la troposfera inferior se correlacionaron principalmente con el gradiente de temperatura, la humedad relativa y la radiación solar. Las concentraciones de CO_2 oscilaron entre 72.3 y 646.5 ppm, para un valor medio de 130.1 ppm.

Palabras clave: vehículos aéreos no tripulados, calidad del aire, contaminantes atmosféricos.

Introduction

Atmospheric composition is strongly associated with a wide variety of aerosols and gases released by different atmospheric pollutant emission sources. However, it is also related to geographical and meteorological aspects, which have an impact on air mass movement. Due to forest fires, different particles and greenhouse gases are released into the atmosphere, such as carbon dioxide (CO_2) and methane (CH_4).

Air pollution is produced by local emissions and 3D atmospheric transport. This means that air pollution results from the mass exchange process that occurs between surfaces and atmospheres. The dynamic structures of the atmospheric boundary layer determine air pollution transportation, accumulation, and

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*Autor para correspondencia
carelo1967@hotmail.com

diffusion. Consequently, the study of vertical air pollutant distribution is significant to provide fundamental information for accurate estimates of dispersion mechanisms for local pollutants found in the troposphere (Zhong-Ren *et al*., 2015).

Forest fires are an important source of pollutant emissions into the atmosphere that have a direct impact on air quality. Forest fires can occur naturally or anthropogenic. It has been found that the emissions produced in forest fires are transported through the air to different areas and over long distances, causing an increase in the concentrations of different pollutants, especially in urban centers. Therefore, air pollution is not a local problem if the pollutants emitted into the atmosphere travel long distances, affecting regions that may even be hundreds or thousands of kilometers from the source (Chacón, 2015).

In recent years, due to technological advancements and decreasing prices, the global UAV market has experienced accelerated growth. Therefore, their applications have rapidly increased in number. The use of UAVs in the environmental sector has brought about considerable improvements in terms of systems focusing on information monitoring and analysis.

Even though UAVs have recently been linked to applications in military fields, their application to atmospheric sciences and environmental monitoring has quickly increased, thanks to the monitoring of carbon dioxide concentrations conducted by Watai *et al*. (2006). UAVs also fill important gaps in the monitoring of air quality because they are lighter and include global positioning systems (GPS). For example, UAVs may be deployed to monitor air quality in difficult access areas with unknown pollution levels, especially since they can provide high spatial-temporal resolutions.

UAVs with small sensors are not only able to compile data at different altitudes, when compared to ground-level traditional methods, but also can obtain the pertaining vertical profiles related to atmospheric pollutants and meteorological variables at much higher spatial resolutions, especially for complex sites (Xiao-Bing *et al*., 2017). Because access by land in rural areas is often filled with obstacles, the most practical manner of using sensors to monitor air quality is through unmanned aerial vehicles (UAVs).

Furthermore, researchers have already used UAVs for the detection of atmospheric gases and aerosols and to characterize the properties of atmospheric aerosols, i.e., light absorption and scattering. In their study, Bates *et al*. created vertical profiles of black carbon atmospheric concentrations using a UAV in a campaign of 18 flights (38 flight hours). The flight plan stated that the UAV would first rise to 2700 m before descending to an altitude corresponding to the maximum value for aerosol concentration. After this, it measured concentration values at said altitude, wherein black carbon concentration levels changed from 0.04 to 0.51 $\mu g/m^3$ (Villa *et al*., 2016).

The proposal by Harrison *et al*. was to use a UAV to research horizontal, vertical, and temporal particle variability at the initial 150 m of the atmosphere. They aimed to prove that UAV-based systems may be useful to validate the next generation of satellite methodologies. The mean PM2.5 concentration for three flights, at variable altitudes, was 36 $\mu g/m^3$. The highest concentration was registered at altitudes lower than 10 m high. A general vertical variation with a standard deviation of only 3.6 $\mu g/m^3$ was shown in the results. At a nearly constant 60-m altitude, the PM2.5 concentration ranged from 21 to 25 $\mu g/m^3$ (Villa *et al*., 2016).

In Hangzhou, China, a UAV was used by Xiao-Bing Li *et al*. to measure the spatial-temporal fluctuations of ozone and meteorological variables. The vertical ozone variation is mainly related to vertical distribution patterns of air temperature and horizontal transportation of air masses from other zones (Xiao-Bing *et al*., 2017), as shown by their results.

Also, in Hangzhou, China, Zhong-Ren *et al*. used a UAV to examine vertical distribution patterns of PM2.5 concentrations ranging from 300 to 1 000 m. Experimental results demonstrated that, overall, PM2.5 concentrations decrease when altitude increases, except in cases where a thermal inversion layer exists Zhong-Ren *et al*. (2015).

In the Chinese Yangtze River Delta region, a UAV was used by Xiao-Bing Li *et al*. to examine vertical distribution patterns for fine particles (PM2.5) in the troposphere at altitudes lower than 1 000 m. Distinctly, the results reveal that PM2.5 concentrations at ground levels in this region, are lower in summer and higher in the winter season. Additionally, PM2.5 concentrations were lower at high altitudes in the morning (Xiao-Bing *et al*., 2018).

1. Iam

The objective is to develop a prototype of a measurement system coupled to a UAV for the measurement of the concentrations of some atmospheric pollutants at different heights in rural environments with difficult access, using sensors and electronic devices available in the national market, or that can be purchased abroad at low cost.

2. Study Zones

The Orinoquía natural region is in the eastern Colombian region. With an area of ~310.000 km^2, this region encompasses the departments of Meta, Arauca, Casanare, and Vichada. Additionally, it is often referred to as the "Eastern Plains" because of its vast plains. The Colombian Orinoquía region expands from the western mountain range foothills to the Orinoco River and the Arauca River to the Guaviare River (Tierra Colombiana, 2019). It is a rural environment in which the most feasible way to measure air quality is through unmanned aerial vehicles (UAVs).

In most of the Orinoquía region, a dry and tropical climate with high temperatures prevails all through the year and two very distinct seasons: one characterized by heavy rains, and the other one, by severe droughts. Regarding its terrain, this region presents extensive plains, and Sierra de la Macarena, Sierra de Chiribiquete, Serranía de Caranacoa, and Mesetas de Yambí are among its main geographical features (Tierra Colombiana, 2019).

Vegetation fires have also been extensively discussed, owing to the impact of their greenhouse gas (GHG) emissions. According to Andreae, these fires usually take place in tropical areas of the Earth. Therefore, these areas are important sources of GHG generation, atmospheric aerosols, and other atmospheric pollutants. In some cases, vegetation is burned as part of forest management to clear land to improve grazing. However, due to its poor management, several environmental changes are often generated on the land (Andreae, 1991).

In Colombia, forest fires are closely associated with socioeconomic factors such as the expansion of the agricultural and livestock frontier, although there are other indirect anthropogenic causes and accidental causes. The probability of fire events increases according to the dry seasons in the different regions of the country. Regarding the Orinoquía region, it is traditional for these events to take place in two periods of the year, the first between December and March and the second between July and August. Several studies have shown that air quality deterioration is caused by emissions produced when vegetation is burned to the establishment of new systems of agricultural production and extraction of hydrocarbons (Torinjano Jiménez, 2023). The trend analysis indicates that there is a clear relationship between the number of forest fires and the concentrations of PM10 and PM2.5 registered in other Colombian cities, such as Bogotá, Medellín, and Bucaramanga (Chacón, 2015).

In February 2018, fires raged through thousands of hectares in the departments of Meta, Guaviare, and Vichada, destroying at least 16 000 ha of savanna. The La Macarena and Tuparro nature parks were important areas where two forest fires occurred. From December to March, forest fires are more frequent every year as it is the dry season. In 2003, Corporinoquia, the Orinoquía Regional Autonomous Corporation, recorded over 1 200 forest fires in the region from the Apure state (Venezuela) to the south of the Meta department. In March 2014, during the summertime, a severe environmental crisis was produced, leaving, among other images, thousands of scorched animals (Hernández, 2019).

In the summer, humidity decreases, and vegetation becomes drier, which makes it more flammable. This is a regular natural phenomenon in places with certain seasonal variations, as in Colombia. Even so, controlled burning is one of the most prominent causes of forest fires as it frequently gets out of control. Farmers use fire to remove vegetation covers for agricultural management purposes and to control pests and weeds. In this sense, controlled fires are also used to remove dried material, aggregate soil nutrients, renew grassland for livestock, and broaden crop areas (Hernández, 2019).

Most Air Quality Monitoring Systems (AQMS) deployed in Colombia exhibit spatial coverage and flexibility limitations. In December 2015, a record number of 163 stations operated by 21 environmental authorities existed throughout the whole national territory (IDEAM, 2017). However, there are areas in the country that report a higher density of monitoring stations than other Colombian areas, such as Orinoquía, wherein there are no AQMS.

3. Materials and Methods

3. 1. Atmospheric Pollutant Measurement System

The device features relatively small dimensions (230 mm × 170 mm × 110 mm) is quite weightless (1.2 kg), and delivers long battery life (~8 h of operation). The measurement system includes electrochemical sensors for carbon dioxide (CO_2), ozone (O_3), carbon monoxide (CO), and methane (CH_4). There are also potentiometric sensors for breathable particles (PM10), fine particles (PM2.5), and ultrafine particles (PM1.0). Additionally, there are sensors for the measurement of physical variables, i.e., altitude, relative humidity, temperature, and solar radiation (figure 1).

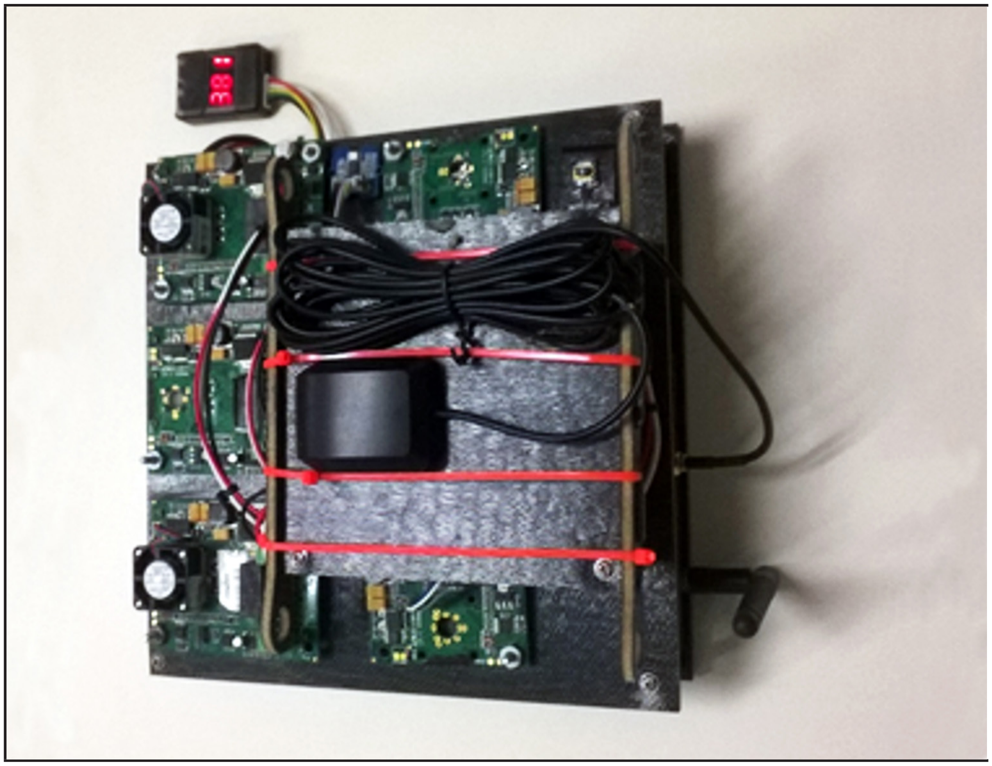


FIGURE 1

Atmospheric pollutant measurement system

Source: photography taken by the authors.

Along with being stored, the information recorded by sensors is georeferenced using a GPS device. Then, the georeferenced information is sent wirelessly via a communication system to a centralized station. The georeferencing mobile equipment used for monitoring air quality was fabricated by researchers at the University of Medellín and the University of San Buenaventura from commercially available sensors and has a patent registered at the Superintendency of Industry and Commerce (Patent No 15-251031) through Resolution No. 19102.

The concentration of a few atmospheric pollutants was measured with this measurement system coupled to a UAV, considering GHG emissions at different altitudes within the lower troposphere layer in the Orinoquía region.

3. 2. Unmanned Aerial Vehicle

Two kinds of UAVs were selected to carry the mobile georeferencing equipment for air quality monitoring. Before field measurements were performed, the measurement equipment was adapted to each UAV.

The first UAV used is a hexacopter that features vertical take-off and landing capabilities and six propellers (figure 2). The position of this hexacopter can be accurately controlled. Additionally, the device is stable, easy to maneuver, resists wind gusts, and its lifted payload is sufficient for measurement system components. However, its flight autonomy is just under 2 h. In preliminary tests, it was established that the maximum flight height would be ~160 m.

The second UAV is a one-propeller fixed-wing device featuring horizontal take-off and landing (figure 3). For the fixed-wing UAV, the flight range is larger. It can spiral over the studied area, and, in preliminary tests, it was established that the maximum flight height was ~260 m.

The positions of the UAV sensors are crucial since the influence exerted by the flight plan on the measurements must be minimized. The best position for hexacopter sensors is at their bottom, which is on top of the landing gear. In fixed-wing UAVs, they must be placed inside the bottom front area.

FIGURE 2

Hexacopter

Source: photography taken by the authors.

FIGURE 3
Fixed-wing unmanned aerial vehicle
Source: photography taken by the authors.

3. 3. Description of Field Measurements

The flights were held on August 23 and 24, 2018 (Thursday and Friday) at the Unipalma facilities in Cumaral, a municipality in the Meta foothills, located 58 km from the department's capital city of Villavicencio (figure 4). The facilities are specifically located at 4°13′33″ north latitude and 73°14′50″ west longitude. The month of August was chosen because, in the Orinoquía region, it is traditional for forest fires to occur in two periods of the year, the first between December and March and the second between July and August.

Unipalma sits at an altitude of 500 m above sea level and reports an annual rainfall of 2 878 mm. There are 153 days of rain, 1 849 h of sunshine, and its mean solar radiation is ~6.5 kWh/m^2. The whole area is almost completely covered by oil palm crops. There are no atmospheric pollutant emission sources nearby the site, such as stationary sources or main routes that may affect or impact the measurements.

For the measurement of pollutant concentrations, two UAVs were used to fly over the areas: a hexacopter and a fixed-wing device. All UAV takeoffs and landings were manually controlled by an expert pilot.

The fixed-wing UAV spirally flew up to ~260 m high, in a staggered fashion, but always in sight. The hexacopter flew up vertically to a height of ~160 m and traveled horizontally over the study area. Both flights lasted between 20 and 30 min each.

During the flight and subsequently, after landing, records of CO_2, CH_4, PM1.0, CO, PM2.5, PM10, O_3, relative humidity, temperature, and solar radiation were stored in each measuring device. Then, these records were downloaded to a PC for subsequent processing and analysis.

FIGURE 4
The Unipalma landing strip
Source: Google Maps.

4. Results

Only the measurements obtained through the hexacopter were reported because of the georeferencing system of the fixed-wing aircraft presented. In addition, the position of the hexacopter can be precisely controlled, it is stable, easy to maneuver, and resistant to gusts of wind, and the payload it can lift is sufficient for the measurement system components. Chart 1 summarizes the CO_2, CO, CH_4, O_3, and particle measurements made at the Unipalma facilities in Cumaral (Meta) on August 21, 2018. These measurements were taken at heights of ~160-260 m above ground level, because in this strip the change in the temperature gradient or the presence of a thermal inversion is observed. As they are preliminary measurements, the measurements had the duration and time stipulated in the indicated chart.

CHART 1
Measurement summary

Parameter	Start time	End time	CO_2 (ppm)	CH_4 (ppm)	CO (ppm)	O_3 (ppm)
Maximum values	9:28:50 a. m.	9:55:53 a. m.	562.5	5.57	4.2	0.5
Minimum values			76.2	2.73	1.9	0.0
Mean			120.5	3.94	2.8	0.4
Maximum values	11:16:47 a. m.	11:38:13 a. m.	646.5	5.96	4.9	0.5
Minimum values			72.3	2.64	1.5	0.0
Mean			142.3	3.94	2.9	0.4

Parameter	Start time	End time	PM1.0 (µg/m^3)	PM2.5 (µg/m^3)	PM10 (µg/m^3)
Maximum values	9:28:50 a. m.	9:55:53 a. m.	17	20	21
Minimum values			0	0	2
Mean			7	9	9
Maximum values	11:16:47 a. m.	11:38:13 a. m.	20	28	28
Minimum values			0	1	1
Mean			3	4	5

Source: own elaboration.

A summary of the meteorological parameters recorded at measurement time is listed in Chart 2. The temperature ranged from 31.6 °C to 40.0 °C, with a mean value of 34.6 °C. Relative humidity ranged from 42.6% to 69.2%, with a mean value of 59.0%. Solar radiation values ranged between 48.1 and 327.9 W/m^2, with a mean value of 123.8 W/m^2. According to IDEAM, solar radiation in the department of Meta is between 4.0 to 4.5 kWh/m^2, or what is the same,166.7 to 187.5 W/m^2 (IDEAM, 2018).

CHART 2
Meteorological parameter summary

Parameter	Start time	End time	Temperature (°C)	Humidity (%)	Solar radiation (W/m^2)
Maximum values	9:28:50 a. m.	9:55:53 a. m.	40.0	69.2	240.6
Minimum values			31.6	47.6	51.1
Mean			34.1	61.3	96.4
Maximum values	11:16:47 a. m.	11:38:13 a. m.	39.9	66.1	327.9
Minimum values			32.7	42.6	48.1
Mean			35.1	56.2	155.4

Source: own elaboration.

CO_2 concentrations ranged from 72.3 to 646.5 ppm. Higher values were reached than those listed by the World Meteorological Organization at the Mauna Loa Observatory (Hawaii) in 2021 when a concentration of 419.13 ppm was reached (NOAA, 2021). CH_4 concentrations ranged from 2.64 to 5.96 ppm, reaching higher values than those recorded by the Intergovernmental Panel on Climate Change at the Izaña Atmospheric Observatory in 2007 when a 1.85 ppm concentration was reached (IPCC, 2007). The CO concentrations ranged between 1.5 and 4.9 ppm. In this area, there are CO_2, CO, CH_4, and emission sources such as forest fires, which produce high concentrations.

PM10 concentrations ranged from 1 to 28 µg/m^3, with a mean value of 7 µg/m^3. O_3 concentrations ranged from 0.0 to 0.5 ppm, reaching higher values than those reported in 2019 by the National Oceanic and Atmospheric Administration, wherein a concentration of 0.34 ppm was reached.

Graph 1 below denotes the variation of meteorological variables at the height reached by the first flight. A temperature increase was observed as height increases up to 230 m, just where thermal inversion ends. Thereafter, a decrease was observed. Additionally, relative humidity decreased as height increased up to 230 m high, precisely where inversion ends. Subsequently, it increases at greater altitudes. The correlation between solar radiation variation and height does not exhibit a well-defined pattern.

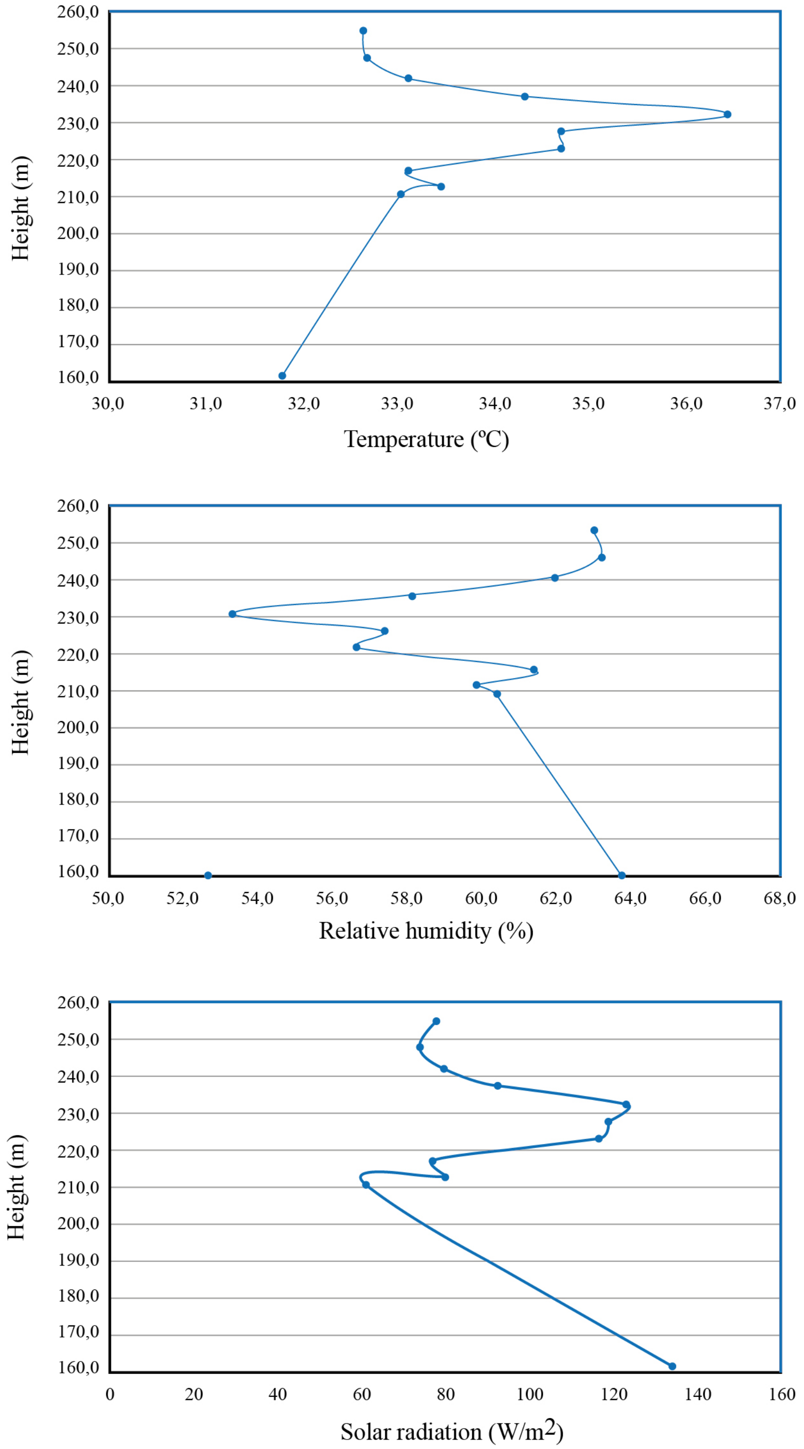
For the first flight, graph 2 denotes pollutant behavior at different heights. To prepare this chart, pollutant concentration means were calculated at height intervals of 5 m, which generated the corresponding vertical profiles. In general, different pollutant concentrations are reduced at heights of ~230 m. At this height, the thermal inversions of the first flight end.

CO_2 concentrations are seemingly influenced by solar radiation, and CH_4 concentrations are affected by temperature gradients and relative humidity. The factors with the greatest impact on the vertical distribution of particle concentrations are air temperature and relative humidity.

Particle concentrations decrease at an altitude of ~230 m, the altitude at which the thermal inversion ends, but these concentrations subsequently increase at higher altitudes. This "unusual" increase from 230 to 247 m high is related to the existence of a temperature inversion layer at heights under 230 m, which is consistent with the results reported by Xiao-Bing *et al.* (2018) and Zhong-Ren *et al.* (2015).

At night, particles can be directed toward the ground. This would increase particle concentrations near the ground. However, the inversion layer blocks this process. Therefore, particle concentrations are higher above the inversion layer than near the ground.

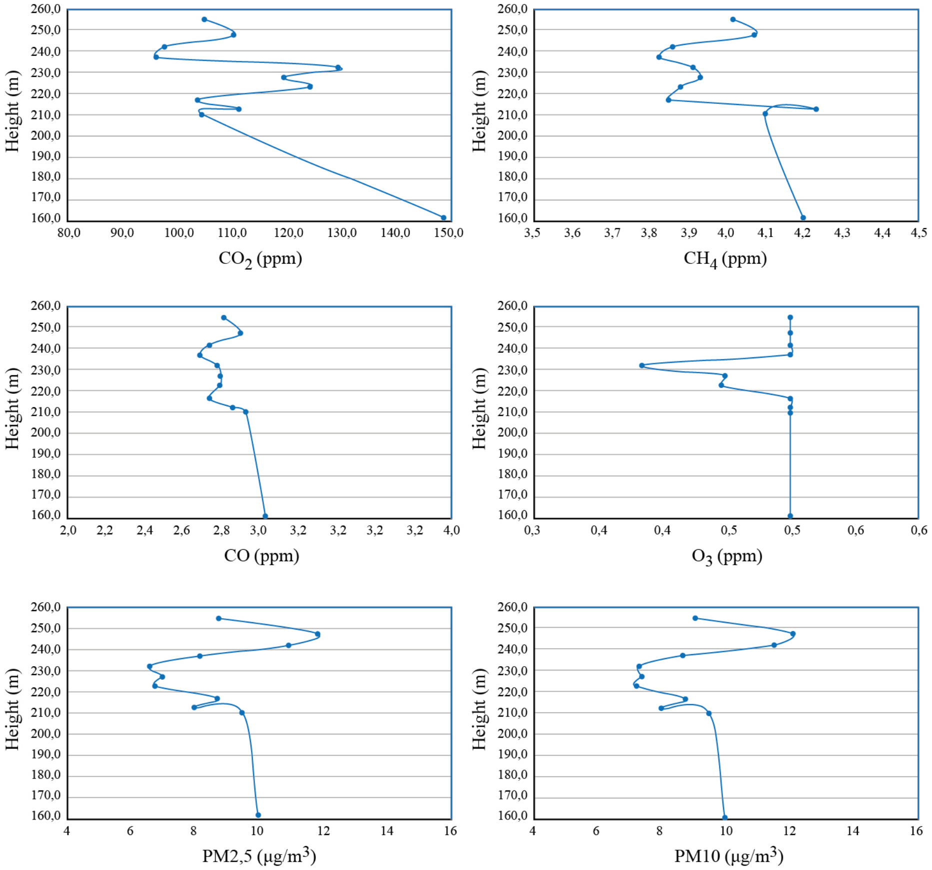
A strong superficial inversion layer, in the morning hours, captures particles, which, according to Zhong-Ren *et al*., may explain their stratification. If the thermal inversion is interrupted, vertical particle transportation occurs, and this may bring about their mixture or dilution. Due to the negative temperature gradient, particle concentrations decrease as heights increase (Zhong-Ren *et al*., 2015).



GRAPH 1

Meteorological variable variation as height increases (for Flight No. 1)

Source: own elaboration.



GRAPH 2

The behavior of pollutants depends on altitude variations (for Flight No. 1)

Source: own elaboration.

The impact of meteorological variables on pollutant dilution, diffusion, and accumulation is extensively acknowledged. The correlation coefficient of Pearson was applied to quantify relationships between several pollutants and meteorological factors. Based on Pearson's data correlation analysis, it is feasible to determine the correlation strength of independent variables and dependent variables. Chart 3 below shows the results.

Pearson's correlation analysis proves that independent variables, such as temperature, relative humidity, and solar radiation, have a high correlation with dependent variables (such as ozone concentration and concentrations of carbon dioxide, methane, and particles). There is an extremely weak correlation between height and dependent variables, except for particles. This is largely due to thermal inversion that ends at ~230 m high.

As it can be observed, there is a negative correlation between the temperature and particle concentration. Conversely, it can be observed that there is a positive correlation between relative humidity and the dependent variables.

Several studies conclude that vertical ozone distribution patterns within the first 1000 m of the lower troposphere layer are affected by many factors. Among them, we can mention solar radiation intensity, meteorological conditions, vertical convection intensity, and the horizontal transportation of the air masses (Xiao-Bing *et al.*, 2017). There was a strong negative relationship between ozone and air temperature ($r = -0.884$). There was a weak negative relationship between ozone and solar radiation ($r = -0.547$). However, the relationship with relative humidity ($r = 0.866$) was strongly positive.

In the same manner as detected by Xiao-Bing *et al.* (2017), the relationship between air temperature and relative humidity ($r = -0.981$) was strongly negative. The relative humidity values were much higher close to the surface. A negative vertical profile exists for altitudes of up to 230 m, and this is exactly the place where the thermal inversion ends.

Carbon dioxide had a strongly correlated relationship with solar radiation ($r = 0.835$). Additionally, PM10 particles exhibited a strong relationship with relative humidity ($r = 0.766$) and temperature ($r = -0.692$) and methane with carbon monoxide ($r = 0.871$).

The correlations between relative humidity and PM10, PM2.5, and PM1.0 concentrations (0.766, 0.830, and 0.798, respectively) were also equally strong. Such results are consistent with the assessments made by Xiao-Bing *et al*. In these studies, they detected that higher air humidity encourages aerosol particle formation because particles can absorb humidity from surrounding environments (Xiao-Bing *et al*., 2018).

CHART 3
Pearson's correlation coefficients for concentrations of several atmospheric pollutants and meteorological parameters

Related variables	Pearson's coefficient
O_3 and Temperature	–0.884
O_3 and Relative Humidity	0.866
O_3 and Solar Radiation	–0.547
Temperature and Relative Humidity	–0.981
CO_2 and Solar Radiation	0.835
PM10 and Temperature	–0.692
CO and CH_4	0.871
PM10 and Altitude	–0.659
PM10 and Relative Humidity	0.766
PM2.5 and Relative Humidity	0.830
PM1.0 and Relative Humidity	0.798

Source: own elaboration.

5. Analysis

In this area, there are CO_2, CO, and CH_4 emission sources such as forest fires. There are also ozone formation processes, which produce high concentrations of these pollutants.

As determined by the studies by Xiao-Bing *et al*., using a UAV is sometimes not feasible for calculating pollutant vertical profiles (Xiao-Bing Li. *et al*., 2017). Certain pollutants measured in this study have no well-defined patterns depending on altitude changes. This means that their concentrations denote either huge or no vertical variations. This occurred with CO_2, CH_4, CO, and O_3. Here, the horizontal transportation of air masses likely affects this situation. In general, different pollutant concentrations decrease at heights of ~230 m. At these heights, thermal inversions of the first flight end.

A strong superficial inversion layer, in the morning hours, captures particles, which, according to Zhong-Ren *et al*., may explain their stratification. If the thermal inversion is interrupted, vertical particle transportation occurs, and this may bring about their mixture or dilution. Due to the negative temperature gradient, particle concentrations decrease as heights increase (Zhong-Ren *et al*., 2015).

Pearson's correlation analysis proves that independent variables, such as temperature, relative humidity, and solar radiation, have a high correlation with dependent variables, such as ozone concentration and concentrations of carbon dioxide, methane, and particles. There is an extremely weak correlation between height and dependent variables, except for particles. This is largely due to thermal inversion that ends at ~230 m high.

Prospective

The future of UAVs to monitor air quality and meteorological variables is promising, thanks to the capacity and flexibility of these devices. At the same time, developments in fields such as information technology and sensor technology enable smaller and lighter devices with the ability to work remotely.

Unmanned aerial vehicles (UAVs) equipped with different sensors to monitor air quality and meteorological variables may offer new approaches and research opportunities on air pollution and emissions monitoring, as well as to study atmospheric trends, such as climate change and the behavior of the environmental temperature gradient. Although the potential of UAVs for research on air quality and lower atmosphere behavior has been established, several challenges still need to be addressed, which are not simply technological, and span policies and regulations, which differ between countries and represent the greatest challenge in facilitating the broader use of UAVs in atmospheric research.

Ambient air pollution has been recognized as one of the most important health risk factors worldwide. The association between adverse health effects and poor air quality has been demonstrated. This requires detailed information on the characteristics of the distribution of aerosols and the concentrations of gaseous pollutants when quantifying their effects on human health and the environment. These reasons promote the use of small, lightweight UAVs for a range of applications, including atmospheric measurements.

UAVs equipped with different sensors can provide more precise information on the distribution of aerosols at different heights above the atmosphere to better understand the air quality and composition of specific layers in the atmosphere. UAVs can cover large areas and make measurements in remote, dangerous, or hard-to-reach locations, increasing operational flexibility and spatial resolution of measurements.

Conclusions

As revealed by preliminary results, it is feasible to monitor air pollutants using a UAV and a measurement system specially adapted for such UAVs. With a measurement system coupled to the UAV, it is possible to register spatial-temporal variations of several atmospheric pollutants and certain meteorological variables. A system of measurement coupled to the UAV evidence sufficient reliability and accuracy for registering spatial-temporal variations for different pollutant concentrations monitored in the lower troposphere layers.

Vertical pollutant concentration distribution patterns monitored in the lower troposphere correlate principally with temperature gradients, relative humidity, and solar radiation. There is a strong correlation between O_3 and temperature and relative humidity. Additionally, PM10 particles exhibit strong correlations with temperature and relative humidity. The correlation between CO_2 and solar radiation is strong, and CO has a strong correlation with CH_4. Finally, large horizontal variations of different monitored pollutant concentrations were also noticed.

CO, CO_2, and CH_4 concentrations are much higher than values recorded by international entities. In this area, there are CO_2, CO, and CH_4 emission sources such as forest fires.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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