Research Article

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Assessment of SIRGAS-CON tropospheric products using ERA5 and IGS

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Abstract: Zenith Tropospheric Delays (ZTDs) are used to correct tropospheric effects that cause a delay in the signal measured by Global Navigation Satellite Systems (GNSS) receivers and obtain accurate measurements. ZTD can be estimated from GNSS processing, which means they may suffer from occasional or systematic errors. Therefore, it is necessary to assess the quality and stability of these data over time, since ZTDs are used in several applications that require centimeter precision. Within this context, this work aims to assess the available ZTD of the whole Geodetic Reference System for the Americas Continuously Operating Network (SIRGAS-CON), consisting of 467 stations, spanning the period from January 2014 to December 2020 using the most recent Numerical Weather Model ERA5 from the European Centre for Medium-Range Weather Forecasts and common stations to the International GNSS Service (IGS) for an intercomparison. Results show that 10% of the stations present some instability, such as periods of highly dispersed data or discontinuities, with more occurrence in stations located in Argentina, Uruguay and Colombia. The remaining 90% proved to have stable and reliable ZTD, both in comparison with ERA5 and IGS.

Keywords: GNSS, Latin America, troposphere, ZTD

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1 Introduction

Global Navigation Satellite Systems (GNSS) are constellations of satellites with global coverage that send position and time information to users on land, sea or air. There are currently some GNSS constellations: Global Positioning System (GPS; United States of America), Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS; Russia), Galileo (Europe) and BeiDou (China). Each satellite constellation is distributed in such a way that it can provide services all over the world (Hofmann-Wellenhof et al. 2007). For the determination of accurate coordinates and monitoring purposes, there are many geodetic stations grouped into global or regional networks equipped with high-performance GNSS receivers (IGS 2022).

The intercontinental network of continuous monitoring GNSS stations, Geodetic Reference System for the Americas Continuously Operating Network (SIRGAS-CON), is a materialization of the Latin American SIRGAS reference system. Its definition corresponds to the International Terrestrial Reference System and is carried out by a regional International Terrestrial Reference Frame densification in Latin America. It was created in 1993 during an International Conference for the definition of a South American geocentric reference system, held in Asunción, Paraguay (SIRGAS 2022).

Currently, SIRGAS-CON has more than 500 GNSS stations, distributed all over Latin America, and some of them are also part of the International GNSS Service (IGS) network. The operational performance of SIRGAS-CON is based on the contributions of more than 50 organizations, which install and operate the permanent stations and voluntarily provide the tracking data for the weekly network processing, performed by the SIRGAS Local Processing Centers and the SIRGAS Combination Centers (SIRGAS 2022). As part of SIRGAS-CON's weekly processing, the SIRGAS Analysis Centers operationally estimate Zenith Tropospheric Delays (ZTDs) for all operational stations with an hourly sampling rate, which account for the tropospheric effects that affect the GNSS signals and consequently degrade the measurements.

Since GNSS observations have a major role in several applications, it is necessary to guarantee the quality and stability of the tropospheric products over time. Some studies about tropospheric delays have been carried out using GNSS data and European Centre for Medium-Range Weather Forecasts (ECMWF) models ERA-Interim and ERA5. For example, Jiang et al. (2020) performed a comparison between both sources over China, finding out that ERA5 ZTD agrees well with GNSS ZTD, with ERA5 achieving a higher precision than ERA-Interim, but for that specific region. Bosser and Bock (2021) performed a comparison between GNSS-derived integrated water vapor (IWV) and the corresponding IWV from ERA-Interim and ERA5, with ERA5 showing an overall improvement over ERA-Interim in representing the spatial and temporal variability of IWV over the study area.

This article aims to evaluate the quality of the SIRGAS-CON ZTD for the period from January 2014 to December 2020, by means of comparison with the ZTD from the best current atmospheric model, ERA5. The study aims to quantify the overall quality of the SIRGAS-CON ZTD, evaluate data consistency and identify possible stability problems.

In addition to the current section, this article has four additional sections. Section 2 describes the estimation of the ZTD from GNSS observations and ERA5. Section 3 comprises a comparison between SIRGAS-CON ZTD and ERA5 ZTD (for all observations from all available GNSS stations) and between SIRGAS-CON ZTD and IGS ZTD for common stations. Section 4 presents the main results and discussion. Section 5 highlights the main conclusions.

2 Description of data sets and ZTD computation

The ZTD can be estimated by different sources and methods, such as GNSS signal delay or Numerical Weather Model (NWM) atmospheric variables. This section describes the characteristics, methods and differences between these two ZTD sources used in this work.

2.1 ZTD derived from GNSS observations

In order to achieve accurate GNSS measurements, it is necessary to account for the tropospheric delays inherent to them. To account for these effects, over the last few years, the analysis centers from GNSS networks have been computing and providing the ZTD for their GNSS stations' observations systematically and operationally. Processing methods may be different for each network and center and are well established, reaching an accuracy of a few millimeters (Niell et al. 2001; Pacione et al. 2011).

The ZTD is the sum of the hydrostatic and wet delays in the zenith direction, namely the Zenith Hydrostatic Delay (ZHD) and the Zenith Wet Delay (ZWD), respectively. It is modeled according to equation (1), transforming the Slant Total Delay (STD), which is the tropospheric delay suffered by the GNSS signal when crossing the atmosphere at different angles of elevation (E), using the mapping functions mf_h and mf_w, corresponding to the hydrostatic and wet components, respectively.

$$\mathrm{STD}(E) = \mathrm{ZHD}mf_h(E) + \mathrm{ZWD}mf_w(E), \tag{1}$$

SIRGAS-CON tropospheric products are estimated for all its stations in highly reliable combined weekly solutions (Mackern et al. 2020). The processing methodology adopted in the estimation of GNSS-derived ZTD has a significant impact on the accuracy of the estimated time series (Stępniak et al. 2022). SIRGAS-CON analysis centers use Bernese GNSS Software v5.2 (BSW52, Dach et al. 2015), and ZTDs are calculated with the final IGS products (orbits and earth rotation parameters, ERP). The operational SIRGAS-CON products are estimated according to the methodology and parameters shown in Table 1 (Mackern et al. 2020).

SIRGAS-CON tropospheric products are available with a latency of approximately 30 days on the SIRGAS webpage, in SINEX TRO files with 1 h temporal resolution since January 2014. The products are freely available for download on the webpage ftp://ftp.sirgas.org/pub/gps/SIRGAS-ZPD (SIRGAS 2022).

Nowadays, the SIRGAS-CON network has a total of more than 560 stations spread all over Latin America and also some of them in the USA, Antarctica, Europe and Africa, as shown in Figure 1, with a historical series of 7 years of data. For this work, all ZTDs available from January 2014 to December 2020 have been considered for analysis, forming a subset of 467 stations, of which 63 are common to the IGS network.

2.2 ERA5 ZTD computation

The NWMs are physical and mathematical models that represent the atmospheric variables, computed from equations that describe their dynamics, using a combination of data from different sources.

ECMWF provides different NWMs, such as the Operational model (ECMWF-Op), with 6 h temporal resolution and

Table 1: Operational SIRGAS processing parameters (Mackern et al. 2020)

		Operational SIRGAS processing
Software		BSW52
Observations		GPS + GLONASS
Sampling interval		30 s
Elevation cut off		3°
Orbits and ERP	Final IGS products	igswwwwD.sp3 igswwww7.erp
Clock corrections	Final IGS products	igswwwwD.sp3
A-priori troposphere modeling and mapping function	Pre-processing	GMF Boehm et al. (2006b) and VMF Boehm et al. (2006a)
	Parameter estimation	VMF C gridded, VMF1 coefficients (00, 06, 12 and 18 UTC)
	Estimation of horizontal gradients	CHENHER model, Chen and Herring (1997) (24 h)
	Parameter spacing	1 or 2 h

0.125° × 0.125° (16 km × 16 km) spatial resolution (Miller et al. 2010); ERA-Interim (Dee et al. 2011), which has a 6 h temporal resolution and 0.75° × 0.75° (80 km × 80 km) spatial resolution; and ERA5 (Hersbach et al. 2018), currently the best and most recent reanalysis model, with 1 h temporal resolution and 0.25° × 0.25° (30 km × 30 km) spatial resolution. ERA5 replaced ERA-Interim, which has been discontinued since August 31, 2019 (ECMWF 2021). ERA5 is available in single-level variables at the surface, some of which are representative of the total atmospheric column (integrated variables), or in 137 vertical levels (3D) for some variables, from the surface up to 0.01 hPa (around an altitude of 80 km), and also interpolated to standard levels, such as pressure levels, at 37 levels with constant pressure, from the surface (1,000 hPa) to 1 hPa (around an altitude of 45–50 km; Vieira et al. 2019a).

ZTD can be obtained from NWM as the sum of ZHD and ZWD. Since the NWM has a different spatial and temporal resolution from the GNSS observations, they need to be interpolated in space and time to derive values for the same instant and location as the GNSS measurements, making them directly comparable. The NWM parameters used to calculate the ZHD and the ZWD are given at the model orography level, making it necessary to reduce the values first computed at the orography level to the height of each GNSS station.

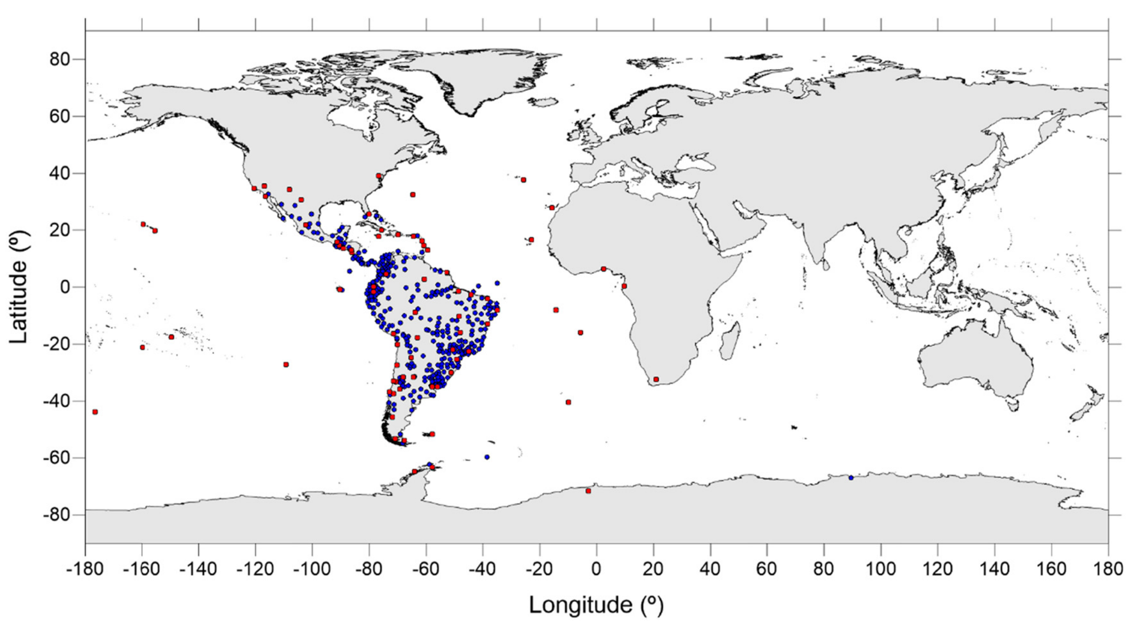

Figure 1: SIRGAS-CON stations represented in blue points and SIRGAS-CON stations common to IGS in red points.

The ZHD corresponds to approximately 90% of the ZTD (Fernandes et al. 2014) and basically depends on the pressure of atmospheric dry gases, which has an almost constant distribution throughout the atmosphere, enabling its computation with an error of less than 1 cm. The ZHD can be computed from ERA5 sea level pressure fields using the modified Saastamoinen model (Davis et al. 1985), according to equation (2):

$$\mathrm{ZHD} = \frac{0.0022768\, p_\mathrm{s}}{1 - 0.00266\cos 2\varphi - 0.28 \times 10^{-6} h_\mathrm{s}}. \quad (2)$$

In equation (2), the ZHD results in meters, φ is the geodetic latitude, h_s is the surface height over the geoid, p_s is the surface pressure, calculated from the surface pressure at sea level p_0, by equation (3), which denotes the pressure variation with altitude (Hopfield 1969).

$$p_\mathrm{s} = p_0 \exp\left[-\frac{g(h_\mathrm{s} - h_0)}{R_0 T_\mathrm{m}}\right]. \quad (3)$$

In equation (3), T_m is the mean temperature value in Kelvin (K) of the layer between heights h_0 and h_s and can be estimated as the mean value between T_0 and T_s temperatures at heights h_0 and h_s, respectively, from T_0 values at mean sea level from Global Pressure and Temperature models (Böhm et al. 2007). R_0 is the specific dry air constant and g is the mean gravity, resulting from equation (4) as follows:

$$g = 9.784(1 - 0.00266\cos 2\varphi - 0.28 \times 10^{-6} h_\mathrm{s}). \quad (4)$$

The ZWD corresponds to approximately 10% of the ZTD (Fernandes et al. 2014, 2021), and it can be computed from NWM single-layer fields of total column water vapor (TCWV), given in mm or the equivalent, kg/m², and 2-m temperature (T_0), which is the air temperature close to the surface, given in Kelvin (K), as presented in equation (5) (Bevis et al. 1992; Bevis et al. 1994):

$$\mathrm{ZWD}(h_0) = \left(0.101995 + \frac{1725.55}{T_\mathrm{m}}\right)\frac{\mathrm{TCWV}}{1{,}000}. \quad (5)$$

T_m is the mean temperature of the troposphere, which can be modeled from T_0, also in K, according to equation (6) (Mendes et al. 2000; Mendes 1999):

$$T_\mathrm{m} = 50.440 + 0.789 T_0. \quad (6)$$

The ZWD obtained by equations (5) and (6) is given at the model orography level. The altitude dependence of ZWD is much more complex than ZHD because it depends essentially on the water vapor, which has non-constant and much more variable distribution throughout the atmosphere, unlike the dry gases. Nevertheless, ZWD height reduction can be modeled according to equation (7) (Kouba 2008) as follows:

$$\mathrm{ZWD}(h) = \mathrm{ZWD}(h_0) e^{\frac{h_0 - h}{2{,}000}}. \quad (7)$$

Even though it is widely used, Kouba reduction is not recommended for height differences greater than 1,000 m (Kouba 2008) and needs some improvements in its modeling (Vieira et al. 2019b).

3 SIRGAS-CON ZTD assessment

NWM is a source of information that makes it possible to analyze SIRGAS-CON products from stations located anywhere, as they are given in global grids and have a long temporal coverage. To compute ZHD and ZWD values from ERA5 for the same location of the GNSS measurements, it is necessary to interpolate ERA5 parameters in space and time. Vieira et al. (2019a) performed an analysis and concluded that hourly intervals do not have a significant impact on the ZWD estimated from ERA5 and that a temporal resolution of 3 h is high enough to ensure the same accuracy of 1 h, showing that ERA5 cannot map the ZWD short space and time scales. Therefore, in this study, an interpolation in time was also performed using ERA5 model grids at 3-h intervals.

With the interpolated parameters, ZHD and ZWD were computed using the equations presented in the previous section. Finally, ZTD is calculated by the sum of the previously computed ZHD and ZWD, at the level of each GNSS station height.

A comparison of the SIRGAS-CON GNSS-derived ZTD with the corresponding ZTD from IGS is also performed for the stations common to both networks, allowing us to evaluate the sensitivity of ZTD estimation from different networks and GNSS processing methodologies.

3.1 Comparison of SIRGAS-CON ZTD with ERA5 ZTD

For each of the 467 SIRGAS-CON stations with available ZTD between January 2014 and December 2020, the mean and standard deviation of the SIRGAS-CON ZTD and the ERA5 ZTD differences were calculated.

The means of the ZTD differences for the various stations are in a range from 0 to 130 mm in absolute value,

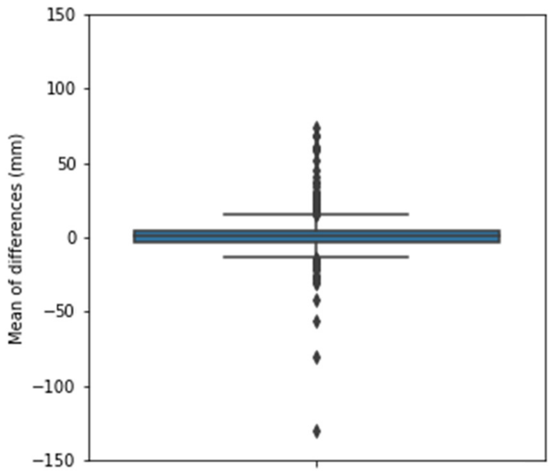

Figure 2: Boxplot of the mean of differences between SIRGAS-CON ZTD and ERA5 ZTD for each station.

from which 97 stations have an absolute mean value greater than 1 cm, 44 stations greater than 2 cm and 19 stations greater than 3 cm, representing 21, 9 and 4% of the total number of analyzed stations, respectively. This indicates that 79% of the stations have a mean difference with respect to ERA5 with an absolute value of less than 1 cm. The mean value of the set of mean differences is 8 mm.

Figure 2 shows the boxplot of the means of the ZTD differences, with the median very close to zero and a large number of outliers over the lower and upper whiskers, with values of −13.6 and 15.1 mm, respectively.

Selecting only the outliers from the boxplot for spatial visualization, as shown in Figure 3, it is noted that the occurrence zone is mainly in the Andes Mountains and other mountainous areas of Central America and the USA. It is possible that the model is not suitable for these zones, as the model's orography is a smoothed version of a Digital Elevation Model (DEM) and may not fit well in mountainous areas because its resolution may not be able to map highly variable topography gradients (Bento et al. 2017). Therefore, only stations that are not in these

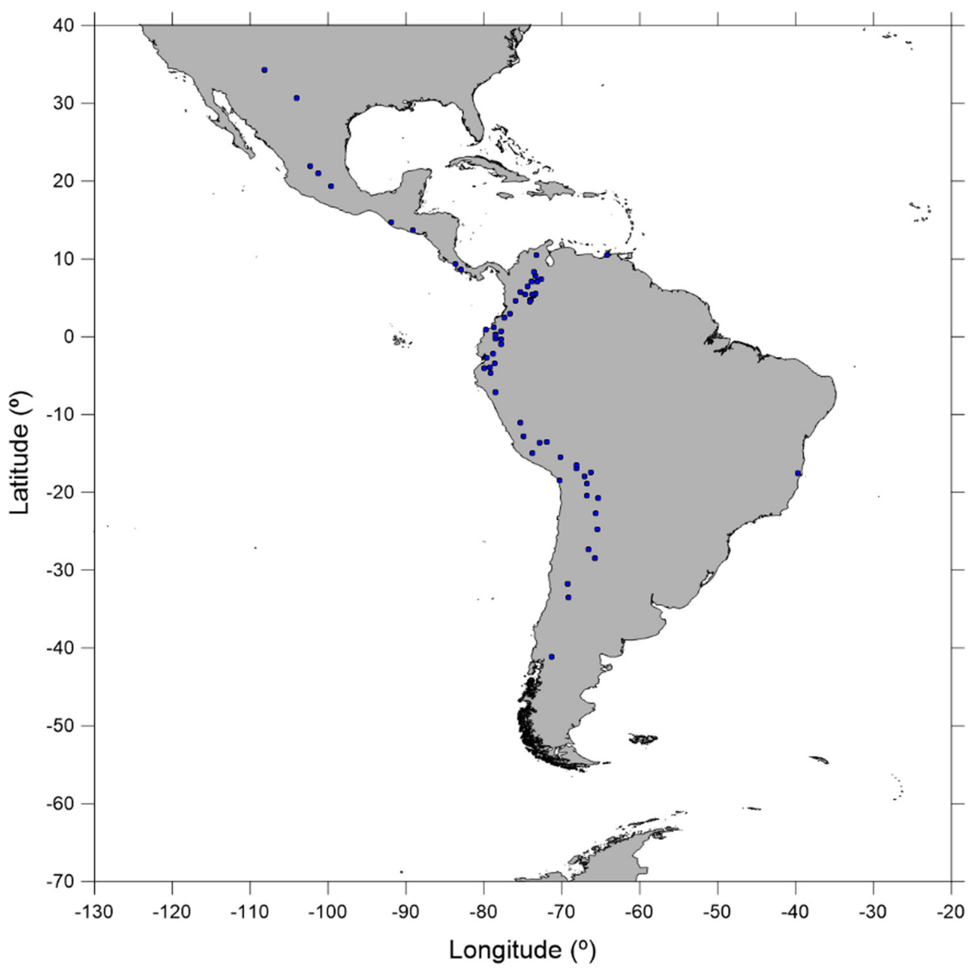

Figure 3: 107 stations located in zones where the NWM may not fit the relief variations well due to its resolution.

zones, stations with orthometric height less than 1,000 m and stations for which the difference between orthometric height and the model orography level is also less than 1,000 m are considered for the subsequent analysis since ZWD reduction for height differences greater than 1,000 m can cause gross errors.

After eliminating the stations located in areas where the comparison with the model may be inadequate (107 in total), 360 stations are left for analysis. For this subset, the means of the differences are in a range of 0–14 mm in absolute value, with 15 stations having values greater than 1 cm, representing 4% of the total analyzed stations. This shows that about 96% of the stations have sub-centimeter precision, regarding the mean of differences with the ERA5.

Regarding the standard deviations of the ZTD differences, considering the original set of 467 stations, the range is from 5 to 50 mm and the mean of standard deviations is 16 mm, with 55 stations greater than 2 cm and eight stations greater than 3 cm, representing 12% and 2% of the total, respectively.

For the subset of 360 stations selected to analyze the means of the ZTD differences, the standard deviations are in a range of 5–40 mm (only one station has a standard deviation of 50 mm in the original set, so the intervals are practically the same), and the mean of standard deviations remains 16 mm, with 36 stations greater than 2 cm and three stations greater than 3 cm, representing 10% and 1% of the subset, respectively. This analysis shows that the problem verified for the means does not happen for the standard deviation. Figure 4 shows the behavior of the differences between the ABRA (panel a) and COEC (panel b) stations, which are examples of stations that have a high bias, but a stable time series with a low standard deviation of 11 and 9 mm, respectively.

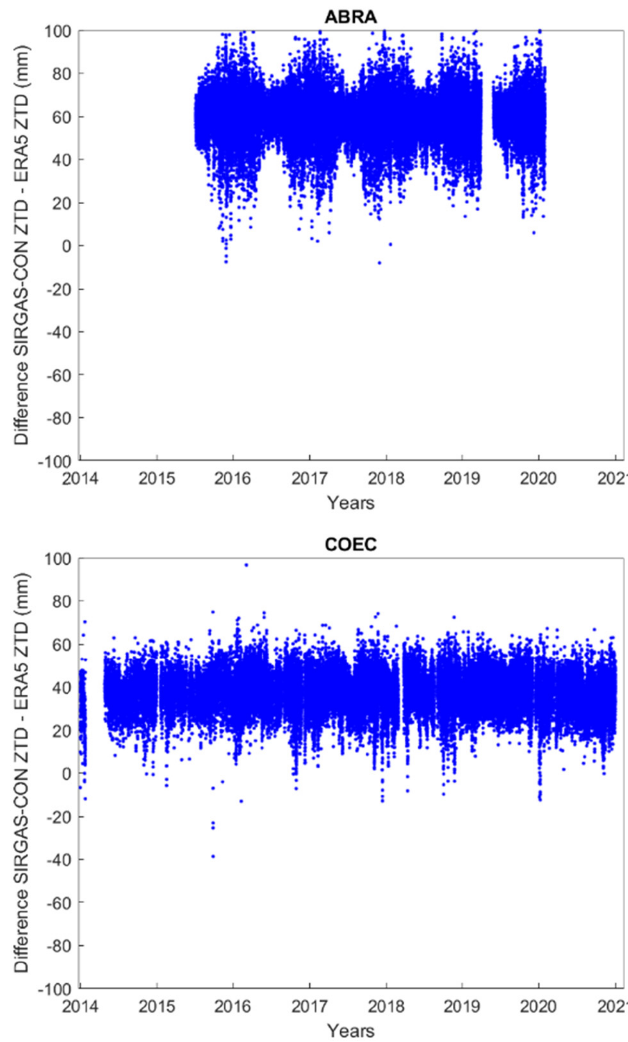

Figure 4: SIRGAS-CON ZTD and ERA5 ZTD differences for stations (a) ABRA, with a mean of 59 mm and standard deviation of 11 mm, and (b) COEC, with a mean of 37 mm and standard deviation of 9 mm.

The root mean square (RMS) of the ZTD differences considering the original set of 467 stations have a range from 5 to 140 mm and the mean value of the set of RMS of 20 mm, with 130 stations greater than 2 cm and 35 stations greater than 3 cm, representing 28 and 8% of the total, respectively.

For the subset of 360 stations, the RMS is in a range from 5 to 40 mm and the mean value of the set of RMS decreases to 17 mm, with 55 stations greater than 2 cm and five stations greater than 3 cm, representing 15% and 1% of the subset, respectively. It is noted that the percentage of stations with RMS greater than 2 cm on the selected set decreases to almost half that on the original set.

These statistics are partly in agreement with the results of similar studies, such as Fernandes et al. (2013a,b), which present for a set of 11 IGS/EUREF Permanent Network (EPN) common stations the mean and standard deviation of the ZTD differences between GNSS and ERA-Interim, the preceding ECMWF reanalysis model, of 4 and 12 mm, respectively. In the same study, the standard deviation of the ZTD differences has a range from 8 to 14 mm. It is important to highlight that the set of stations analyzed in this work is much larger and that the GNSS stations of the previous work are located in the temperate zone, while most of the SIRGAS-CON stations are located in the tropical zone, where the ZWD is much more variable and can reach much higher values, which may cause the much larger range of the standard deviation.

The variability of the standard deviation of the ZTD differences between SIRGAS-CON and ERA5 is shown on the map in Figure 5, for all 467 stations with available

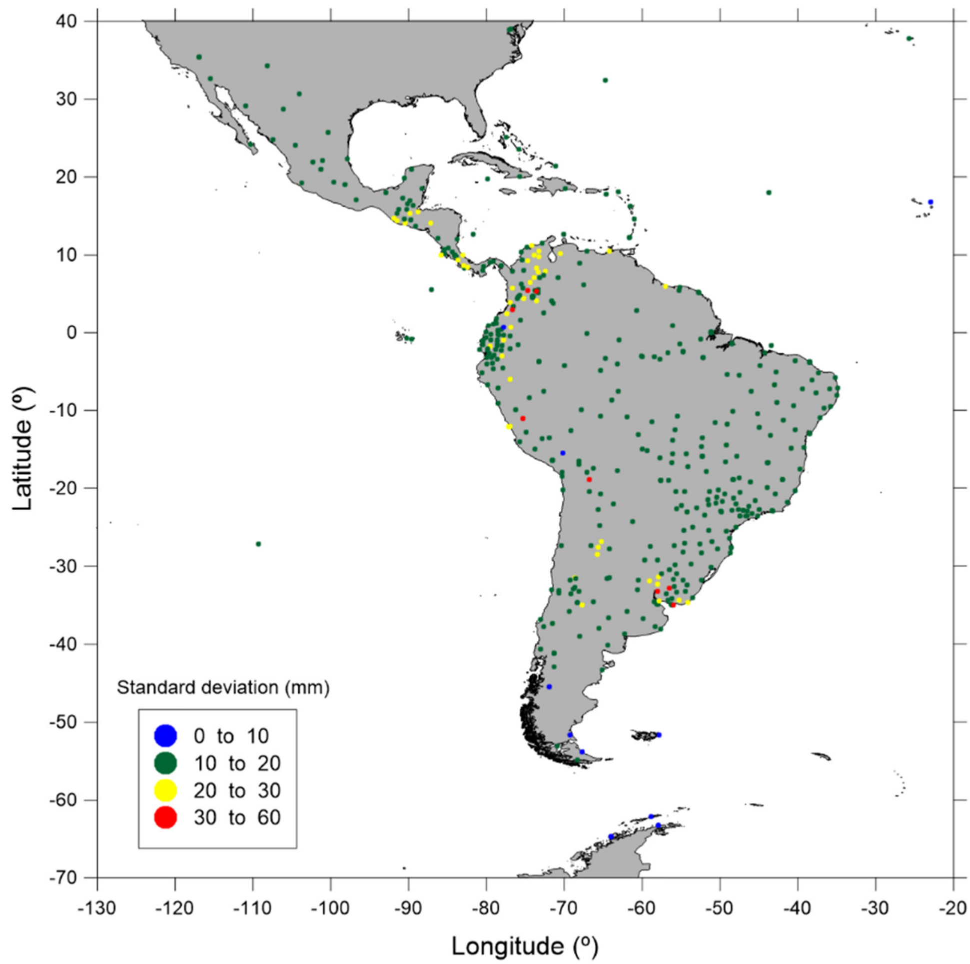

Figure 5: SIRGAS-CON stations with colors representing the standard deviation of the differences between SIRGAS-CON ZTD and ERA5 ZTD for each station.

ZTD. The green points represent the stations with a standard deviation between 10 and 20 mm, the interval that contains most of the stations.

The blue points represent stations with a standard deviation lower than 10 mm. The regions that have most of the stations with standard deviations in the lowest range, represented by the blue points, are the extreme south of South America, in the Patagonia region and the Antarctic continent. The yellow and red points represent stations with the highest standard deviations. There is a greater concentration of these stations in the equatorial zone, and some are in other regions, such as Uruguay. The pattern of the standard deviation shown on the map is in accordance with the natural ZWD variability, which is greater in the tropics and lower in areas closer to the poles. However, those stations with a high standard deviation in Uruguay are not supposed to have those values, since they are located in the temperate zone, which indicates that these stations may have some problems with their GNSS ZTD solutions.

Although the ZHD corresponds to 90% of the ZTD, it has a standard deviation of up to 3 cm, and it is much more constant throughout the atmosphere and easier to model than the ZWD, which corresponds only to 10% of the ZTD and has a standard deviation value of up to 15 cm (about five times larger than that of ZHD), evidencing that it is much more variable and difficult to model, with values ranging from 0 to 50 cm (Fernandes et al. 2021). Therefore, most of the ZTD variability comes from ZWD.

The stations located in latitudes inside or near the polar zones have a lower and less variable ZTD, since the water vapor in the atmosphere in this region is also lower and less variable, while the opposite happens in the tropics and close to the equator, where the water vapor becomes larger and more variable. Figure 6 shows the OHI2 (panel a) and LIMN (panel b) stations. The OHI2 station is located in Antarctica (63° 19′ 15.960″ S, 57° 54′ 4.680 W″) and has a continuous time series over the years, and it is a good example of a stable station that has ZTD differences between both sources agreeing very

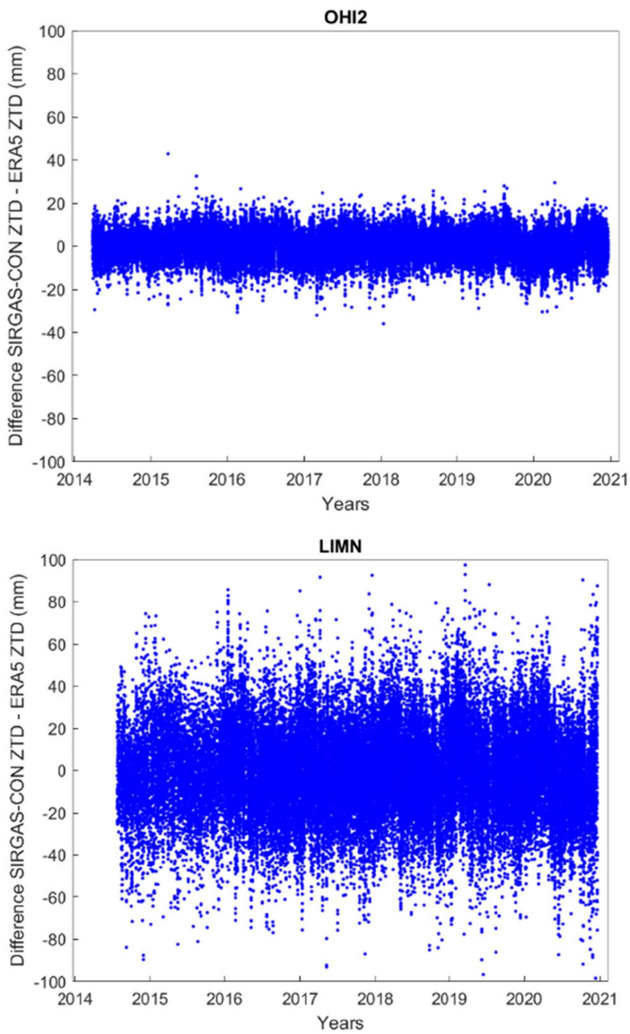

Figure 6: SIRGAS-CON ZTD and ERA5 ZTD differences for stations (a) OHI2 and (b) LIMN.

well, with a mean very close to zero and low dispersion (standard deviation of 6 mm). In contrast, the LIMN station, located in Costa Rica, is in the tropical zone (9° 59′ 35.125″ N, 83° 01′ 34.930″ W) and has also a continuous and stable time series, with a mean that is also close to zero but high dispersion (standard deviation of 20 mm). This exemplifies the variation of water vapor as the latitude changes.

The regions closer to the equator are warmer and wetter and have the highest ZWD absolute values (Fernandes et al. 2013a,b). Southwards of the tropics, as the latitudes increase, the amount of water vapor in the atmosphere decreases as well as its variability, so it is expected that the standard deviation of the corresponding ZTD differences also decreases.

On the map in Figure 5, it is possible to observe some stations with a high standard deviation greater than 20 mm in Uruguay and along the west of South America. This can indicate the presence of instrumental errors, processing errors or even errors in station coordinates (the coordinates used are from SIRGAS-CON log files, also available on the SIRGAS webpage [SIRGAS 2022]), since they are located in the temperate zone and the standard deviations are expected to be lower.

The stations UYPT and UYSO, as shown in Figure 7a and b, respectively, have a stable series for most of the period, with an expected dispersion caused by the seasonal signal, characterized by an increase in the ZTD variability in the summer and a decrease in the winter, but there is a period in the time series when the dispersion deviates from their normal pattern and remains with very large ZTD differences until the end of the time series. These stations have a high standard deviation due to

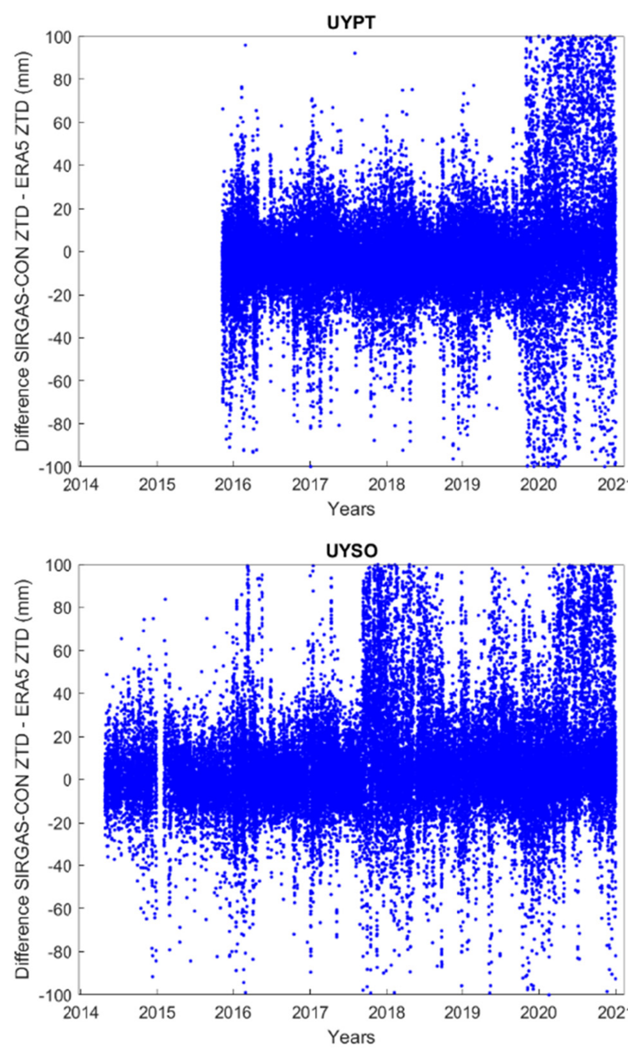

Figure 7: SIRGAS-CON ZTD and ERA5 ZTD differences for stations (a) UYPT and (b) UYSO.

these periods of high dispersion, but the mean of differences is not affected, having values close to zero, since the dispersion of the differences, even in the periods when it is highly dispersed, is often almost symmetrical.

Some stations have short periods of high dispersion of differences, as for BCH1 and CXEC stations, shown in Figure 8a and b, respectively. Despite this inconsistency, the standard deviation is 13 mm for the BCH1 station and 15 mm for the CXEC station, below the mean of standard deviations of the whole set. This happens because there is a low percentage of GNSS ZTD observations in specific short periods of the time series causing the high dispersion. In these cases, graphical analysis proves to be helpful to detect these types of inconsistencies. Another problem detected by graphical analysis which is sometimes not detected by general statistics is a discontinuity, detected by a tendency change in the means of the ZTD differences. These discontinuities can be caused by various reasons, such as changes in data acquisition equipment (antenna, receiver, etc.), changes in the processing method or errors in station coordinates. An example of this case is the AUTF station, which has for its differences with ERA5 a mean of −1 mm and a standard deviation of 11 mm. These statistics can be considered a good indicator but it is possible to see in Figure 9a that at the beginning of 2017 there is a sudden decrease in the values of the differences when compared to the period just before this occurrence. There was also an increase at the beginning of 2018, but the mean did not return to the value it had before the first decrease. The BEJA station, as shown in Figure 9b, is another example of a discontinuity. For this analysis, a LOESS (locally weighted

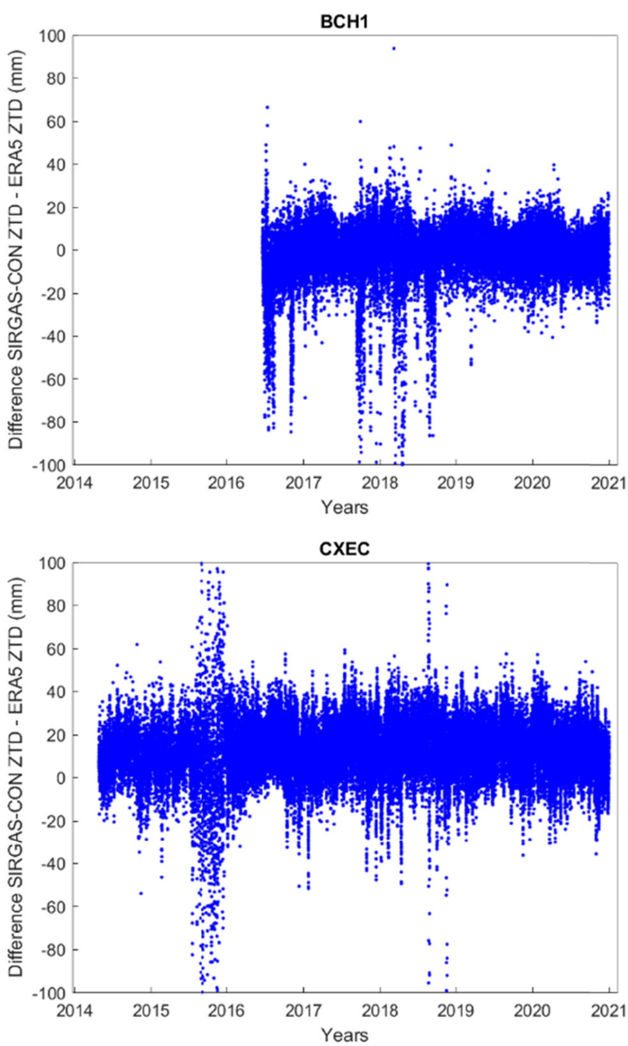

Figure 8: SIRGAS-CON ZTD and ERA5 ZTD differences for stations (a) BCH1 and (b) CXEC.

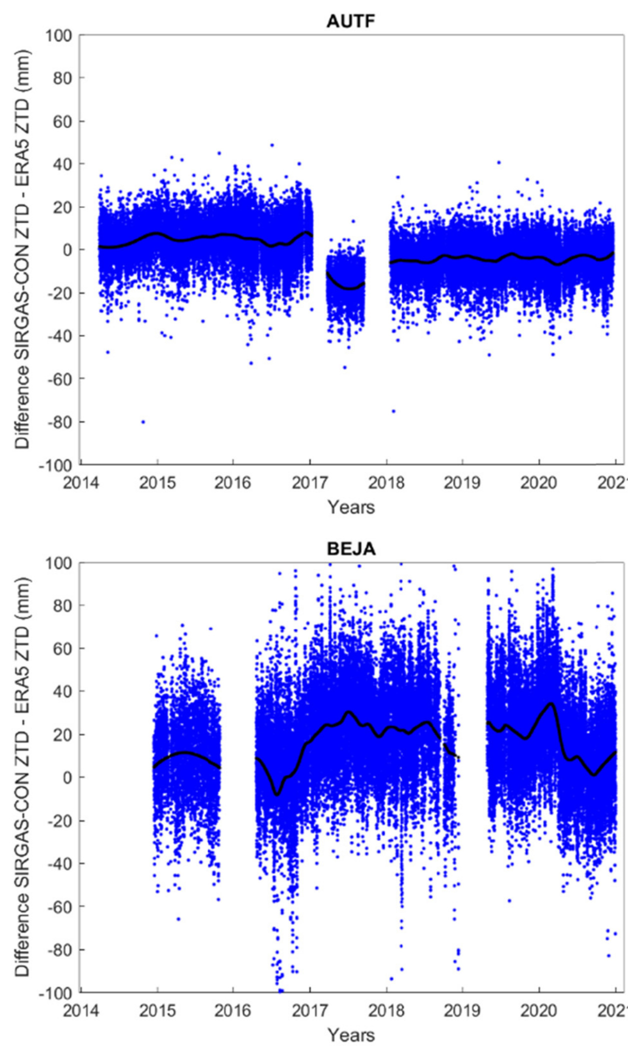

Figure 9: SIRGAS-CON ZTD and ERA5 ZTD differences for stations (a) AUTF and (b) BEJA.

non-parametric regression fitting using a second-order polynomial) smoothing filter (Marsh 2022) has been used to highlight the discontinuities.

3.2 Intercomparison between SIRGAS-CON, ERA5 and IGS ZTD

There are 63 stations in SIRGAS-CON that are also part of the IGS global network. To support the understanding of the differences between SIRGAS-CON ZTD and ERA5 ZTD analyzed in the previous section, a comparison between SIRGAS-CON ZTD and the corresponding IGS ZTD was performed.

Regarding these differences, considering the whole set of 63 stations common to both networks, the means are in the range from −1 to 6 mm. The standard deviations are in the range from 3 to 16 mm, and the RMS are at most 1 mm larger than the standard deviation, except for MDO1, PALM and PALV stations, which are 2 mm larger. The differences between both GNSS solutions are mostly small, but six stations have standard deviations and RMS of ZTD differences greater than 1 cm, shown in Table 2, which may indicate the presence of errors in one of the solutions. The mean values of the means, standard deviations and RMS for this set of stations are 1, 7 and 7 mm, respectively.

These statistics show a good agreement between both GNSS solutions. Results are in agreement with other studies, as in Fernandes et al. (2013a,b), which present 3 mm in mean and 5 mm in the standard deviation of the ZTD differences in a comparison between different GNSS solutions using 51 IGS and EPN common stations spanning 2002–2009. The same work presents absolute means between 2 and 4 mm and standard deviations between 2 and 7 mm, considering each station individually. Mackern et al. (2020) present 2 mm in mean and 7 mm in RMS using 15 IGS and SIRGAS-CON common stations, spanning 2014 to 2019.

Table 2: Stations with a standard deviation of ZTD differences between SIRGAS-CON and IGS greater than 10 mm

Station	Standard deviation of ZTD differences (mm)
MGUE	10
BOGT	11
FALK	11
COYQ	13
QUI3	14
GOLD	16

The differences between GNSS and model ZTD are usually greater than those between two different GNSS solutions (Fernandes et al. 2013a,b). One of the reasons for the first differences being greater than the second is the need to reduce the ZHD and ZWD derived from the model orography level to the station level, which has an associated error, whereas there is no height reduction in the comparison between different solutions for the same GNSS station from different networks. Figure 10 shows the ZTD differences for station PIE1 when comparing data from the three different sources, showing that these differences have different biases. The bias is associated with the height reduction, while the range of the differences and the seasonal signal are associated with the low capacity of the NWM to describe the peaks of the seasonal signal since the NWM is a smoothed representation of the ZTD field.

A case that presents an inconsistency between both GNSS solutions is the station MGUE, with a period of high dispersion in the differences between SIRGAS-CON ZTD and IGS ZTD from the end of 2016 to the first half of 2018, shown in Figure 11a. An intercomparison of both solutions with NWM helps to find out if these instabilities come from SIRGAS-CON or IGS data. The differences for this station between IGS ZTD and ERA5 ZTD and between SIRGAS-CON ZTD and ERA5 ZTD are shown in Figure 11b and Figure 11c, respectively.

When comparing the three plots, it is clear that the high dispersion in the differences for the aforementioned period is present in the SIRGAS-CON ZTD differences with ERA5 ZTD. It is concluded that the data dispersion comes from SIRGAS-CON ZTD. Another case of instability is the

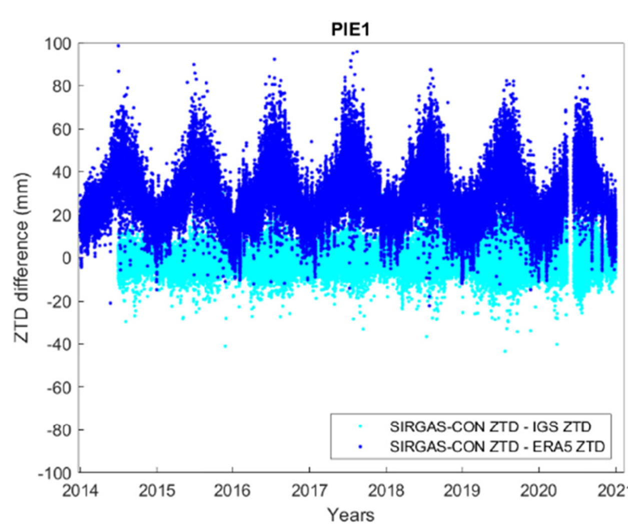

Figure 10: SIRGAS-CON ZTD and ERA5 ZTD (blue) and SIRGAS-CON ZTD and IGS ZTD (cyan) differences for station PIE1.

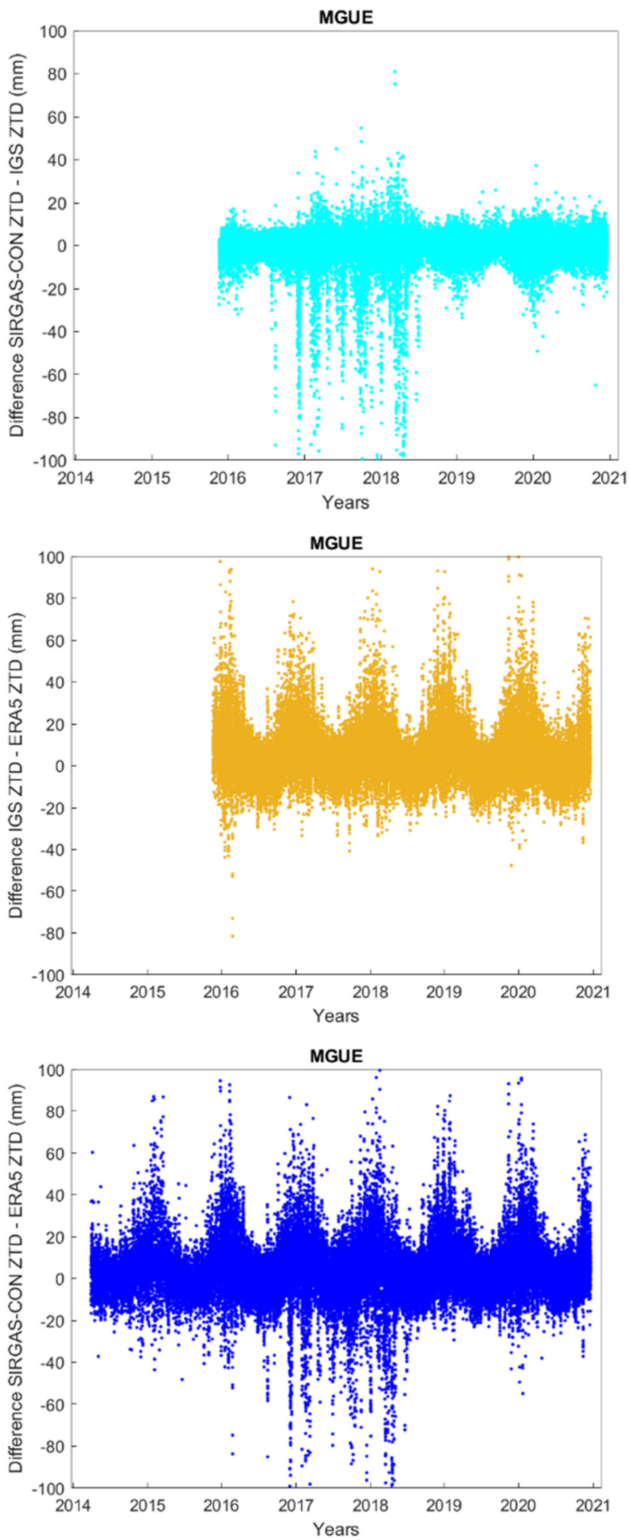

Figure 11: Differences between (a) SIRGAS-CON ZTD and IGS ZTD; (b) IGS ZTD and ERA5 ZTD; and (c) SIRGAS-CON ZTD and ERA5 ZTD for station MGUE.

SALU station, as shown in Figure 12. The three plots analyzed together suggest that the discontinuity comes from IGS ZTD.

This analysis shows that the comparison of ZTD from different types of sources may have different characteristics and magnitudes. The intercomparison helps to understand these characteristics and come to the conclusion that a comparison just between two different sources may be insufficient.

4 Results and discussion

A set of 467 SIRGAS-CON GNSS stations was considered for ZTD analysis. First, the mean differences between SIRGAS-CON ZTD and ERA5 ZTD were analyzed. Some stations have a bias but a stable time series (symmetrical around the mean and without highly dispersed data). The bias generally occurs because of the height reduction from model orography level to GNSS station heights. Large biases may be associated with locations where the difference between both levels is more than 1,000 m or stations located in zones where the NWM may not fit well, such as mountainous regions, which means the bias does not occur because of bad GNSS ZTD data. A subset of 360 stations not in these conditions was analyzed and showed that the means of ZTD differences decreased, but the standard deviation did not change significantly, since the bias is a systematic error that affects only the mean (and consequently the RMS). However, it is important to show this analysis and highlight this problem since the total set has stations at different locations and conditions, and in many of them, it is not possible to obtain ERA5 ZTD without the error caused by the height reduction or model inadequacy.

Since the goal of this article is to evaluate the quality and stability of GNSS ZTD data and the identified bias is not a GNSS error, the whole set of 467 stations is still considered for final analysis, focusing only on highly dispersion periods and discontinuities in time series, which are instabilities in the data set, even if some of them present a noticeable bias caused by height reduction or NWM inadequacy in mountainous zones.

Considering the whole set of 467 analyzed SIRGAS-CON stations, 31 stations, as shown in Table 3, were identified as having some period of high dispersion of the SIRGAS-CON ZTD differences with the ERA5 ZTD, which

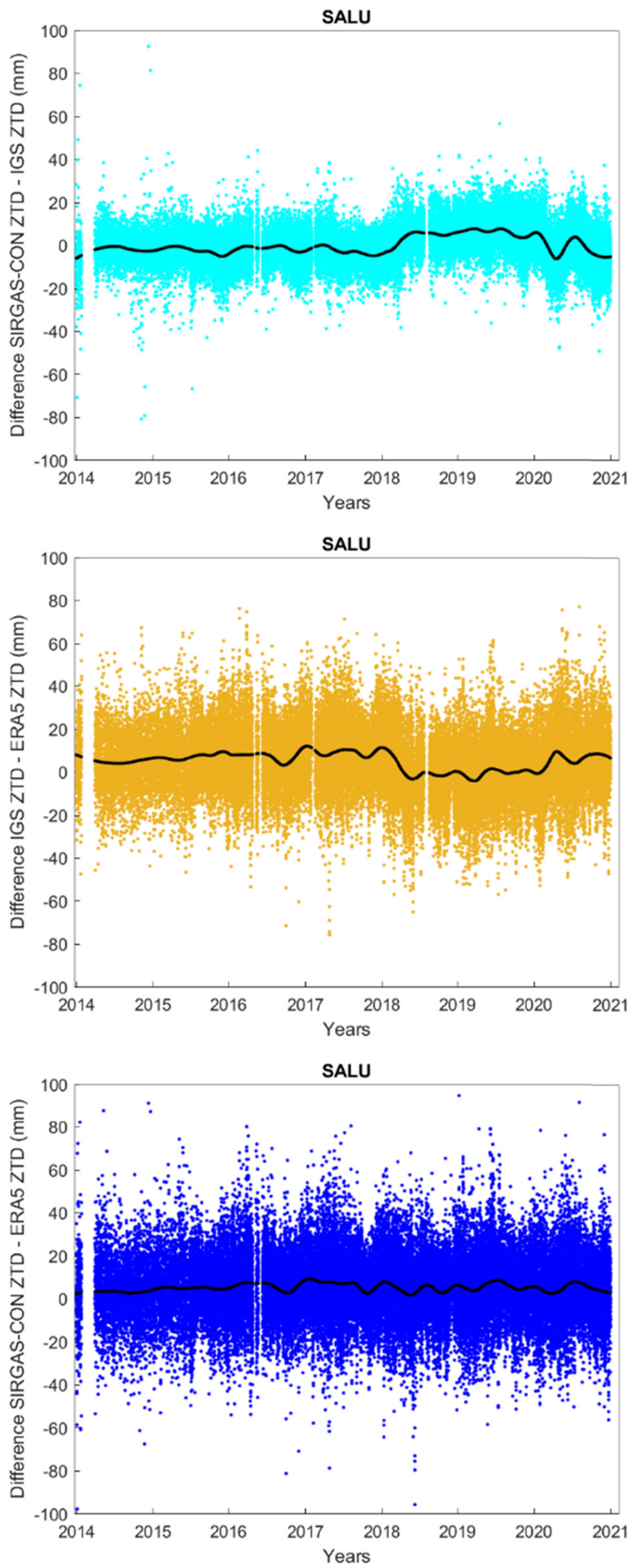

Figure 12: Differences between (a) SIRGAS-CON ZTD and IGS ZTD; (b) IGS ZTD and ERA5 ZTD; and (c) SIRGAS-CON ZTD and ERA5 ZTD for station SALU.

Table 3: GNSS stations with periods of high dispersion in ZTD

GNSS station	Period of high dispersion
BCH1	2016, 2017–2018
CXEC	2015
DORA	2014–2021
ECEC	2015–2016, 2017–2018
ESQU	2016–2018
GOLD	2017
GUAY	2020
GZEC	2015
JBAL	2019–2020
JU03	2018–2020
MGUE	2016–2018
MRLS	2018–2019
MZAL	2020
MZGA	2019–2020
NEVA	2015–2020
OAX2	2017–2018
OSOR	2016–2018
PJEC	2015
RDEO	2016–2017
TEG2	2017–2018
USCL	2020–2020
UYCO	2019–2020
UYIF	2019–2020
UYLA	2019–2020
UYLP	2017–2018, 2019–2020
UYPA	2017–2018, 2019–2020
UYPT	2019–2020
UYSA	2019–2020
UYSO	2017–2018, 2019–2020
UYTA	2017, 2019
YOPA	2015

corresponds to 7% of the whole set. Half of these stations identified as problematic are located in Uruguay (9 stations) and Argentina (7 stations). The map in Figure 13 shows the spatial distribution of these stations, and it is possible to see small groups of nearby stations in the regions of Argentina, Chile, Colombia, Equator and Uruguay. It is also possible to note that the period of high dispersion is almost always the same (2017–2018 and 2019–2020) for most stations located in Uruguay and Argentina. These results suggest that this seems to be related to the data processing at the centers responsible for processing data for these countries over the mentioned period.

Removing the stations present in Table 3 from the set of 467 stations, the generated subset of 436 stations has a standard deviation of ZTD differences in the range of 5–27 mm, a decrease of 23 mm. The mean of standard deviation remains 16 mm.

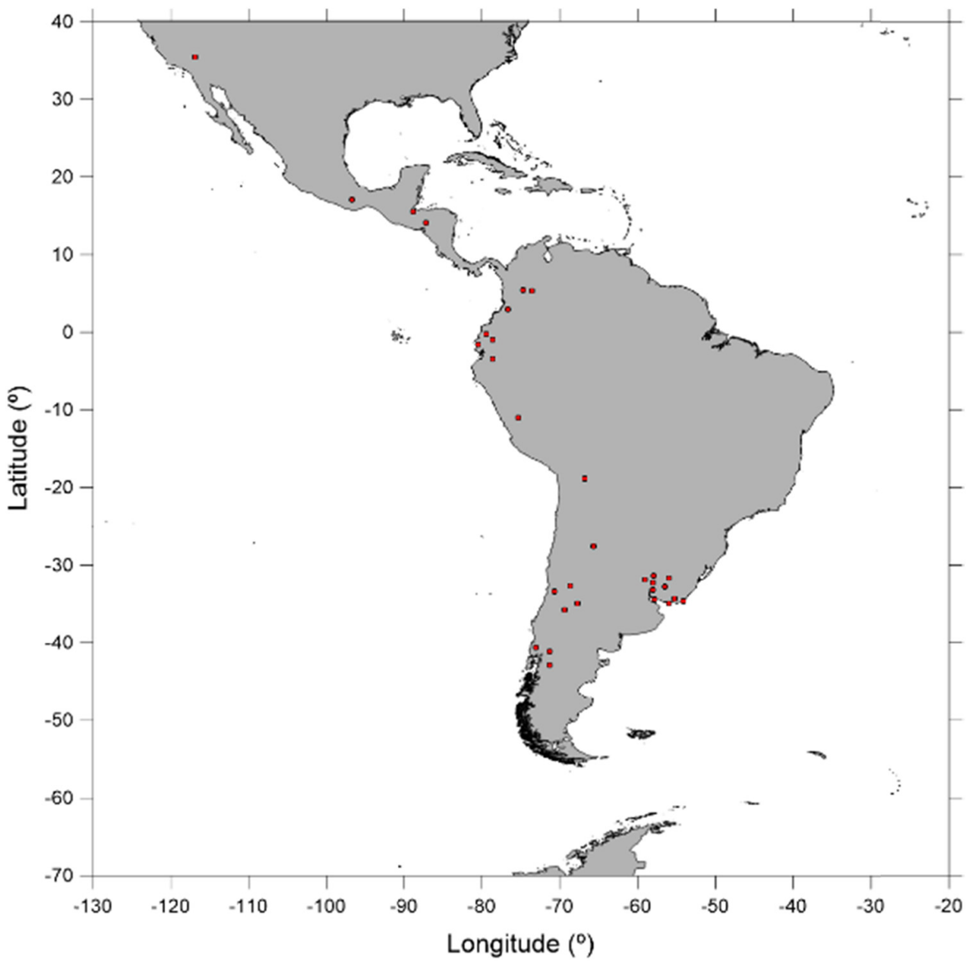

Figure 13: Distribution of SIRGAS-CON stations with some period of high dispersion in the ZTD differences.

Sixteen stations were identified as having some period of discontinuities in the means of ZTD differences, as shown in Table 4, which corresponds to 3% of the original set. Colombia has the largest number of stations identified in this case, with seven stations, corresponding to 44% of this subset. The map in Figure 14 shows the spatial distribution of these stations, and it is possible to see that most of them are located in the north and northwest of South America. In some cases, these discontinuities may be attributed to changes in the processing methodology in the associated processing centers.

Bringing together all the stations of both cases (high dispersion and discontinuities), they represent 10% of the whole set considered for the final analysis, which means that using the ERA5 as a reference, no instability problems were found in 90% of the SIRGAS-CON stations. It is important to emphasize that some stations have interruptions in the time series and periods with few

Table 4: GNSS stations with periods of discontinuities in ZTD

GNSS station	Period of discontinuity
AGCA	2014–2020
ALBE	2019–2020
AUTF	2016–2017, 2017–2018
BATF	2014–2020
BEJA	2016–2020
BNGA	2017–2018
CALL	2016–2018
CLEC	2016–2018
CUCU	2015–2020
ESMR	2016–2019
NEIA	2016–2017
NJEC	2016–2020
PI01	2015–2020
SINC	2016–2017, 2020
TINT	2014–2016
VALL	2019–2020

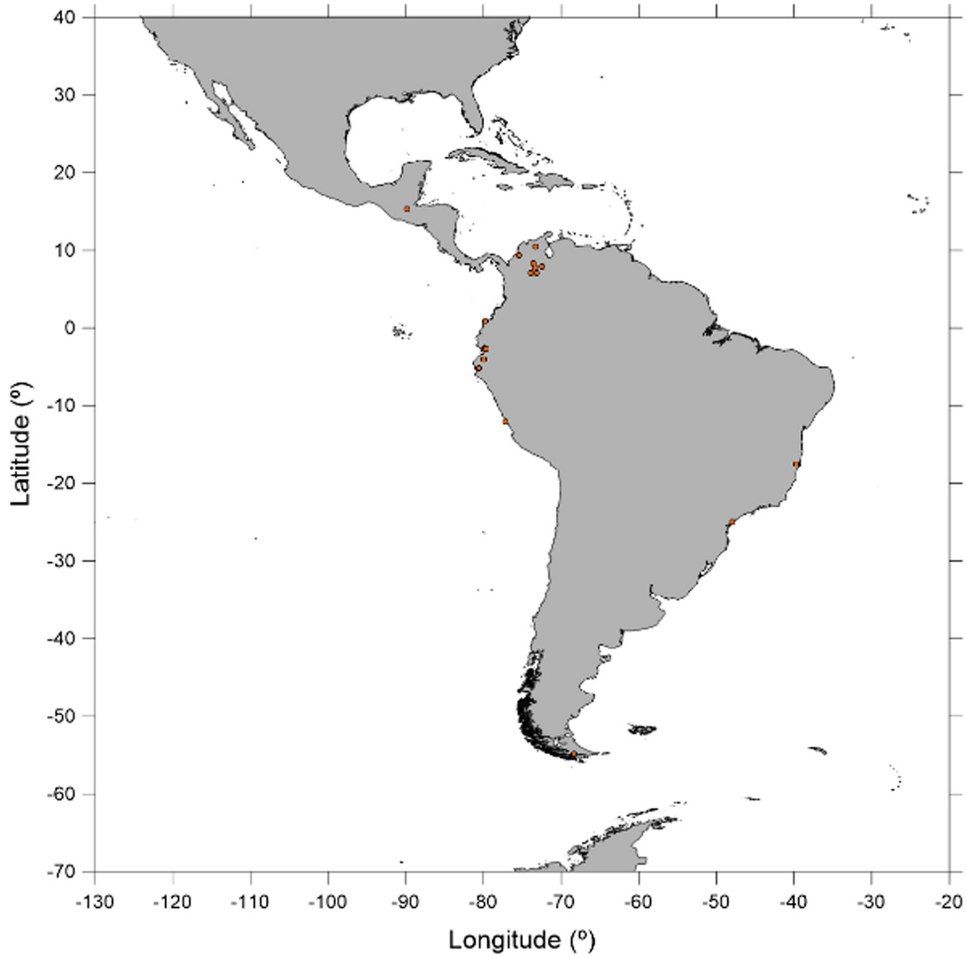

Figure 14: Distribution of SIRGAS-CON stations with some period of discontinuity in the ZTD differences.

data that make this type of analysis not possible, and no conclusion can be drawn for them.

5 Conclusions

The main objective of this work was to evaluate the quality and stability of the SIRGAS-CON tropospheric products using ERA5 as a reference. A comparison between SIRGAS-CON ZTD and ERA5-derived ZTD was performed, as well as an intercomparison between SIRGAS-CON, ERA5 and IGS ZTD to support the understanding of the differences when comparing ZTD from different sources: model and GNSS, the latter from different networks and processing centers.

Although the NWM is a good source to perform this assessment, it has its limitations, such as the need to reduce the ZWD due to height differences between the model's orography level and the GNSS station orthometric height or due to model inadequacy in zones where its resolution may not be able to describe variations caused by high topographic gradients, leading to a bias in the ZTD differences. This is a problem inherent to the ZTD height reduction, which means that it is not associated with bad GNSS ZTD data.

On the other hand, highly dispersed data and discontinuities indicate problems in GNSS data. Some periods of high dispersion and discontinuities were identified in the comparison between SIRGAS-CON ZTD and ERA5 ZTD and in the intercomparison with IGS ZTD. In both GNSS networks, a few stations with instabilities were identified.

In SIRGAS-CON ZTD, 31 stations were identified as having some periods of high dispersion in the ZTD differences, half of them in Uruguay and Argentina. Small groups of these stations were identified in Argentina, Chile, Colombia, Equator and Uruguay. The periods of high dispersion for most stations located in Uruguay and Argentina occur in 2017–2018 and 2019–2020. Sixteen stations were identified as having some discontinuities, and most of these stations are located in the north and northwest of South America, with seven of them located in Colombia.

The final conclusion is that about 90% of SIRGAS-CON stations reveal to provide reliable ZTD, without any significant instability or inconsistency.

This work shows that it is important to perform a continuous ZTD data quality assessment and monitoring to ensure the quality and stability of the data required for use in various applications. Data instabilities can be an indicator of the presence of occasional or systematic errors, which can be caused for various reasons, such as changes in data acquisition equipment (antenna, receiver, etc.), changes in the processing method or errors in station coordinates. It is expected that the periodic monitoring and assessment of the data using different methodologies will help detect and mitigate possible problems and that these will be corrected, leading to improved SIRGAS-CON ZTD products.

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