

Surveying Colombia's Highest Mountains - Pico Bolivar and Pico Cristóbal Colon Elevation Survey 2024

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Abstract

Pico Cristóbal Colon and Pico Bolivar are the highest peaks in Colombia and were last accurately surveyed in 1939 with Colon measured at 5775m and Bolivar 5773m. Both peaks have permanent icecapped summits. For this study multiple differential GPS units and an Abney level were used to measure updated elevations of each peak with sub-meter accuracy. Bolivar is now 5720.42m +/- 0.08m and Colon is now 5712.79m +/- 0.87m (orthometric height using Colombia 2004 geoid). Bolivar has melted down 53m and Colon has melted down 62m since 1939. Bolivar is now the highest mountain in Colombia.

Introduction

The highest peaks in Colombia are Pico Cristóbal Colon and Pico Bolivar, located in the Santa Marta Mountains in the north of the country. Pico Bolivar was first climbed on Feb 2, 1939 by Krause, Praolini, and Pichler. Krause surveyed the summit elevation using a hypsometer and measured 5520m [1]. This measurement was later corrected by the Augustin Codazzi geographic institute to 5794m, though the error bounds on the measurement were not given [1].

Pico Colon was first climbed a month later, on March 16, 1939, by Praolini, Bakewell and Wood. This climb was part of the larger American Cabot expedition, which conducted a trigonometric survey of the area considered the most accurate ever done. That expedition measured Pico Colon 5775m and Pico Bolivar 5773m [2]. For that expedition surveyors took an Abney level to the summit of Colon and measured that Bolivar was 2m shorter. Thus, since 1939 Pico Colon has been recognized as the highest peak in Colombia.

The next measurement was conducted in 1989, when Cristóbal Von Rotkirch and Juan Pablo Ruiz used an altimeter brought to each summit to measure Colon 5775m and Bolivar 5790m [1]. In general, altimeters have much higher errors than an Abney level or trigonometric survey, so this merely showed the peaks were of similar elevation. Colon was still recognized as the country highpoint.

More recent satellite-based measurements from the 2001 SRTM mission [4] showed Colon higher than Bolivar, though vertical errors can be up to 16m for sampled points and measurements were only taken every 30m horizontal spacing. So those measurements are not definitive. The most accurate measurements to date have been the 1939 trigonometric survey.

Since the late 1990s this mountainous area has been largely off limits to climbing. The area around the summits is controlled by four indigenous groups: Kogi, Arhuaco, Cancuamos, and Wigua.

In 2015 Petter Bjorstad and John Biggar secured permission from the Kogi to climb both peaks. They climbed Colon but not Bolivar. A handheld GPS on the summit of Colon recorded an elevation of 5730m (WGS84 EGM96 geoid). This is approximately 5725m in Colombia 2004 geoid [6]. Handheld GPS units generally have vertical accuracy around +/-10m.

In 2022 Cristian Alarcon brought a handheld GPS to the summit of Colon and measured 5721m (Colombia 2004 geoid).

In December 2024 permission was granted by the Arhuaco tribe for the author to conduct an elevation survey of both peaks using professional surveying equipment with sub-meter vertical accuracy.

Methodology

Summit Measurements

A Trimble DA2 differential GPS (dGPS) unit was brought to the summit of Bolivar on Dec 23 at 11am and data logged for 45 minutes. Data was post processed using TrimbleRTX [7] and CSRS-PPP [8] methods. This gave an absolute elevation measurement for Bolivar (denoted as Z_B). Note: dGPS units are capable of 2cm vertical accuracy, much more accurate than consumer-grade handheld GPS units.

A 10 arcminute 5x Sokkia Abney level was used to measure angular declination from Bolivar to Colon. Using known coordinates of each summit, a distance between summits was calculated. The declination angle was then used with this distance and basic trigonometry to calculate a relative height (Fig. 1a),

$$\Delta = d \tan \theta. \quad (1)$$

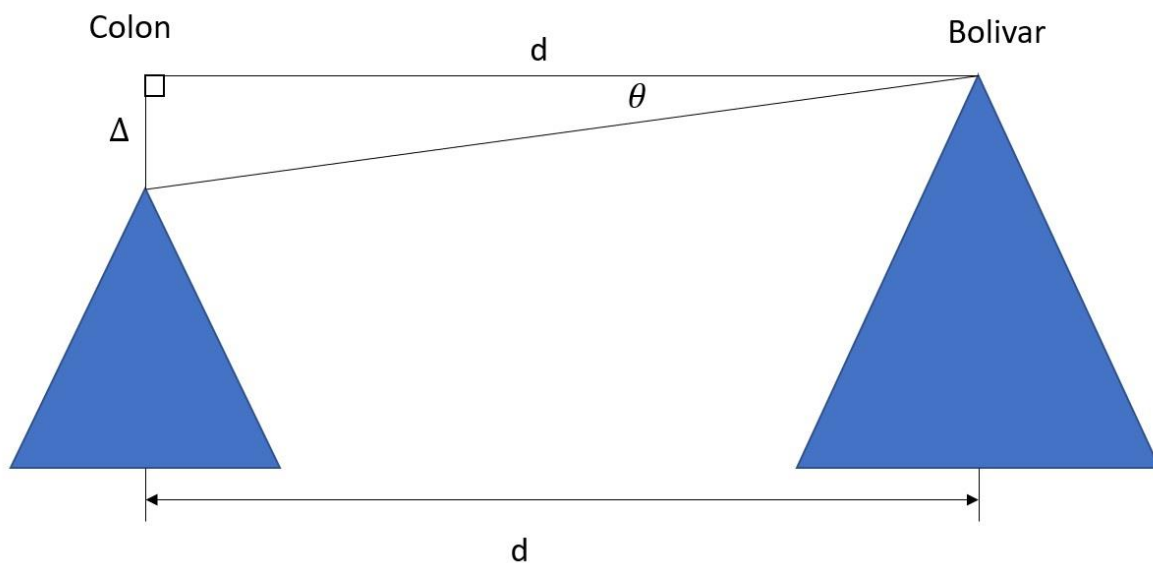


Figure 1a: Measuring relative height between Colon and Bolivar from the summit of Bolivar.

The relative height was subtracted from the measured Bolivar height to calculate the absolute elevation of Colon, Z_C . This is given by

$$Z_C = Z_B - \Delta. \quad (2)$$

A view of the DA2 set up on the summit of Bolivar is shown in Fig. 1b.



Figure 1b: The Trimble DA2 set up on the summit of Bolivar with bottom of antenna level with highest snow. View looks East with Colon visible in background.

Basecamp Measurements

Two dGPS units (Trimble DA2 and Trimble Promark 220) were mounted for one hour on a hill near basecamp and Abney level measurements taken looking up at each peak from this location (Fig. 2a). Trigonometry was used to find the relative heights of each peak above the dGPS units, using equations

$$h_1 = d_1 \tan \theta_1 \quad (3)$$

and

$$h_2 = d_2 \tan \theta_2. \quad (4)$$

Distances d_1 and d_2 were found using known coordinates of each summit and measured coordinates of the dGPS units.

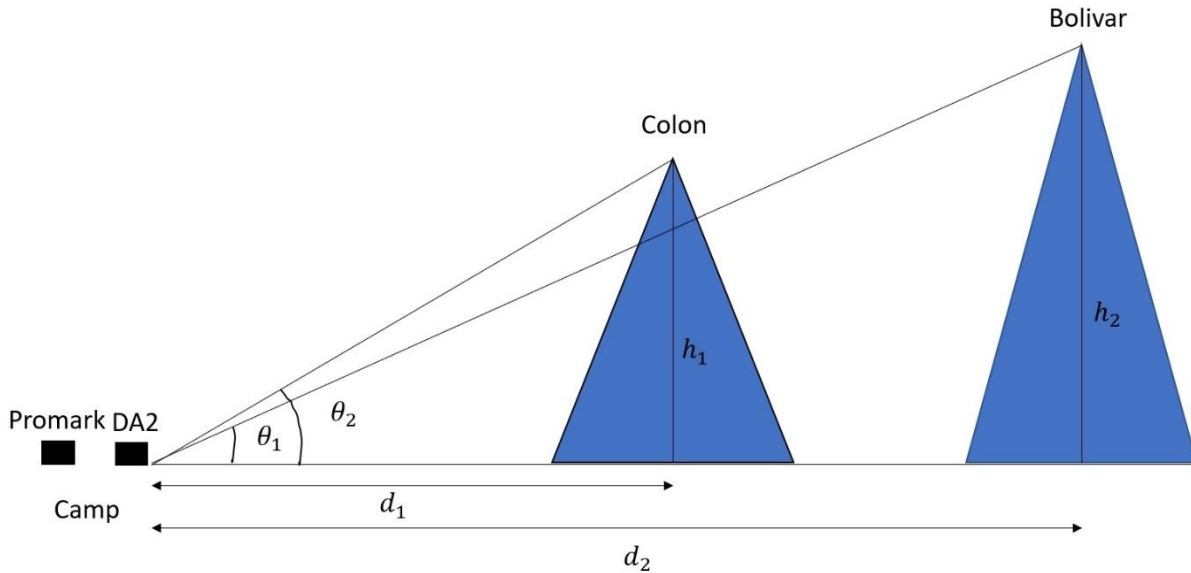


Figure 2a: Measuring the absolute and relative heights of Colon and Bolivar from basecamp

The relative height between the peaks was calculated as

$$\Delta = h_2 - h_1. \quad (5)$$

The absolute height of each peak was calculated as

$$Z_C = Z_{camp} + h_1 \quad (6)$$

for Colon and

$$Z_B = Z_{camp} + h_2. \quad (7)$$

for Bolivar, where Z_{camp} represents the measured elevation of the dGPS units at camp. The dGPS units and Abney level can be seen set up at basecamp in Fig. 2b.



Figure 2b: The DA2 and Promark dGPS units set up at basecamp with view looking south to both summits. The Abney level is being held by the author.

Approach Pass Measurements

Additionally, the DA2 dGPS was mounted at a pass on the approach hike with good visibility to each summit, Colon and Bolivar. An inclinometer with 0.5-deg resolution and 30x zoom was used to measure the declination φ from the summit of Bolivar to the summit of Colon from this location (Fig. 3a Front View).

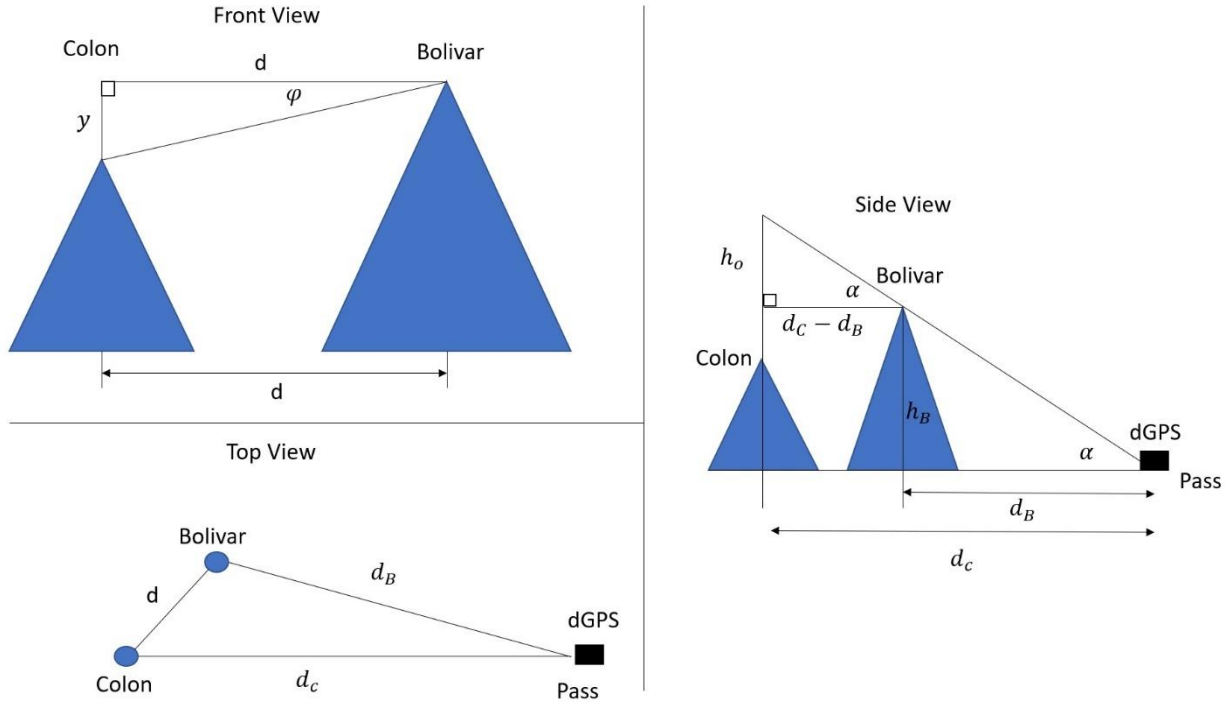


Figure 3a: Measuring the relative height of Colon and Bolivar from a pass on the approach hike

If both peaks were equidistant from the pass, then this would mean the relative height would be given by $y = d \tan \varphi$. However, because Bolivar was closer to the pass than Colon (Fig. 3a Top View, Side View), this overestimates Bolivar's height by h_o . Thus, a correction needs to be added to find the final relative height Bolivar above Colon is $\Delta = y - h_o$. This simplifies to

$$\Delta = d \tan \varphi - (d_c - d_B) \tan \alpha. \quad (8)$$

The angle α could be measured with the Abney level or by using the measured height of Bolivar and the measured height of the dGPS to find the difference in heights, $h_B = Z_B - Z_{pass}$. The later method was employed for this analysis, because it resulted in smaller error.

This means

$$\tan \alpha = \frac{h_B}{d_B} = \frac{Z_B - Z_{pass}}{d_B}. \quad (9)$$

The distance d_B is measured from the known coordinates of the dGPS and of the summit of Bolivar. Thus, the final equation for the relative height between Colon and Bolivar in terms of measured parameters is

$$\Delta = d \tan \varphi - (d_c - d_B) \frac{Z_B - Z_{pass}}{d_B}. \quad (10)$$

From this result, an absolute height of Colon can be calculated by

$$Z_C = Z_B - \Delta. \quad (11)$$

The view of the DA2 at the approach pass is shown in Fig. 3b.



Figure 3b: The DA2 dGPS unit set up at the approach pass view Colon and Bolivar visible in the background.

Handheld GPS Measurements from Each Summit

An additional measurement of relative height was taken by bringing a handheld GPS unit to each summit on the same day and taking the difference in measured values. A handheld unit is much less accurate than a dGPS, and is generally assumed to have vertical errors around +/-10m.

Photographic Analysis

Finally, photographic analysis was used to measure a relative height between Bolivar and Colon. Geopix photo analysis software [5] was used to analyze a photograph taken in January 2024 from the summit of Colon looking towards Bolivar (Fig. 4). This software allows measurement of the relative height between a peak in the photograph and the camera. It requires entering the coordinates, elevations, and pixel locations of multiple background peaks visible in the photo, as well as the coordinates and pixel location of the peak of interest.

The software accounts for image distortion, atmospheric distortion, and other effects. The software has been validated on over a dozen peaks in Washington, USA, using Lidar, Theodolite surveys, and differential GPS surveys. It outputs a relative height along with standard deviation.

For this analysis ten background peaks were identified and used.



Figure 4: Photograph from the summit of Colon looking towards Bolivar from January 2024 used for photographic analysis.

Results

All absolute elevations will be reported as orthometric height using Colombia 2004 geoid.

Summit Measurements

The DA2 dGPS on the summit of Bolivar logged data for 45 minutes and was post processed using TrimbleRTX [7] and CSRS-PPP [8] methods.

The measured elevation was 5720.42m +/- 0.08m.

The Abney level was used to measure an angular declination of 40 arcminutes from the summit of Bolivar down to the summit of Colon. Using the measured coordinates from the summit of Bolivar from the dGPS, and previously-measured coordinates of the summit of Colon from 2015 [6], the horizontal distance between the summits was calculated as 655m.

Using equation (1), this means the relative height of Bolivar above Colon is 7.63m. The error in the measurement is ± 5 arcminutes based on the resolution of the Abney level. This means the relative height is $7.63\text{m} \pm 0.87\text{m}$. Thus, the absolute height of Colon, from equation (2), is $5712.79\text{m} \pm 0.87\text{m}$.

Basecamp Measurements

The Promark and DA2 dGPS units measured an absolute height of $4561.58\text{m} \pm 0.04\text{m}$ after logging data for one hour at basecamp. The Abney level measured an inclination of 24 degrees 0 arcminutes up to Bolivar and 24 degrees 40 arcminutes up to Colon. Using the measured coordinates of the dGPS and the known coordinates of the summit of Colon and Bolivar, the horizontal distance to Colon was calculated as 2512m and the horizontal distance to Bolivar was 2608m.

Using equations (3)-(7) along with the measured elevation of the dGPS units, Colon was measured at $5714.9\text{m} \pm 3.6\text{m}$ and Bolivar $5722.8\text{m} \pm 3.8\text{m}$. These measurements assume an error of ± 5 arcminutes for the Abney level based on its resolution. Thus, these measurements found Bolivar 7.9m taller than Colon.

Approach Pass Measurements

At the approach pass, the DA2 measured an absolute elevation of $4193.60\text{m} \pm 0.20\text{m}$. The inclinometer measured an angle of 2.5-3.0 degree declination from the summit of Bolivar to the summit of Colon. Using the measured coordinates of the DA2 and the known coordinates of the summits of Bolivar and of Colon, the distances were calculated to be 21.9km to Colon and 22.2km to Bolivar. Bolivar was measured at 1526m above the pass elevation.

Using equations (8)-(11), this results in a measurement of Bolivar 5.6m – 10.8m taller than Colon.

Note that at distances greater than roughly 3km, Earth curvature corrections generally start affecting absolute elevation results by over 1m vertical. Because these measurements in this analysis are for relative heights, not absolute, the Earth curvature corrections are not applied.

The peaks only differed in horizontal distance from the measurement location by 300m, resulting in a 0.02m difference in Earth curvature corrections from one peak relative to the other. This is well within the error bounds of the measurement, and is neglected for this analysis.

Handheld GPS Measurements

A handheld GPS unit was brought by a different group to the summit of Colon at 7am, Dec 18 and the summit of Bolivar at 1pm on Dec 18. The unit measured Bolivar 10m taller than Colon. Error bounds were not given, but are assumed to be roughly +/- 10m.

Photographic Measurements

The photograph in Fig. 4 was used, and ten background peaks were identified and entered into Geopix (Table 1). The camera was assumed to be at the height of the summit of Colon, as is evident in the picture and described by the photographer. The software measured Bolivar is 7.3m +/- 2.4m taller than Colon (95% confidence interval).

Table 1: Background peaks used for Geopix photographic analysis.

Lat	Lon	Elev (m)	Pixel X	Pixel Y	Peak
10.435	-73.920556	1805	151	713	Cuchilla de las Coplas
10.748889	-73.744167	4530	213	735	Cerro Marmillo South Peak
10.627778	-73.830833	3120	266	724	Pico Achocuimeina
10.72346	-73.76607	4130	270	733	Cuchilla de Yarina
10.6275	-73.856111	2995	386	716	Pico Catorivan
10.793611	-73.783055	4660	894	694	Cuchilla Sigungarua south peak
10.80041	-73.78078	4675	947	694	Peak 4675
10.799722	-73.785833	4680	955	691	Cuchilla Sigungarua west peak
10.82229	-73.76835	4695	1119	708	Peak 4695
10.840809	-73.705688	5620	1414	653	Simmonds

Results of the relative heights from each measurement method can be seen in the box-and-whisker plot shown in Fig. 5. The box is centered around the mean measurement, with the box edges extending to +/- one sigma error, and the whiskers extending to +/- two sigma error, denoting the 95% confidence interval. When sigma values are not known, the whiskers are shown to extend to the edges of the error bounds of the measurement.

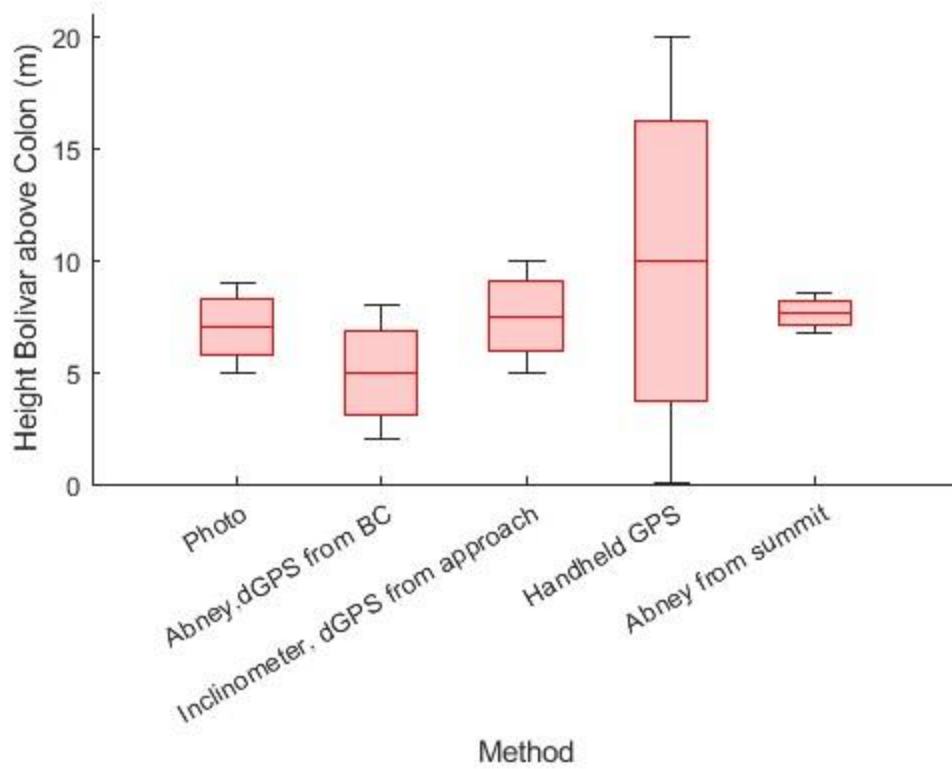


Figure 5: Relative height measurements Bolivar above Colon for each different measurement technique.

The absolute heights of Colon and Bolivar between 1939 and 2024 are plotted in Fig. 6.

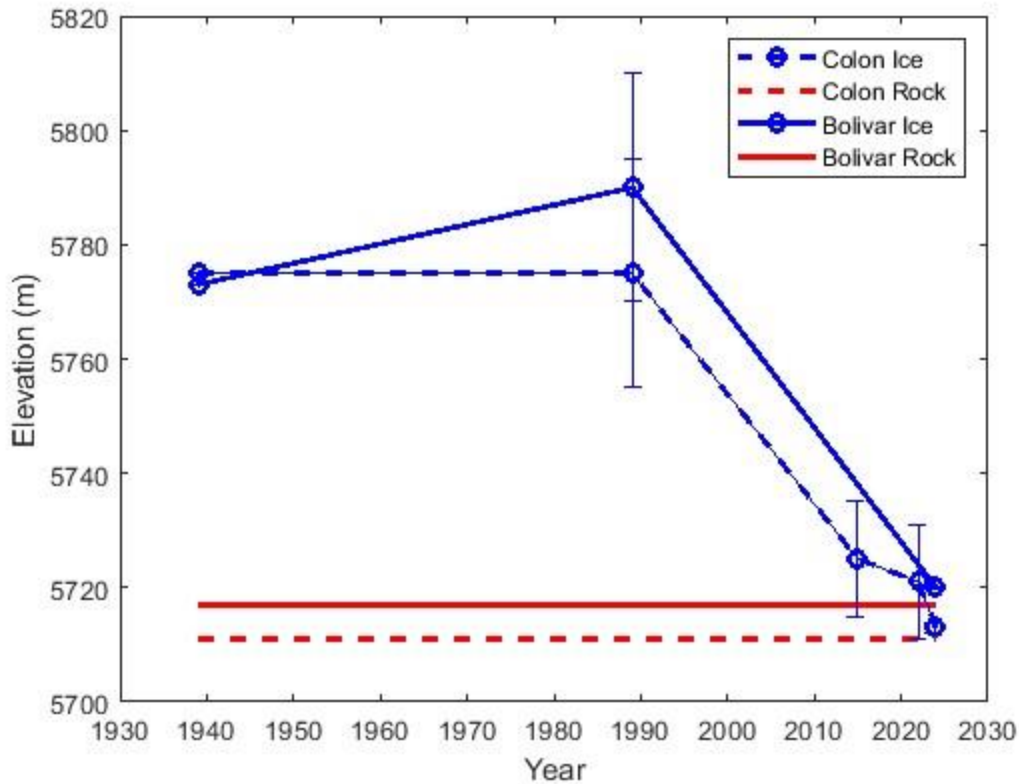


Figure 6: Absolute heights of Colon and Bolivar 1939-2024.

In this figure the blue lines represent the heights of the top of the icecaps, which are the highest points on each peak. The red lines represent the heights of the highest visible rocks. These are estimated at 2m below the summit of Colon (Fig 7.) and 3m below the summit of Bolivar (Fig.8) based on these figures and other closer photographs.

The solid lines represent Bolivar and the dashed lines represent Colon. Measurements are used from 1939, 1989, 2015, 2022, and 2024. Error bounds are given or estimated. The 2024 measurements are used from the dGPS measurement taken on the summit of Bolivar and the Abney level measurement from Bolivar to Colon.



Figure 7: Location of highest visible rock on Colon (red arrow), Dec 23, 2024. Photograph taken from the summit of Bolivar looking East.



Figure 8: Location of highest visibly rock on Bolivar (red arrow) Dec 23, 2024. Photograph taken from the upper East ridge of Bolivar looking towards the summit.

To understand the elevation loss, historical climate data for temperature and precipitation from 1979-2024 is shown in Fig. 9 for Pico Colon using the ERA5 dataset [9]. This plot shows modeled temperature anomalies from historical means (top) and modeled precipitation anomalies from historical means (bottom).

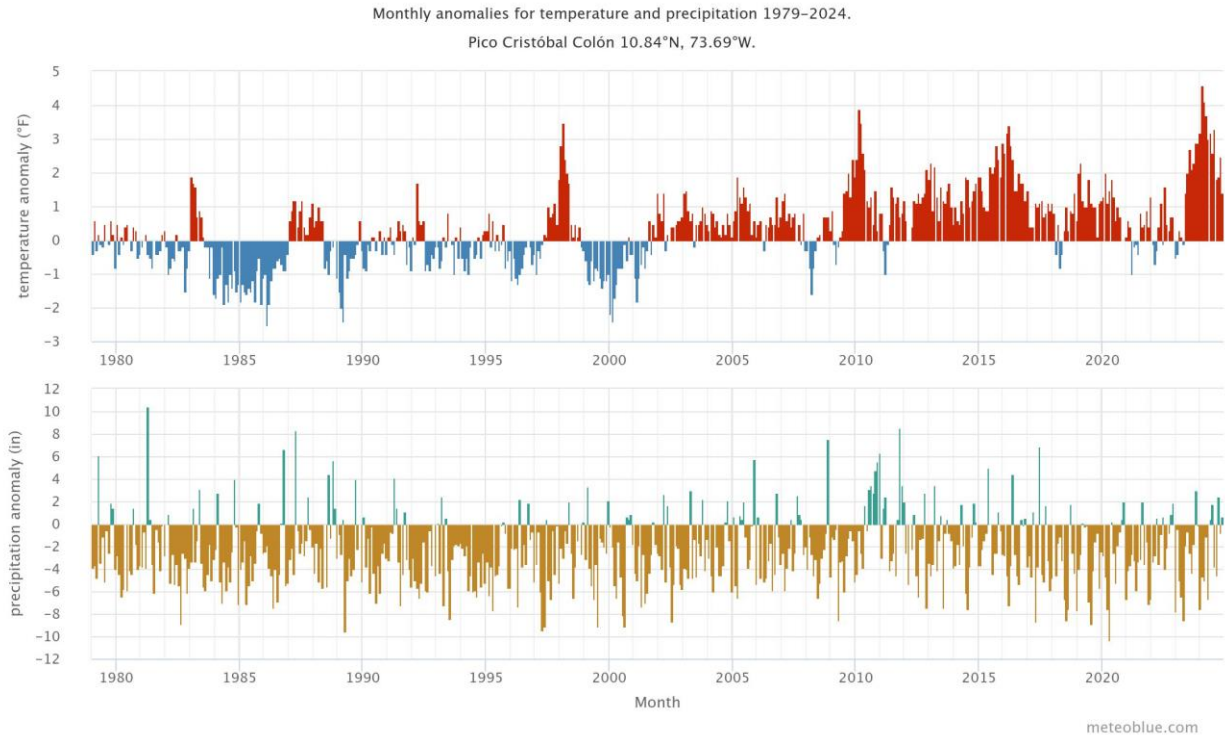


Figure 9: Modeled historical temperature and precipitation anomalies for Pico Colon 1979 – 2024 [9].

Discussion

All five measurement methods are consistent that Bolivar is taller than Colon. The measurement with the smallest error bounds is the Abney level measurement from the summit of Bolivar to the summit of Colon. This measured Bolivar 7.63m taller than Colon.

All absolute elevation measurements are also consistent with overlapping error bounds for each peak. The final result is reported as the measurement with the lowest error. That is the dGPS measurement from the summit of Bolivar and the Abney level measurement from Bolivar to Colon. The final reported absolute elevations are thus Bolivar 5720.42m +/- 0.08m and Colon 5712.79m +/- 0.87m (orthometric height, Colombia 2004 geoid).

Bolivar is now taller than Colon and is the highest mountain in Colombia. It is unclear when Bolivar overtook Colon in elevation. Colon was 2m taller than Bolivar in 1939. The 1989 altimeter readings measured Bolivar taller, but within the error bounds of the measurement. Thus, it is only known that in 1989 Colon and Bolivar were of similar heights to each other, and of similar heights to the 1939 measurement.

The 2015, 2022, and 2024 measurements all show significant elevation loss from 1939. Based on Fig. 6 it appears the elevation loss began in the 1990s or early 2000s. By 2024 Bolivar has melted down 53m since 1939 and Colon has melted down 62m since 1939.

This means Colon melted down at a faster average rate than Bolivar. Based on their current states, Bolivar is a much sharper peak and Colon is much more rounded. It is possible this played a factor in the different melting rates.

The highest visible rocks are only a few meters below the summits of each peak. It appears if the current melt rate continues, each summit will melt down to rock within the next few years. When this happens, Bolivar will have an elevation of approximately 5717m and Colon an elevation of approximately 5711m. Thus, Bolivar will likely remain the country highpoint.

Modeled historical temperature and precipitation anomalies (Fig. 9) appear to be consistent with the observed loss in elevation. Temperatures have dramatically increased on the summit starting in the early 2000s. At the same time, precipitation has decreased relative to historical average values. These two factors may each have contributed to melting of the icecap summits and significant elevation loss of both peaks.

Conclusion

Pico Bolivar is now the highest mountain in Colombia with an elevation 5720.42m. Pico Colon, formerly the country highpoint in 1939, is now the second highest mountain in Colombia with an elevation of 5712.79m. Bolivar has melted down 53m since 1939 and Colon has melted down 62m.

Acknowledgements

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