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**MAESTRÍA EN CIENCIAS CON MENCIÓN EN GESTIÓN
AMBIENTAL Y DESARROLLO SOSTENIBLE**

Tesis

**Avances tecnológicos en alta montaña: desarrollo de una
aplicación de realidad aumentada e IoT para el monitoreo
de la capa de nieve en el nevado Huascarán, Perú**

Joselyn Esther Zapata Paulini

Para optar el Grado Académico de
Maestro en Ciencias con Mención en
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Lima, 2025

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Technological advances in high mountains: Development of an augmented reality and IoT Application for snow cover monitoring on Huascaran, Peru

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ABSTRACT

Climate change has had a negative impact on Andean glaciers, especially on the snow-capped Huascaran in Peru, which has experienced a loss of 42 % of its glacier mass. Lack of access to accurate snowpack data complicates understanding and informed decision-making in mountainous environments. To address this problem, an application has been developed based on an AR-IoT architecture that integrates augmented reality (AR) and the Internet of Things (IoT) for the periodic monitoring of snow cover on the Huascaran snow-capped mountain. This application uses data collected from meteorological repositories and simulates IoT interactions, while a mobile app offers an interactive and understandable visualization of the data. The Scrum methodology was applied iteratively, from the creation of the 3D model to the connection with the Ubidots platform to store and share the data. The analysis of 58 readings, obtained between April and May 2023, showed correlations between variables such as snow depth, temperature, and wind speed, which served to validate the operation of the AR-IoT technology implemented. These variables offer an initial understanding of atmospheric conditions in high mountains. In addition, the technology developed has the potential to expand to include more relevant data in future analyses. The tool demonstrates the effectiveness of combining these technologies for monitoring high mountain snow cover and making informed decisions about water resources management.

1. Introduction

In a world where climate change is portrayed as one of the most urgent and complex challenges of the environment and society, the conservation of high mountain ecosystems has assumed vital importance (Algarra et al., 2019; de Gabriel Hernando et al. 2021). This places a significant emphasis on optimal environmental management of water resources, fueled by the increasing concern for their current utilization (Mingyue et al., 2024). The conservation of natural resources, the maintenance of ecosystems and human well-being are at the heart of this interest, with water as a key resource for life and human development. Ensuring their availability and proper management is a priority for both society and decision-makers (Patel et al., 2019).

In this context, Andean glaciers play a fundamental role in the environmental management of water resources in the mountainous regions of South America (Ríos-Pulgarín et al., 2022). They act as important reservoirs of fresh water, regulating the flow of rivers and supplying water to communities, ecosystems and economic activities downstream (Laqui et al., 2023). Although climate change is a

significant factor in the accelerated retreat of Andean glaciers, human activities such as land use and natural climate variations also play a role (Climate Action Network Latinoamérica 2013; Lüning et al., 2022; Pastorino et al., 2024). These factors combined affect the water storage capacity of glaciers and present challenges for their management in the region (Lüning et al., 2022). A United Nations report (UNESCO and UNEP 2016), highlights that the ice cover of the Cordillera Blanca, the largest tropical mountain range in the Andean region, has decreased by 30 % since 1930. This has led to the disappearance of 151 glaciers of less than one square kilometer each, with the smallest glaciers being the most severely affected by climate change (Tarabochia, 2023). The snow-capped Huascaran, located in Ancash, Peru, is a prominent part of the Cordillera Blanca and one of the highest snow-capped peaks in the world. Unfortunately, in recent years it has experienced a dramatic reduction in its glacial mass, with significant water losses, which aggravates the water crisis in the region. In 2016 alone, it recorded a staggering 42 % reduction in its extent, resulting in a decrease in water volume of 1,361.9 million cubic meters, ending in a significant water loss of 63 % (INGEMMET 2023).

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In response to these challenges, monitoring Andean glaciers has become a key tool for understanding and effectively managing water resources, as it provides valuable information on their evolution, including changes in their extent, volume, and behavior (Laqui et al., 2023). The implementation of advanced technologies has allowed the collection of real-time data on the evolution of glaciers, allowing the impacts of climate change on water resources to be assessed, the identification of risks associated with glacial melting, and the design of adaptation and mitigation strategies (Kimothi et al., 2022; Paul et al., 2012; Zapata-Paulini et al., 2023). In particular, the integration of technologies such as Augmented Reality (AR) and the Internet of Things (IoT) has opened up new possibilities in various areas (Dansana et al., 2022; Liu et al., 2022; Morris and Yeboah, 2023; Zhang et al., 2022), and one of them is periodic monitoring in high mountains. These tools allow up-to-date data to be obtained and visualized on mobile devices using AR, facilitating decision-making in challenging environments and improving access to information for risk management and the formulation of adaptation strategies (Morris and Yeboah, 2023). Through the combination of IoT sensors and AR platforms, it is possible to obtain up-to-date data on snow cover, weather conditions and other key factors in glaciers, transmitting the information to a centralized platform (Morris and Yeboah, 2023; Zhang et al., 2022), contributing significantly to environmental sustainability and adaptation to climate change.

The review of the scientific literature reinforces the importance of technological collaboration in high mountain environments, where the active participation of experts from various disciplines is encouraged (Berberi et al., 2023; Dobрева et al., 2017; Kattel et al., 2023). Technological collaboration, considered as the cornerstone that drives the successful implementation of advanced monitoring systems (Dobрева et al., 2017). Previous studies have demonstrated the usefulness of technologies such as AR and IoT in various areas, from remote sensing in alpine areas, which identifies and selects deglaciated areas in mountain ranges (Gennaro et al., 2023), to monitoring snow accumulation using GNSS (Global Navigation Satellite System) and meteorological instruments (White et al., 2023). In addition, it has demonstrated the effectiveness of these technologies in precision agriculture for farmers with no previous experience in advanced technologies (Phupattanasilp and Tong, 2019) and in their effectiveness in accessing information (Fuentes et al., 2021). This research underscores the transformative potential of such innovations in resource management in challenging environments.

The objective of this article is to develop a technological tool that integrates IoT and AR technologies for the periodic monitoring of snow cover in the snowy Huascan, in order to provide accessible data that helps manage risks related to water availability and quality. The tool seeks to improve understanding of changes in snow cover and their potential impact on water scarcity or flood risk. To this end, a mobile application has been designed that uses AR and IoT to process and visualize data obtained from existing meteorological repositories, allowing users to assess the current conditions of the glacier and make decisions based on updated information.

2. Materials and methods

This section explores the relevance of glacier monitoring in the Andean mountains and details the materials and methods used to integrate AR and IoT in a snow cover monitoring application around the Huascan snow-capped mountain.

2.1. Importance of snow cover monitoring in Andean Mountain glaciers

Monitoring Andean glaciers is essential to address issues related to security, water management, and understanding the effects of climate change on these vulnerable ecosystems. Snow cover assessment is not only crucial to ensure the water security of nearby communities and urban areas, but also to mitigate threats such as floods and droughts. The

lack of accessible data on temperature and precipitation in high mountains limits the ability to fully understand climatic conditions in these areas (González Trueba and Serrano Cañadas, 2010). Variations in the amount of snow fall can trigger premature snowmelt, increase the risk of avalanches, and contribute to long-term water scarcity (Programme of the European Union, Copernicus, and ECMWF 2023).

In Peru, the scarcity of advanced technologies for in situ monitoring of glaciers is notable, especially the lack of meteorological technology and sensors, according to the SENAMHI report, currently only three of these weather stations are available (Suarez Alayza, 2016). The implementation of state-of-the-art sensors would improve water management and reduce the risk of natural disasters. Integrating these sensors with satellite surveys would offer a more comprehensive view of the situation in Peruvian snow-capped mountains, overcoming the current limitations in glaciological measurements (INAIGEM 2023). Although advanced technologies do not replace traditional methods, they can reduce human intervention, making monitoring more efficient and continuous.

Real-time monitoring of snow cover through monitoring systems can prevent flooding and facilitate mitigation and planning measures (UNESCO and UNEP 2016; Tarabochia, 2023). Andean glaciers are mostly sensitive to the effects of climate change due to temperature variations; therefore, they require constant monitoring to adapt and manage impacts on water availability, biodiversity and the stability of natural ecosystems (INGEMMET 2023).

2.2. Description of technologies

2.2.1. Augmented Reality

AR is an interactive experience that enhances reality with computer-generated information. By employing software, applications, and hardware as AR viewers, digital elements are superimposed on real environments and objects, enhancing the user experience. This transformation turns your environment into an interactive learning space, especially valuable in manufacturing and Industry 4.0 contexts. AR enables industrial users to fully integrate with systems and machines, leveraging technologies and IoT with human inventiveness, observation, and creativity (Unity 2021; Unity Technologies 2022; SAP Insights 2023).

The AR device downloads data about the object from the cloud, overlaying digital information using markers or trackers such as GPS, accelerometers, and barometric sensors, thus creating a three-dimensional interface (SAP Insights 2023). With real-time data, the user interacts with the object or environment through gestures, touch screens or voice, sending commands to the cloud.

2.2.2. Internet of things

According to (Fuentes et al., 2021; SAP 2023), IoT comprises the wireless connection to the Internet of any object or entity, highlighting those objects equipped with sensors and software to transmit data, inform users, or automate processes. After IoT devices collect and transmit data, the essential stage is to maximize their utility. This is where artificial intelligence technologies come in, empowering IoT networks through advanced analytics and machine learning processes to obtain more accurate and sophisticated results.

Regarding their operation IoT devices play the role of remote observers, recording and communicating data for evaluation and application (Batsi and Tennina, 2024), in a process composed of four essential phases. These include data collection through sensors, data transmission through network connections, data processing through specific software, and finally, the implementation of actions based on the analysis of the accumulated information (Arntz et al., 2022; Cabanillas-Carbonell and Zapata-Paulini, 2019).

2.2.3. AR-IOT technology

The integration of AR-IOT technology has proven to be a highly effective and less error-prone solution compared to traditional data

visualization methods. Its accessibility and ease of use make it an ideal tool for users with no previous experience in advanced technologies, such as farmers or natural resource managers, allowing them to access critical information intuitively. In addition, this technology has been instrumental in optimizing energy consumption, showing feasibility in the implementation of technologies that were previously considered costly or difficult to manage (Phupattanasilp and Tong, 2019).

The study (Fuentes et al., 2021) highlights a key innovation in addressing the display limitations of IoT devices that lack expensive output peripherals. By integrating AR into smartphones, accessible, real-time visualization of IoT data is enabled, offering a cost-effective solution without compromising the quality or security of the information displayed. The built-in AR security layer ensures data privacy, while tests have confirmed the effectiveness of this solution in visualizing and monitoring IoT devices, optimizing the interaction between smartphones, IoT platforms, and the devices themselves. This makes it a powerful tool for IoT management in industrial, laboratory, or research environments.

These previous applications underline the great potential of AR-IoT technologies in various fields. Their ability to improve visualization, optimize resources and provide a secure and efficient platform for device management highlights their relevance in the transformation of monitoring and management systems, such as the specific case of snow cover tracking in the Huascaran snow-capped mountain.

2.2.4. Ubidots

Ubidots is a cloud-based IoT platform that offers services for IoT application development and management. It simplifies the creation, implementation, and supervision of IoT solutions, enabling users to connect, visualize, and analyze device data in real-time. Ubidots provides a user-friendly interface along with tools for customizing controls, including rules and notifications. Additionally, it supports a diverse range of IoT sensors applied in various sectors such as agriculture, health, and industry (Ubidots 2023).

The distinguishing feature of Ubidots lies in its emphasis on ease of use and accessibility, which enables both beginners and experienced developers to leverage its services to develop in the IoT space (Cruz et al., 2023). Its ability to handle real-time data and supply custom visualizations makes it an attractive choice for those looking to run IoT projects efficiently, while maintaining an accessible learning curve (Babalola et al.2023; Nurvianti et al., 2023).

2.2.5. Data collection instrument

Data collection is performed by collecting information from meteorological repositories, such as SENAMHI and NASA's POWER Data Access Viewer, which provide solar and meteorological datasets (NASA

Prediction of Worldwide Energy Resources 2023). Instead of physical sensors, a simulation of IoT interaction, focusing on variables such as snow depth and weather conditions, is carried out to demonstrate the performance of the implemented AR-IoT technology. This simulation is performed using the MQTTLens software, which allows an efficient integration with the IoT technology (Elegeert et al., 2022). Subsequently, an exploratory data analysis was applied to obtain a more detailed understanding of the collected information, which helped to validate the performance of the developed architecture.

2.3. Case study

2.3.1. Application architecture

The application architecture merges Unity and Vuforia to develop an AR application that visualizes three environmental variables: temperature ($^{\circ}\text{C}$), snow depth (cm), and wind speed (km/h). As illustrated in Fig. 1, the data is obtained from meteorological repositories and used to simulate IoT interactions, emulating the operation of hardware devices. This information is sent to the Ubidots cloud platform, which receives, stores and organizes the data into graphs for analysis. In the Unity environment, the mobile application and its AR interface are developed, which is linked to a visual marker through Vuforia. The application projects a personalized 3D model, showing the information and spaces where the collected data will be displayed in an understandable and interactive way. The reading of data from Ubidots to Unity is done in JSON format, which facilitates its integration into the interface and improves the visualization of the information, providing periodic monitoring of snow cover and atmospheric conditions in high mountains.

2.3.2. Agile Scrum methodology

Scrum is an agile methodology in which a set of effective practices are employed on a regular basis to work collaboratively in teams and obtain maximum performance in a project. These practices complement each other and their choice is based on a study of how highly productive teams work (Ágiles, 2023). In Scrum, frequent partial deliveries of the final product are carried out and prioritized according to the benefits they bring to the project's target. For this reason, Scrum is particularly suitable for projects in complex environments, where it is necessary to obtain results quickly, where requirements are changing or poorly defined, and where innovation, competitiveness, flexibility, and productivity are fundamental aspects.

2.3.2.1. Scrum 1. Initially, the data was collected from meteorological repositories between April 10 and May 8, 2023, at two different times each day, in the snow-capped Huascaran, Peru, at an altitude of 6,000 m

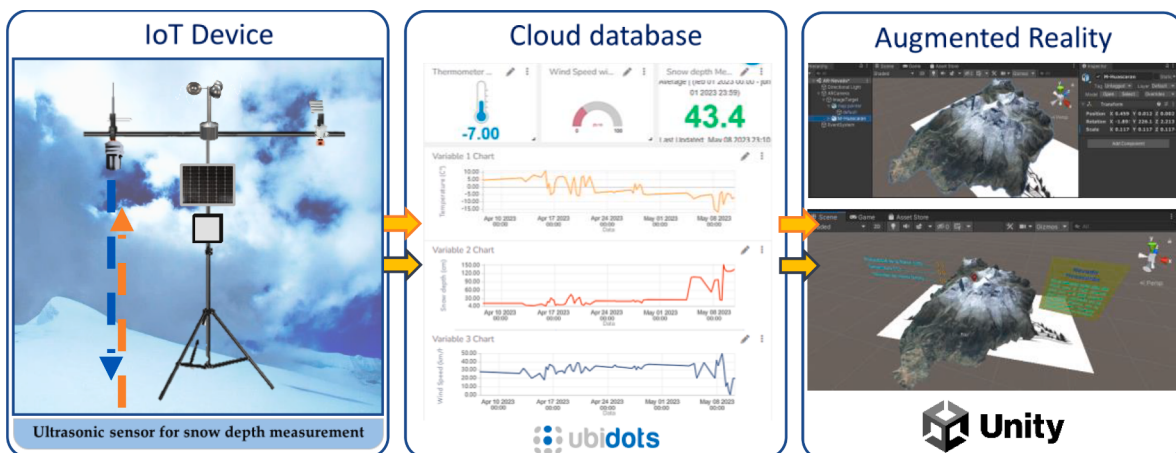


Fig. 1. Overview of the AR-IoT system architecture used in the application.

above sea level, between the two highest peaks of the mountain. For the storage and monitoring of environmental variables, the Ubidots platform was used, a cloud-based IoT solution that facilitates visualization through a control panel (see Fig. 2). Ubidots provides a REST API that enables data reading and writing, and supports MQTT and HTTP protocols, used in IoT for communication between applications and networks. In addition, the platform guarantees the security of the stored data through exclusive access to authorized users through API keys, thus ensuring a controlled and secure environment for the management of the information collected.

2.3.2.2. Scrum 2. In this stage, a more detailed analysis of the data stored in Ubidots was carried out using Exploratory Data Analysis (EDA) using Python language. To do this, the data was exported to a file in ".csv" format, and the missing values were removed using Google Colab, in addition to merging repeated columns using the drop() and reduce() functions. After applying the filters, with the info() function, 58 data distributed in 6 columns were obtained and shown in Table 1.

During the analysis of the readings obtained during the study period, the distributions of the snow depth, temperature, and wind speed variables of Huascarán were examined and their respective histograms were generated. After performing the analysis on the Huascarán snow depth variable, it was found that the distribution of the data does not follow a normal behavior at all (Fig. 3). According to the Box Plot, the snow depth presents some atypical values such as 153.2 cm (the highest) and 4 cm (the minimum), presenting an average of 24 cm.

When analyzing the distribution of temperature values, it was observed that the values are well distributed, slightly skewed to the right with a large number of values below zero (Fig. 4). The readings were found to be below 12°C as shown in the Box Plot, with a mean of approximately -3°C. The distribution of values ranges from -17 to 11°C.

For wind speed distribution, it was observed that the values are well-distributed and slightly skewed to the left (Fig. 5). According to the Box Plot, it was identified that the mean of the data is 32 km/h, there are some outliers. The distribution of values ranges from 0 to 50 km/h, centering a large number of wind speed values between 30 and 40 km/h.

Likewise, patterns and relationships between variables were identified, for this purpose Pearson's correlation coefficient was used, which represents a measure of the linear relationship between two variables X and Y taking values from -1 to 1 (Ghosh et al., 2022; Hernández et al., 2018). The range of values $r_{xy} = \pm 1$, establishes a perfect positive or negative linear association, respectively, between the two variables. On the other hand, an $r_{xy} = 0$, indicates that there is

Table 1

Verification of data types in the observation set.

#	Column	Non-Null Count	Dtype
0	timestamp	58 non-null	int64
1	day-huascarán	58 non-null	int64
2	context_day	58 non-null	object
3	snow-depth-huascarán	58 non-null	float64
4	temperature-huascarán	58 non-null	float64
5	wind-speed-huascarán	58 non-null	float64

dtypes: float64(3), int64(2), object(1)

no linear relationship between the analyzed characteristics, although it is not conclusive evidence of independence (Hernández et al., 2018). By performing EDA on the information collected during systematic monitoring, the correlation matrix was calculated (Fig. 6). This process allowed the detection of patterns, and a heat map was generated as a useful visualization to understand the underlying structure of the data (Zhu et al., 2022).

Fig. 6 shows that the correlation between the variable wind speed and temperature of Huascarán is -0.098, which indicates that they have a weak negative correlation. It is interpreted that a higher wind speed is associated with a decrease in the recorded temperature. The correlation between the variables snow depth and temperature is -0.7, which indicates that it is strongly negatively correlated. Greater depth of snow cover is interpreted to be strongly related to lower snow temperature.

2.3.2.3. Scrum 3. In this stage, the creation of the 3D model of the Huascarán Mountain began, developed almost in parallel with the first captures of the meteorological data, in order to provide a visual and understandable representation of the current conditions of the snow-capped mountain. 3D data was imported from Google Maps into Blender using RenderDoc software for frame capture and graphical debugging (Gil, 2022; RenderDoc 2024). This allowed the source file to be downloaded with the frames and textures of the desired location on Google Maps, in this case the snow-capped Huascarán. And later in Blender, texturing, modeling customization and rendering of the 3D model were carried out. Fig. 7 illustrates the stages of the process of creating the 3D model in Blender, which was eventually exported to Unity in ".fdx" format.

2.3.2.4. Scrum 4. At this stage, AR was used to provide an immersive and immersive experience by combining the real world with virtual elements, allowing users to interact more intuitively and excitingly with

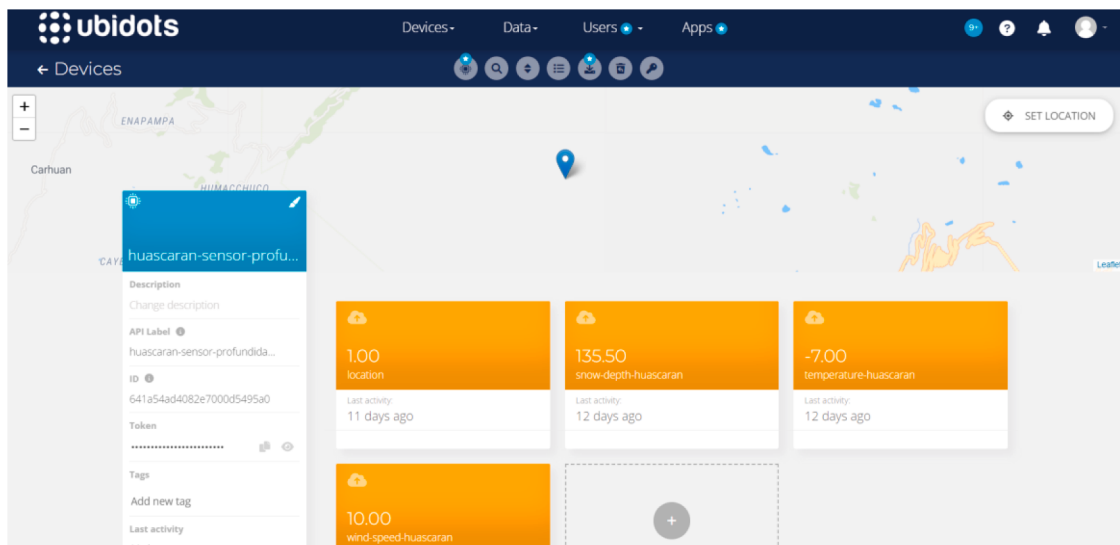


Fig. 2. IoT Device control interface in Ubidots for monitoring and management.

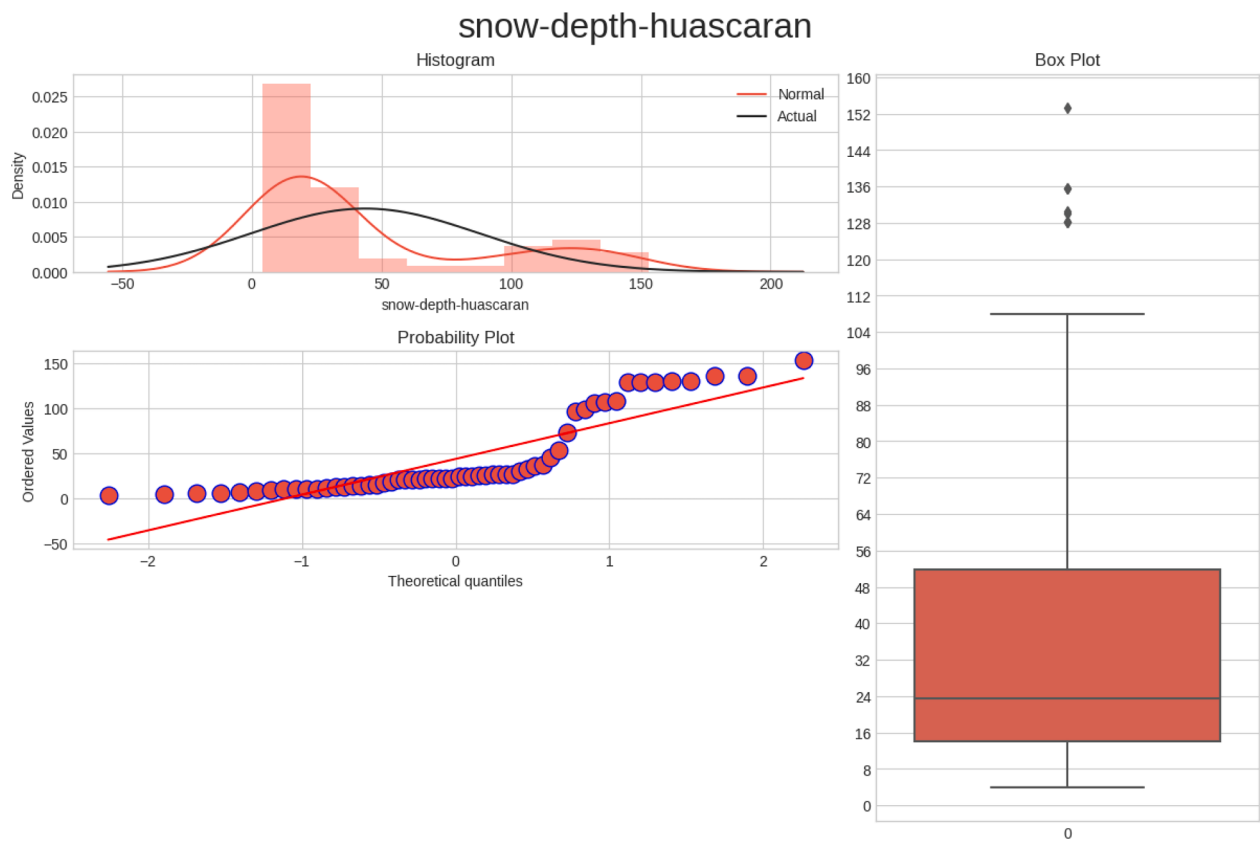


Fig. 3. Distribution of values of the snow depth variable of Huascarán snow-capped mountain.

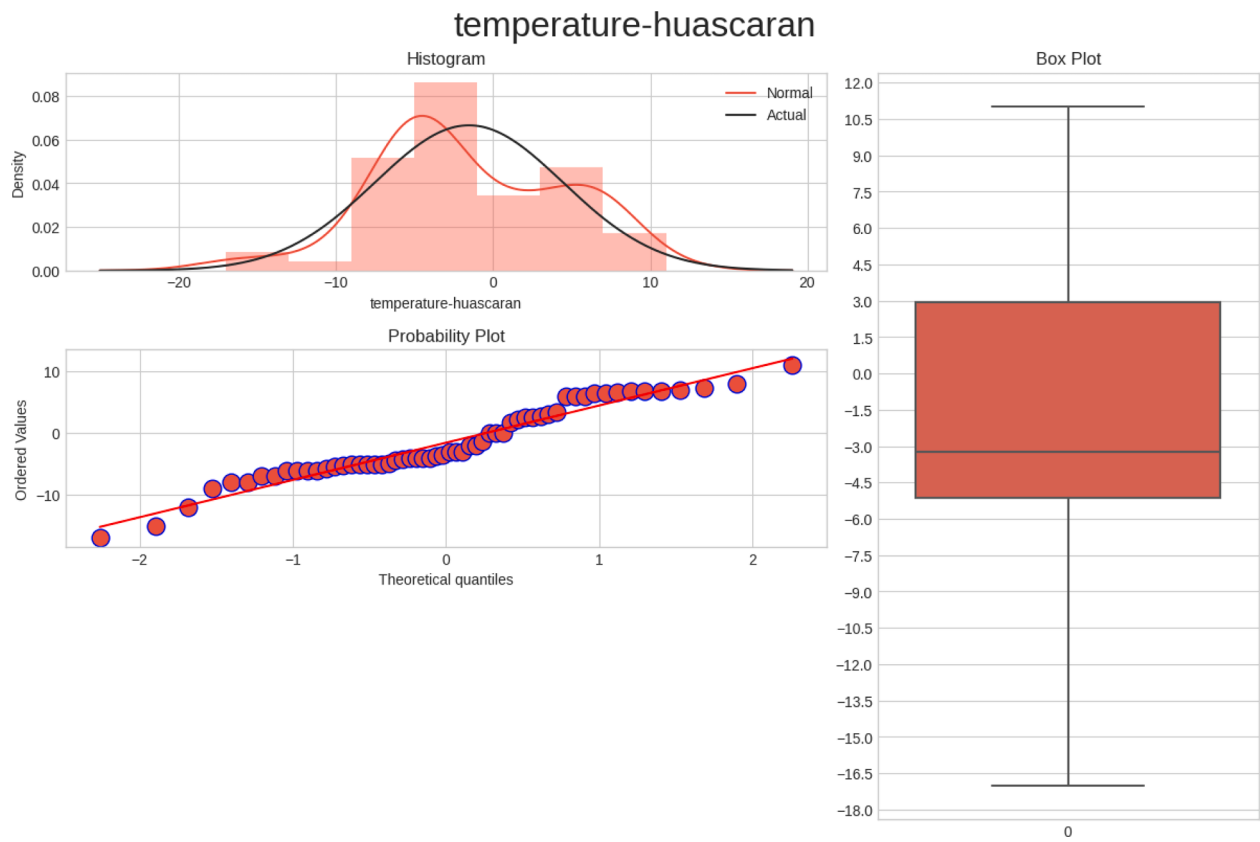


Fig. 4. Distribution of values of the variable temperature of Huascarán snow-capped mountain.

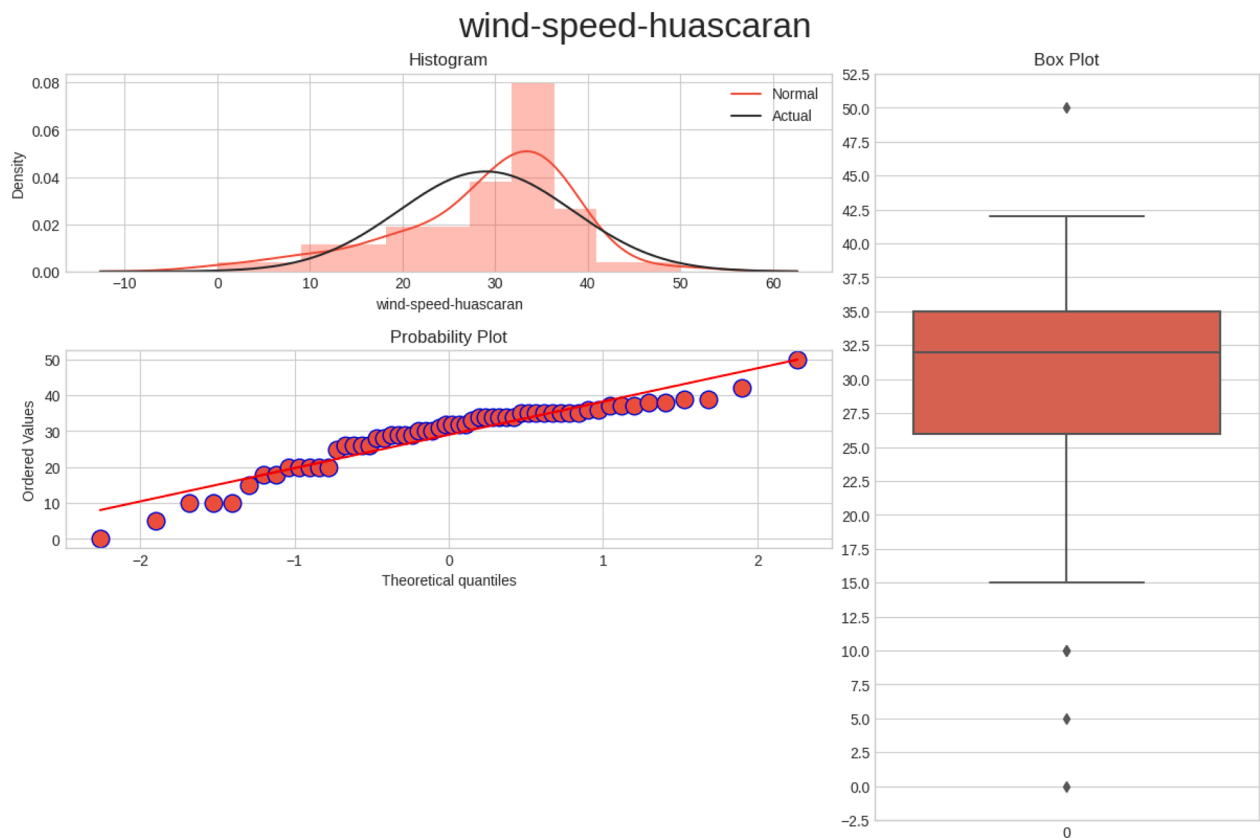


Fig. 5. Distribution of values of the wind speed variable of Huascarán.

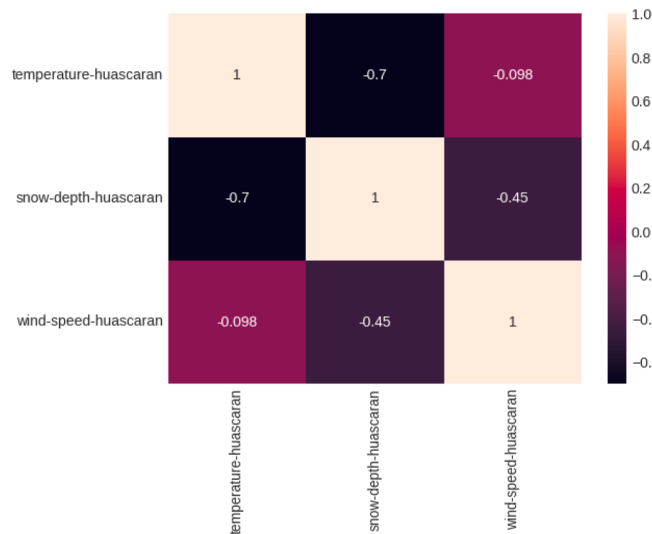


Fig. 6. Correlation Matrix showing relationships between key variables.

information and digital objects. This technology facilitates the visualization and understanding of complex information by superimposing virtual elements in the real world. For example, in fields such as medicine, architecture, or education, 3D models, real-time data or visual instructions can be displayed to facilitate learning and understanding.

The AR application, crafted in Unity 3D, was meticulously organized by arranging scenes and scripts, tailored to accommodate the specific number of variables under control. The process commenced with the establishment of the Database in Vuforia an AR and Mixed Reality (MR) application development platform. Vuforia utilizes markers, which can

be images or objects, serving as information triggers in the application. When the device camera recognizes these markers in the real world during the execution of an AR or MR application, it activates the visualization of virtual content (Unity 3D 2023; Vuforia 2023). After importing the Vuforia SDK and its license to Unity, the connection with Ubidots was made to display the data taken from the sensors to be transmitted through an HTTP connection protocol (Part 4 2023), using the URL of the device and the API key as shown below: `https://industrial.api.ubidots.com/api/v1.6/devices/{dispositivo_id}/values?token={api_key}` (Ubidots 2023). As well as making use of the JSON format that includes the values of the device connected to the database in the cloud, to implement them in real-time in the 3D model (see Fig. 8). To achieve this, custom scripts were created in C# using Microsoft Visual Studio, which were attached to the scene components created with Unity. This allowed the IoT data to be added to the developed application.

Fig. 8 illustrates the AR scene developed in Unity, where the data captured by the sensors will be displayed along with their reading date. This scene consists of the Vuforia marker, where the data derived from Ubidots will be projected. Below the values, there is a graphic representation of the Huascarán snow-capped mountain, showing the location of the ultrasonic sensor that acquires the physical variables. In addition, a brief description of the mountain under study is included.

3. Results

Over the course of the monitoring period, weather data was collected at Ubidots, where the variables of snow depth, air temperature, and wind speed were controlled as the primary variables. Fig. 9 illustrates the control panels corresponding to these variables, showing the information collected for the Huascarán snow-capped mountain during the months of April and May 2023, after the IOT simulations.

As shown in the line graph (Fig. 10), which has been generated from

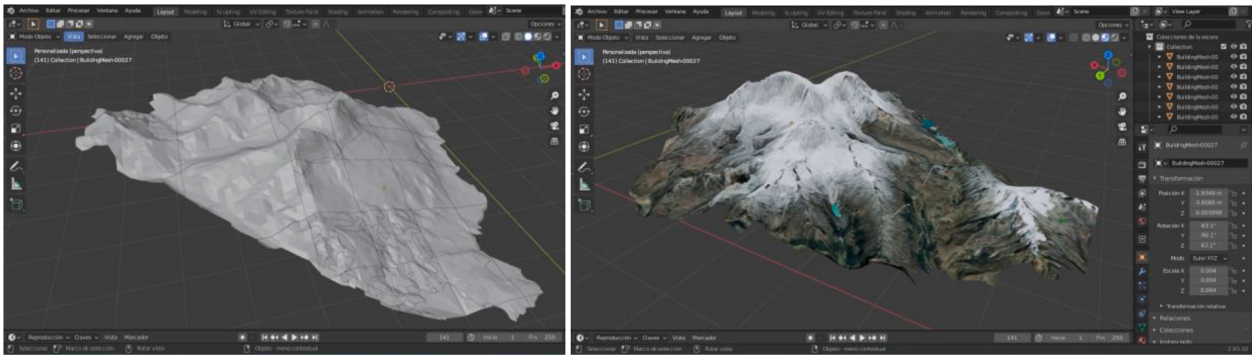


Fig. 7. 3D Model of the Huascaran snow-capped mountain: Texturing and customization in Blender.

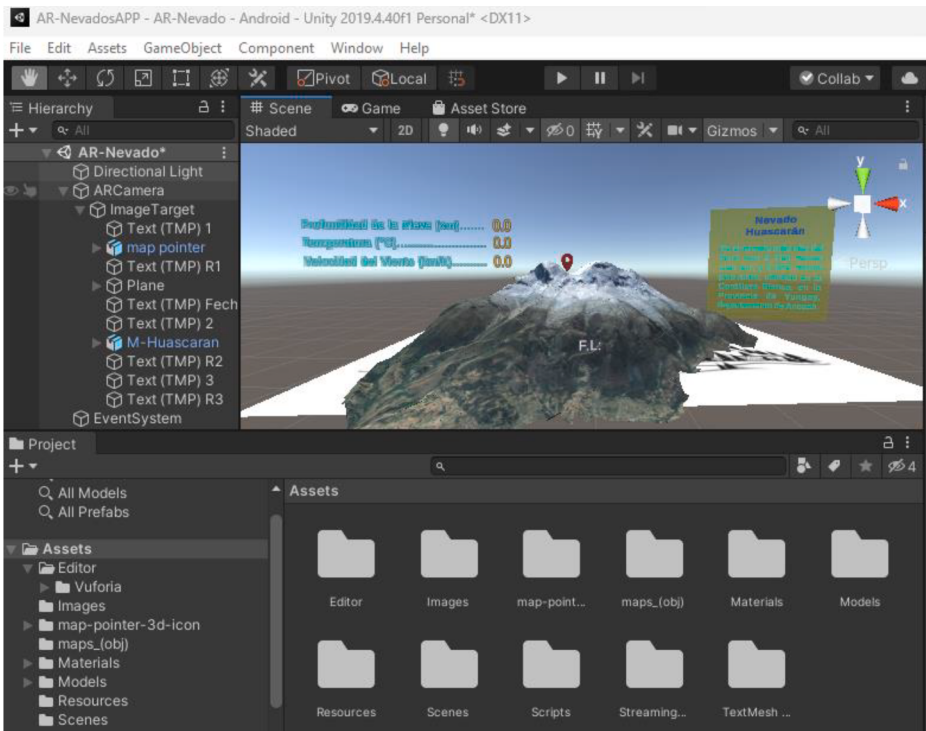


Fig. 8. Augmented Reality scene displaying the integration of virtual elements in the application.



Fig. 9. Dashboard view of variables in Ubidots for real-time data visualization.

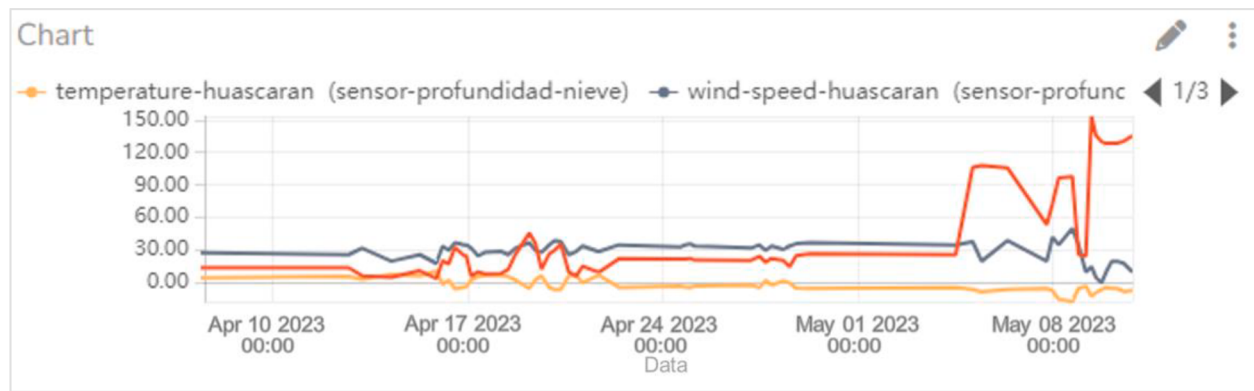


Fig. 10. Time series line graph depicting trends in the variables in Ubidots.

the data recorded in Ubidots, the behavior of the variables during the study period can be observed. It should be noted that most of the time as the wind speed increases, the air temperature decreases, creating an environment conducive to increasing the depth of the snow cover in the Huascaran snow-capped mountain. However, in the month of May, abnormalities are shown, especially with the data recorded with the wind speed. On the other hand, snow depth increased greatly, while air temperatures presented their lowest readings in the first week of May, maintaining the same pattern as in April.

In relation to the EDA, Figs 11 and 12 offer a detailed view of the temporal distribution of the variables under study throughout the months of monitoring. Fig. 11 presents descriptive statistics, including histograms (Figs 11A, B, C), count, mean, mean, standard deviation, minimum, percentiles (25 %, 50 %, 75 %), and maximum. These provide a quick, visual summary of the characteristics of the variety. The mean and percentiles (Figs 11D, E, F) reveal central trends and distribution of the data. In addition, Figs 11G and H present scatter plots, highlighting

relationships between variables on the "x" and "y" axes. These plots were designed for a general understanding of the structure of the data and the identification of potential outliers or problems. Taken together, these visualizations contribute to a deeper understanding of the data, serving as valuable tools for further analysis and informed decision-making.

Fig. 12 shows the three-dimensional (3D) scatter plot of the variables, with different markers, classifying them by color, opacities and shape according to the data; the readings belonging to May are in the form of circles, while those for April are squares. A great difference can be appreciated between both months, being May the month with a greater margin and, on average, the highest snow cover depth readings.

After the application developed in Unity for Android devices is connected to the cloud database and launched, the camera is launched to search for the marker where the 3D model is displayed along with the sensor data obtained from the IoT device. Fig. 13 shows the data for snow cover depth, air temperature, wind speed, date of data reading and location. In addition, by rotating the marker, or the cell phone around

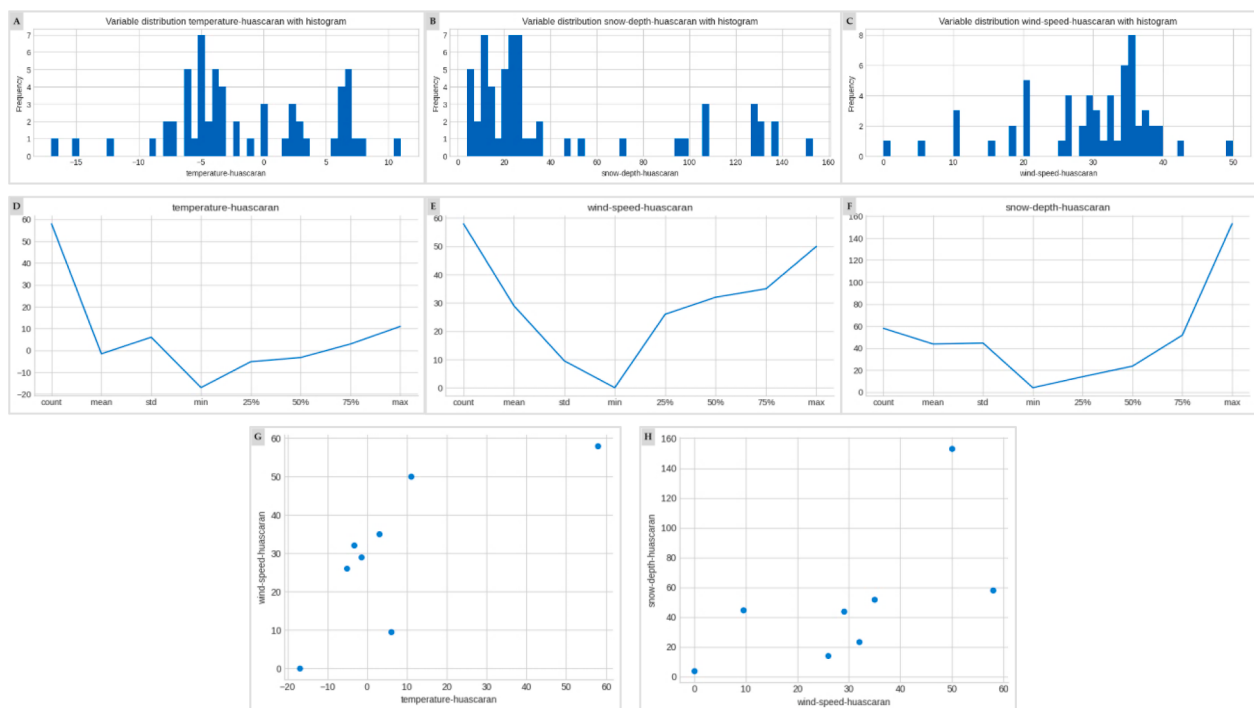


Fig. 11. Descriptive statistics of the variables under study (temperature, wind speed and snow depth). A. Distribution of the data of the temperature-huascaran variable with histogram. B. Distribution of wind-speed-huascaran variable data with histogram. C. Distribution of snow-depth-huascaran variable data with histogram. D. Line graph of the description of the temperature-huascaran variable. E. Line graph of the description of the wind-speed-huascaran variable. F. Line graph of the description of the snow-depth-huascaran variable. G. Scatter plot of wind-speed-huascaran and temperature-huascaran variables. H. Scatter plot of snow-depth-huascaran and wind-speed-huascaran variables.

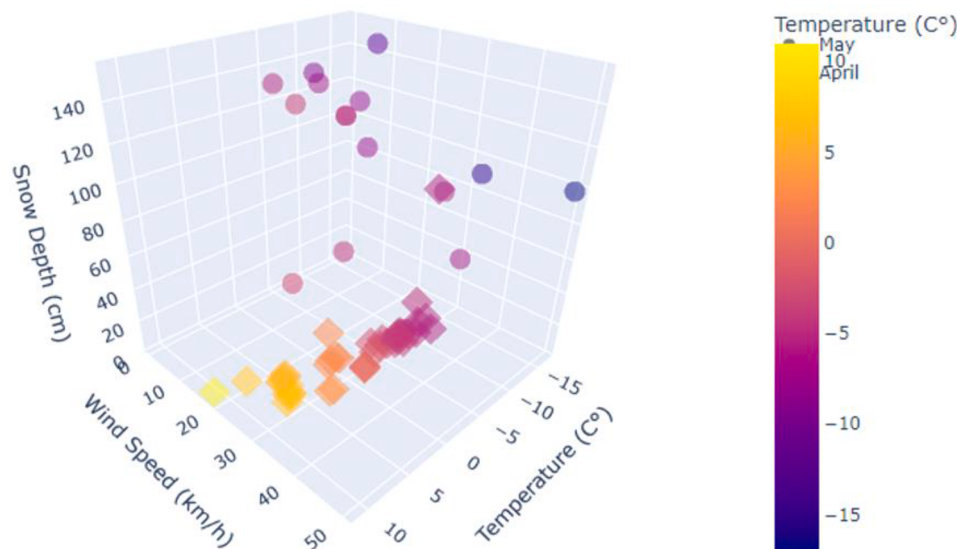


Fig. 12. 3D scatter plot illustrating the relationship between multiple variables.

the marker, the current model of the Huascarán snow-capped mountain and a brief description of it can be displayed in full. Likewise, pressing the next button displays the last 4 recorded readings and the graphs derived from the analysis of the data obtained from the sensors to provide greater detail of the study.

4. Discussions

The integration of AR-IoT technologies in the application for the periodic monitoring of snow cover in the snowy Huascarán Mountain has proven to be very beneficial. The Ubidots cloud IoT platform has been essential in offering an efficient and secure means for data management and storage. This platform not only facilitates the direct collection of data from IoT devices, but, in the context of this research, allowed the real-time storage and visualization of the data after the IoT simulations. This ensures smooth integration with advanced technologies, improving the effectiveness of monitoring and interpretation of snowpack information.

The use of AR has enabled an innovative and understandable representation of the data, providing an interactive visualization of snowpack and weather conditions. Through AR, users can overlay relevant information on the physical environment, improving understanding of current conditions and allowing for a more accurate assessment of changes in the glacier. This interactive visualization not only facilitates a more intuitive understanding of climate and glacier conditions, but also supports decision-making based on accurate and up-to-date data.

As part of this research, a total of 58 readings of data from meteorological repositories were collected, such as air temperature, wind speed, and snow depth (Table 1). This data was processed through IoT protocols and stored on the Ubidots cloud platform. The preliminary analyses of the variables were carried out to examine the behavior of these variables during the months of April and May 2023 in the snow-capped Huascarán.

The actual results, as shown in Fig. 6, revealed a positive correlation between increased wind speed and reduced air temperature, creating an environment conducive to a slight increase in snow depth. In addition, outliers were identified for all three variables in early May, with snow depth showing the largest fluctuations (Figs. 10 and 11), even reaching 153.2 cm (Fig. 3). These findings highlight the influence of climate change on the variability and uncertainty of precipitation patterns and snow depth, which directly impacts the availability and quality of water resources.

The interdependence between these factors underscores the importance of addressing both climate change and water management challenges in an integrated manner to ensure long-term water security (Thapa et al., 2021; Thapliyal et al., 2024). The vulnerability of the system to environmental variations, evidenced by the dependence of these climatic variables on snow cover, indicates that the long-term effectiveness and stability of the application could be conditioned by unpredictable climatic factors (Thapa et al., 2021; Zemlianskova et al., 2023). Therefore, a detailed understanding of these dynamics is crucial to improve the management and adaptation of water resources in high mountain contexts.

5. Conclusions

Monitoring snowpack on Andean Mountain glaciers is crucial for people's safety, water management, and understanding the impacts of climate change. The availability of real-time information on snow cover through monitoring systems allows for informed decision-making, risk mitigation, and effective planning for the management of these fragile ecosystems.

The research has demonstrated that the integration of AR-IoT technologies for periodic monitoring of snow cover on Huascarán is an effective and valuable tool for improving understanding of changes in Andean glaciers. The Ubidots platform has enabled efficient and secure storage of data, facilitating the monitoring of variables through IoT, while AR has provided an interactive and accessible visualization of information, improving the user experience and interpretation of data. This combination of AR and IoT has been important in providing an understandable and accurate view of climatic and glacial conditions, aiding decision-making based on up-to-date and detailed information.

The tool developed not only facilitates the continuous monitoring of the snow cover in the snow-capped Huascarán, but also has the potential to be expanded to include more variables and improve decision-making in relation to water availability and quality, helping to mitigate the risks associated with the water crisis in the region.

In summary, the integration of advanced technologies in environmental monitoring not only provides valuable insights into snowpack behavior, but also underscores the need for coordinated and sustainable strategies to address the impacts of climate change on water resources. For future studies, it is recommended to explore additional climate indicators, integrate data from more extensive sensor networks, and develop predictive models based on machine learning algorithms, which



Fig. 13. IoT and AR application showing in: A. They show the data captured by the sensor: depth, temperature, wind speed, date of reading the data and location belonging to the first scene; B. Description of the snow-capped Huascarán. C. History and graphs of the behavior of the data belonging to the second scene.

would strengthen the understanding of snowpack evolution and facilitate more efficient management of natural resources.

Limitations

Current glaciological measurements focus on perimetric and intermediate areas due to the difficulties of access to the summits. The implementation of modern sensors and satellite surveys could overcome these limitations and enable accurate measurements at the summits of snow-capped peaks.

The limited availability of accurate data on snow cover, its depth, and specific climatological parameters for certain seasons of the year makes it difficult to create comprehensive datasets for data analysis. This lack of specific information may influence the robustness of the results obtained.

The lack of 3D models developed for the Peruvian snow-capped mountains is another limitation. The lack of three-dimensional

representations of the snow-capped mountains makes it difficult to visualize and understand the topography and evolution over time, crucial aspects for the comprehensive understanding of climatic phenomena in these regions.

Ethical Statement

This research project on "Avances Tecnológicos en Alta Montaña: Desarrollo de una Aplicación de Realidad Aumentada e IoT para el Monitoreo de la capa de nieve en el Nevado Huascarán, Perú, 2023" was approved by the Institutional Research Ethics Committee of the Universidad Continental in January 2024. The ethics approval code is N°080-2024-CIEI-UC.

CRedit authorship contribution statement

Joselyn Zapata-Paulini: Writing – review & editing, Writing –

original draft, Validation, Methodology, Investigation, Data curation, Conceptualization. **Leslie Lescano:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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