Comments on “Comparison of GNSS integrated water vapor and NWM reanalysis data over Central and South America”

The authors would like to thank both anonymous reviewers for their contributions, which have enriched our work. We have taken all their comments and suggested corrections and we have completely changed the manuscript in the title and structure as well as in the organization and quantity of contents and results we had shown.

In brief we enumerate the most important modifications present in this new version of the manuscript:

a) the classification of the stations following the geopotential height difference (small, large and critical) was dismissed and the complete set of stations was analyzed as a whole. Thus, new tables, figures and plots were adequate to this.

b) Geopotential heights were changed by geopotentials [m^2 s^{-2}] and the nomenclature was also changed: z lower case instead of z upper case.

c) Figure 1 was eliminated

d) New table 1 shows geopotential GNSS and the static geopotential values assigned by the models to each GNSS site. The geopotential for ERA Interim and geopotential for MERRA2 come from a bi-linear interpolation of the given static geopotential values at the 4 grid points surrounded the GNSS site.

e) A discussion about the behavior of the mean IWV from the reanalysis models with respect to the mean IWV_{GNSS} highlights overestimations and underestimations is incorporated. New plots are also incorporated to easily follow the discussion of the new findings.

f) A new Table 3 was included in order to demonstrate the robustness of our numerical integration method for reproducing IWV values at ERA Interim grid points around each GNSS site. For this calculation we used the q and t data (specific humidity and temperature) given at 37 atmospheric pressure levels. This q, t and p set is the same data used for the calculation of the integral correction.

g) Likewise, and following the suggestion, new figures were incorporated to improve the visualization of the results of the comparison between the models and GNSS, prior to the application of the integral correction.

h) The scheme of application of the correction for a given example was clarified in its caption and through new text incorporated in the main body of the manuscript.

i) The correction is presented with a new equation independently of the integral definition of the IWV. Moreover, the different possible signs for the correction are included in this new mathematical expression.

j) The previous classification by height differences (small, large, critical) is sketched out without mentioning it in the new presentation of the results. The residuals of the differences (IWV_{GNSS} -$IWV_{ERA\ Interim}$) before and after applying the integral correction are shown in a new figure. The new figure also shows the results for cases where the model geopotential is located above the GNSS geopotential (right column) and below the GNSS potential (left column).

k) Also following the suggestion, the title was changed since the region of South and Central America only refers to the GNSS sites available for this work and we do not perform any analysis of the IWV behavior in the region.

Following, the detailed answers to each of the reviewers:

Answers to Anonymous Referee # 1:

Application of the correction

This comment was considered and the integral correction strategy was applied to the whole set of data. Effectively, as you affirmed, the correction applied to the stations formerly classified as “small” is slight but still it is an improvement.

Definition of the correction

The correction was defined independently of the integral definition of IWV. Both negative and positive results are included in equation (7) because the sign is given by the difference between atmospheric pressure values (P_{GNSS} - P_{NWM}). For a sake of clarity some paragraph were also included and a better explanation of the example (now Figure 3) is also given.

Computation of the correction

According to the recommendations received by both reviewers, the structure and presentation of the work has changed. We have placed in the methodology section: the calculation of the GNSS geopotential from the geodetic coordinates of the station, the comparison of the mean values of both models with respect to the mean values IWV_{GNSS}, as well as the quantification of the geopotential differences and a brief summary of the method for calculating the correction.

The details of the calculation of the correction are presented in the following section and finally the results section only presents results after having applied the correction.

Thus, the way we compute and applied the proposed correction was clarified in the main text. Moreover, the suggestion of this reviewer was taken into consideration and the numerical integration procedure was tested for the whole set of stations. In the new Table 3 the mean values of the difference IWV from ERA Interim and the same IWV from a numerical integration of over q at each grid point is shown. The integral is computed from 1 hPa till the static geopotential height at each grid point and we used data given at 37 pressure levels from ERA Interim. Each of the 4 columns correspond to the 4 grid-point around the GNSS station. The averages and standard deviations were computed over the period 2007-2013.

In addition, we have also calculated the alternative suggested by this reviewer:

We have computed the integral over q from 1 hPa till the geopotential corresponding to GNSS at the 4 grid points surrounding the GNSS station. Then the value at the GNSS site was calculated using a bi-linear interpolation. However, given that the results proved to be very similar to our procedure (both the mean values and their dispersions), we have decided to omit them in favour of the extension of the work and given that this strategy does not add up different results.

Note that this strategy differs from the integral performed at grid points from 1 hPa to the static geopotential of each point. These results were incorporated as before mentioned in Table 3.

Temporal interpolation:

A paragraph was included to explain how the different time intervals of the datasets were handled.

Specific comments:

1. L. 22-23 abstract

The discussion was included in the main part of the manuscript

2. P. 2 L. 22

Corrected. A new sentence was added

3. P. 3 L 21-22 and P. 4 section 2.1

Following your advise we just explain the main characteristics of the data set and removed the incomplete presentation, we also refer the reader to the work from Bianchi et al, 2016a for further technical details.

5. P. 6 eq. 5

The application of equation 5 is clarified in the text. This is the necessary formula to estimate the atmospheric pressure p at z_{GNSS} as well as at the geopotential of the each grid point around the GNSS site.

These geopotentials (GNSS and the 4 grid points) are not necessarily coincident (generally they are not) with the geopotential correspondent to the 37 given pressure levels. As a matter of fact temperature (T) and pressure (p) data at each level are necessary to compute the p unknown at each geopotencial by using eq. 5. The unknown temperature at these geopotentials is estimated by assuming the rate 0.006499 °K/m. Thus, the unknown temperature is given by the numerator of Eq. 5.

6. P. 7 L 22

Yes, "interannual" averages refer to the mean value over the complete period 2007-2013. The sentence was clarified and this terminology avoided.

7. Section 4.1

Following your suggestion the tables were reworked and also graphics were added to enrich the comparison. Thank you.

8. P. 8 L. 8

The expression "model failure" was eliminated. The section was rewritten.

9. P. 8, L 9

This part was removed. The classification in: small, critical and large was dismissed.

10. P 9 L. 29 (and eq. 5)

The methodology section was rewritten and it includes the explanation of Δz. On the other hand the meaning of δz, within equation 5, was clarified.

11. P. 10. L. 3

We emphasize this point with more discussion and a new figure

12. P 18

The figure was removed

Technical corrections

1. P1 L. 22

The abstract was rewritten.

2. P. 2 L. 3

Corrected

3. P.4 L.9

removed from the main text

4. Section 2.1.1 should probably be section 2.2

Corrected

5. to 8.

These parts were eliminated from the main text

9. P. 21 former Fig 4

This figure was eliminated since its purpose was to show the behavior of the stations classified as small for not applying there the correction.

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Answers to Anonymous Referee # 2:

Reviewer #2 made all comments and corrections in the text. Because the main text has changed dramatically, we will answer here the questions that need further explanation since the grammatical errors disappeared when rewriting or eliminate those parts of the text.

***Page 3:* #5: vague statement.**

The exact quantity of years was included in the text

***Page 3:* #6: in Geodesy, we usually designated H for geopotential height and Z for the third component of the Cartesian coordinate system**

Yes, it is true but some authors also designate H for the orthometric height in order to distinguish it from h the ellipsoidal height. Therefore, we decided to adopt z (lower case) and express the differences in terms of geopotential (not geopotential height). In this way, we use the data from the models as they are provided (geopotential in m^2/s^2) and only the GNSS height has to be converted.

***Page 3:* #8-9 why 100 m and not 90 m, 110 or another value?**

These comments were taken into account and the entire available dataset was studied without discrimination.

Page 4: ***#1 to #4.***

The description of the geodetic processing was incomplete and resulted unclear. Because we used IWV from GNSS from a previously published study, we reformulate the section including just the reference of the source and the mean characteristics of the dataset.

Page 4: #*5*

A mention to the partial evaluation of MERRA2 was included.

Page 5: #1.to #11 ; Page 6: #5 to #7; Page 7: #4 to #6, #8

The sections *Methodology* and the subsection *Computation of the integral correction* were rewritten. For a sake of clarity, the different paragraphs were reordered and some other sentences added.

In this new text we took into account the items highlighted by the reviewer:

A clarification of how the geopotential GNSS was calculated from geodetic data,

An explanation about how the geopotential GNSS (z_{GNSS}) and the static geopotential data from the models at the 4 grid points (z^{i}_{NWM}) are related. We also explained how we computed p, t and q at z_{GNSS} and at z^{i}_{NWM} . Or in other words, an explanation of how the formulas were used.

We also described how the correction is calculated and how to take into account the sign of the correction.

We also highlighted which is the difference between Δz and δz.

Finally, A more detailed description of the example (see Figure 2) was included

Page 6: #1 and #2

The former discrimination in small, large and critical height differences was dismissed in this new manuscript.

Page 6: #3 and #4

Given that any structure smaller than the resolution of the model could not be evidenced and considering that many of the GNSS stations of the available dataset are in mountain areas, the model with the smallest grid was chosen. It is expected that stations located near or at mountainous regions will suffer great height changes in short distances. We assume that the model with the finest grid can better reflect this situation. Moreover, we better explained why we also took into account results from Zhu et al. (2014) to back up this decision.

Page 7: #7

The suggested reference was incorporated

Page 7: #9 to #11; Page 8: #7, Page 9: #1, Page 10: #1

The section Results was rewritten and now it incorporates the old section Application of the integral correction. Then, it includes only the results after the application of the integral correction.

On the other hand, the comparison between IWV_{GNSS} and IWV_{NWM} was moved to the section Methodology.

The title was changed.

<u>Page 10:</u> #2

The section discussion and conclusions was rewritten too. The agreement with the state-of-the-art literature was also highlighted.

About originality of the work: although the application of an altitude correction is not new, in fact it is commonly accepted and silently assumed, it is not widely studied. In other words, the statistical quantification of the differences between IWV from NWM and GNSS is not extensively known.

In this paper we offer an analysis of the differences that users of IWV data from NWM in South and Central America might encounter if they intend to use such data as a substitute for IWV_{GNSS} values.

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Comparison of GNSS integrated water vapor and NWM reanalysis data over Central and South America

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Abstract. We compared and analyzed data of vertically Integrated Water Vapor (IWV) from two different re-analysis models (ERA-Interim from ECMWF and MERRA-2 from NASA's Global Modeling and Assimilation Office) with respect to IWV values from Global Navigation Satellite Systems (GNSS) at 53 stations of Central and South America during the 7-year period from January 2007 till December 2013.

The comparison was performed taking into account the geopotential height differences between each GNSS station and the correspondent values assigned by the models. Thus, the set of GNSS stations was divided into 3 groups: Small, Large and Critical height difference stations. Moreover, the performance of the re-analysis models was also analyzed by using an additional classification of three levels according to the mean IWV ($\overline{IWV}$) value expected at the station: $\overline{IWV} > 30\ kg\ m^{-2}$, $12\ kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$ and $\overline{IWV} < 12\ kg\ m^{-2}$.

Both models ($IWV_{ERA-Interim}$ and $IWV_{MERRA-2}$) offered a very good representation of the IWV from GNSS values (IWV_{GNSS}) for stations with a Small height difference (smaller than 100 meters). That is to say, the differences between the mean values of IWV from GNSS ($\overline{IWV}_{GNSS}$) with respect to the IWV averages from both re-analysis models are always below 7 % of the $\overline{IWV}_{GNSS}$ in the worse case.

In general, the discrepancies between the re-analysis models with respect to IWV_{GNSS} raise as the geopotential height difference between the GNSS station and the static geopotential height interpolated from the models grows. Effectively, the difference between IWV_{GNSS} and IWV from the re-analysis models can be as large as 10 $kg\ m^{-2}$ for stations with a critical height difference (larger than 500 meters). For this reason, we proposed a numerical correction that compensates the effect of the geopotential height difference and the results were tested with values from ERA-Interim.

The suggested correction was successful and reduces the differences $|IWV_{GNSS} - IWV_{ERA-Interim}|$ to less than a 7 % of the mean IWV_{GNSS} values. This strategy is especially recommended for stations that were classified as Critical, most of them located in mountainous areas of South America. In the case of Large height difference stations, the correction procedure is not advisable either for a coastal station and/or stations in islands. Generally in those cases, two or more grid point are on the water. Thus, the interpolated IWV value for the re-analysis model will be overestimated. At one hand, if the geopotential height of the model is smaller than the geopotential height of the GNSS station, the subtracting numerical correction would compensate this overestimation of IWV near the water and thus the strategy will represent an improvement. On the other

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hand, if the relationship between the geopotential heights is the opposite, the correction will be additive causing thus a worse agreement between both time series.

Keyboards: 3394 Instruments and techniques; 6904 Atmospheric propagation; 6964 Radio wave propagation.

1 Introduction

Water vapor is an abundant natural greenhouse gas of the atmosphere. The knowledge of its variability in time and space is very important to understand the global climate system (Dessler et al., 2008). Most of the regional comparisons of IWV from GNSS are aimed at validating the technique by comparing with radiosonde and radiometers where available. A complete example of this is the work of Van Malderen et al. (2014) who compared IWV GPS (Global Positioning System) with IWV derived from ground-based sun photometers, radiosondes and satellite-based values from GOME, SCIAMACHY, GOME-2 and AIRS instruments at 28 sites in the northern hemisphere. Because their comparison is oriented to climatology application, they deal with long-term time series (+ 10 years). The authors asseverate that the mean biases of the GPS with the different instruments vary only between -0.3 and 0.5 $kg\,m^{-2}$ but there are large standard deviations especially for the satellite instruments.

However, some other comparisons examine the IWV_{GNSS} values with respect to the respective estimates from Numerical Weather Models (NWM). If focusing on the application of the current state-of-the-art reanalysis ERA-Interim from the European Centre for Medium-Range Weather Forecasts (ECMWF), both in local and global scale, some recent papers deserve to be mentioned: Heise et al. (2009) used ground pressure data from ECMWF to calculate IWV from 5-minutes Zenith Total Delay (ZTD) at stations without meteorological data available. The authors also validate their results with stations with local measurements of pressure and temperature. They also compare IWV from GPS with respect to IWV from ERA-Interim on a global scale. The authors found that IWV from GPS and ECMWF show well agreement on most stations on the global scale except in mountain regions. They also addressed that temporal station pressure interpolation may result in up to 0.5 $kg\,m^{-2}$ IWV uncertainty if a local weather event happened. That is because of a misrepresentation of ECMWF analysis, especially in the tropics.

Buehler et al. (2012) compare IWV values over Kiruna in the north of Sweden from five different techniques (Radiosondes, GPS, ground-based Fourier-Transform InfraRed (FTIR) spectrometer, ground-based microwave radiometer, and satellite-based microwave radiometer) with IWV from ERA-Interim reanalysis. The processed GPS dataset covers a ten-year period from November 1996 to November 2006. The authors found a good overall agreement between IWV from ERA-Interim and from GPS being the mean of differences -0.29 ± 1.02 $kg\,m^{-2}$. They also point out that ERA-Interim is drier than the GPS at small IWV values and slightly moister at high IWV values (above 15 $kg\,m^{-2}$).

Ning et al. (2013) evaluate IWV from GPS in comparison with IWV from ERA-Interim and IWV from the regional Rossby Centre Atmospheric (RCA) climate model at 99 European sites for a 14-year period. Because RCA is not an assimilation

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model, the standard deviation of the difference RCA-GPS resulted 3 times larger than the subtraction ERA-Interim minus GPS. The IWV difference for individual sites varies from -0.21 up to 1.12 $kg\,m^{-2}$ and the corresponding standard deviation is 0.35 $kg\,m^{-2}$. In this work, the authors also highlight that the models overestimate IWV for sites near the sea.

Bordi et al. (2014) studied global trend patterns of a yearly mean of IWV from ERA-20CM and ERA-Interim. The authors highlight a regional dipole pattern of inter-annual climate variability over South America from ERA-Interim data. According to this study, the Andean Amazon basin and Northeast Brazil are characterized by rising and decreasing water content associated with water vapor convergence (divergence) and upward (downward) mass fluxes, respectively. Besides, the authors also compared IWV from ERA-Interim with the values estimated at 2 GPS stations in Bogotá and Brasilia. Such comparison on monthly timescale made known a systematic bias attributed to a lack of coincidence in the elevation of the GPS stations and the model grid points.

Tsidu et al. (2015) presented a comparison between IWV from a Fourier Transform InfraRed spectrometer (FTIR, at Addis Ababa), GPS, radiosondes, and ERA-Interim over Ethiopia for the period 2007-2011. The study is focused on the characterization of the different error sources affecting the data time series. In particular, from the study of diurnal and seasonal variabilities, the authors addressed differences in the magnitude and sign of IWV bias between ERA-Interim and GPS. They linked this effect with the sensitivity of the convection model with respect to the topography.

Wang et al. (2015) performed a 12-year comparison of IWV from 3 third generation atmospheric reanalysis models including ERA-Interim, MERRA and the Climate Forecast System Reanalysis (CFSR) on a global scale. IWV values from the reanalysis models were also compared with radiosonde observations in land and Remote Sensing Systems (RSS) on satellites over oceans. The authors asseverate that the main discrepancies of the 3 datasets among them are in Central Africa, Northern South America, and highlands.

~~In this paper, we investigate the differences between IWV_{GNSS} resulted from a geodetic process of (GPS + GLONASS) data collected during more than 5 years in South America (Bianchi et al., 2016a) and IWV values given by ERA-Interim and MERRA-2. The comparison was performed taking into account the geopotential height differences (ΔZ) between each GNSS station and the correspondent height values assigned by the models. Provided that both models showed a very good representation of the IWV values for stations with a Small height difference, we used this set of stations with ΔZ smaller than 100 meters, to deeply analyze the expected seasonal behavior according to the inter-annual mean of IWV from GNSS expected at the station. In order to take into account the differences found in IWV values from the models at stations with ΔZ larger than 100 m., we proposed a numerical correction. The strategy was tested for ERA-Interim re-analysis model and it shows to be successful. Section 2 describes the different sets of data used in this study. Follows the explanation of the methodology and~~ the presentation of the results obtained after applying the proposed correction to IWV values from ERA-Interim.

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2 Data

2.1 IWV from GNSS

In this study, the GNSS data is the main source of information for the spatial and temporal distribution of water vapor. Thus, the main variable considered is the IWV estimated from the delay caused by the troposphere to the GNSS radio signals during its travel from the satellite to the ground receiver. The total delay projected onto the zenith direction (ZTD) is usually split into two contributions: the hydrostatic delay (ZHD, Zenith Hydrostatic Delay) depending merely on the atmospheric pressure and the Zenith Wet Delay (ZWD) depending mainly on the humidity. Finally, IWV_{GNSS} can be obtained from ZWD multiplying it by a function of the mean temperature of the atmosphere.

The reference database of IWV_{GNSS} (GPS + GLONASS) used in this study come from a geodetic process over 136 tracking stations in the American Continent placed from southern California to Antarctic during the 7-year period from January 2007 till December 2013 (Bianchi et al., 2016b). Specifically, the data series of IWV_{GNSS} used in this study is restricted to those 69 stations with IWV time series spanning more than 5 years.

The GNSS observations were processing at a double difference level with the Bernese GNSS Software 5.2 (Dach et al., 2015) where all the models and conventions employed are recommended by the International Earth Rotation and Reference Systems Service (IERS). The geodetic process used Vienna Mapping Function 1 (VMF1) (Boehm et al., 2006). The ZTD were represented as 30-minutes linear piecewise estimates and compared with three solutions contributing to the International GNSS Service (IGS) for the repro2 reanalysis. The comparison of ZTD results shows the expected consistency between estimations from the homogeneous but independent analysis. Afterward, to achieve IWV_{GNSS} estimations, it is necessary to subtract the modeled ZHD from the ZTD data in order to obtain ZWD. ZHD are computed following Davis et al. (1985) and considering observed pressure measurements from nearby GNSS stations. Finally, the IWV_{GNSS} values every 30 minutes are obtained from ZWD by using the proportionality constant from Askne and Nordius (1987). More details of the ZTD geodetic processing and the steps to obtain the IWV values are at Bianchi et al. (2016a).

2.1.1 IWV from NWM

The values of columnar Integrated content of Water Vapor (IWV) as reanalysis products from ERA-Interim (Dee et al., 2011) and MERRA-2 (Gelaro et al., 2017; Bosilovich et al., 2015) were evaluated in this study. The horizontal resolutions are $0.25° \times 0.25°$ for ERA-Interim and $0.625° \times 0.50°$ for MERRA-2, respectively. Because ERA-Interim data is given 4 times a day, in order to perform the comparison and even if MERRA-2 gives hourly data, we pick up IWV data from MERRA-2 every 6 hours at 0, 6, 12 and 18 hours of Universal Time.

ERA-Interim is the global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). It covers the period from 1979 up today and supersedes the ERA-40 reanalysis. ERA-Interim address some difficulties of ERA-40 in data assimilation mainly related to the representation of the hydrological cycle, the quality of the stratospheric circulation, and the consistency in time of reanalyzed geophysical fields (Dee et al., 2011).

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MERRA-2 is the successor of The Modern-Era Retrospective Analysis for Research and Applications (MERRA) from NASA's Global Modeling and Assimilation Office (Rienecker et al., 2011). MERRA-2 represents a quality improvement compared with MERRA because of the trends and jumps linked to changes in the observing systems. Additionally, MERRA-2 assimilates observations not available to MERRA and reduces bias and imbalances in the water cycle (Gelaro et al., 2017). Moreover, the longitudinal resolution of MERRA-2 data is changed from $0.667°$ in MERRA to $0.625°$ whereas the latitudinal resolution remains unchanged ($0.5°$) (Bosilovich et al., 2015).

To this application we used the gridded values of the vertical Integral of Water Vapor (IWV) from both re-analysis models. Because the comparison is performed at each GNSS station, a bilinear interpolation of each gridded data set was performed. In addition, we use values of air temperature (T) and specific humidity (q) from ERA-Interim for the calculation of the correction to the IWV values. Both, q and T, are given in 37 levels of atmospheric pressure from 1000 to 1 hPa.

3 Methodology:

3.1 Stations classification criteria

Even when both reanalysis model give gridded values of the vertical integral of the water vapor, the solution provided by each model is linked to its respective geopotential surface invariant. Usually, IWV values are interpolated from the original grid by applying bilinear interpolation. Nevertheless, elevation differences between geopotential height from each model grid and GNSS height must be addressed. Effectively, if the height of a given point from a model is located lower than the position of the receiver, the model integrates a larger column of water vapor and the opposite if the model locates upper than it.

We performed the present comparison establishing a selection criterion according to the difference of geopotential height (Z) between each reanalysis model and the GNSS height at the station. In order to compute the geopotential height of the GNSS stations (Z_{GNSS}) we followed Van Dam et al. (2010) algorithm. First we obtained the orthometric height at each GNSS station by correcting the ellipsoidal height with the EGM08 model (Pavlis et al., 2012). For a given GNSS station, the respective geopotential height from each of the 2 reanalysis models resulted from a bilinear interpolation of each respective gridded dataset.

Thus, if ΔZ refers to the difference between Z_{GNSS} and Z_{NWM} (see Figure 1),

$$|\Delta Z| = |Z_{GNSS} - Z_{NWM}| \tag{1}$$

where NWM corresponds to ERA-Interim or MERRA-2. We classified the whole set of stations in 3 categories: a) Small height difference ($|\Delta Z| < 100m.$) b) Large height difference ($100m. \leq |\Delta Z| \leq 500m.$) and c) Critical height difference ($|\Delta Z| > 500m.$).

Table 1 shows the geodetic coordinates as well as the climate classification of Köppen-Geiger (K-G) (Peel et al., 2007) and the $|\Delta Z|$ classification for both models. Subsequently, we selected the common stations that address the adopted criteria simultaneously in both NWM. Thus the original set of 69 stations is reduced to 53 stations. Figure 2 shows the 53 GNSS stations arrangement according to $|\Delta Z|$ differences with respect to ERA-Interim.

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3.2 Computation of the integral correction

Once we detected the cases in which the application of a correction is necessary, we proceed to describe the proposed integral correction. It will be calculated only for one of the two tested re-analysis models.

Zhu (2014) compare the results of several reanalysis projects with independent sounding observations recorded in the Eastern Himalayas during June 2010. Among all the reanalysis models, ERA-Interim and MERRA were included. The authors analyze temperature, specific humidity, u-wind, and v-wind between 100 hPa and 650 hPa. They found that ERA-Interim showed the best performance for all variables including specific humidity the key variable to produce the integrated water vapor. Even if we tested MERRA-2, which is an improvement of MERRA, ERA-Interim is having a smaller grid. Thus, following Zhu (2014) criteria and taking advantage of a thinner grid, we used air temperature (T) and specific humidity (q) on 37 pressure levels from ERA-Interim data to test the proposed correction. Following we describe how this correction is computed.

The starting data are the GNSS geopotential height (Z_{GNSS}) that is set as a reference, and the value of the geopotential height from ERA-Interim (Z_{model}) obtained after a bi-linear interpolation. According to our classification, these two values are not the same but may differ several hundred meters. Because the geodetic coordinates (ϕ, λ, h) of the GNSS station are known, we can compute the respective geopotential height as (Van Dam et al., 2010)

$$Z_{GNSS} = \frac{g_s(\phi)\, C(\phi)\, h}{g_0\, (C(\phi) + h)} \tag{2}$$

where $g_0 = 9.80665\ m\, s^{-2}$ is the normal gravity at 45° latitudes, the ellipsoidal height (h) is referred to the ellipsoid WGS84 and thus the radius of the ellipsoid at geodetic latitude ϕ is,

$$C(\phi) = \left(\frac{cos^2(\phi)}{a^2} + \frac{sin^2(\phi)}{b^2}\right)^{-1/2} \tag{3}$$

with $a = 6378137m.$ and $b = 6356752.3142m.$ are the semimajor and semiminor axis of the WGS84 ellipsoid, respectively (Hofmann-Wellenhof and Moritz, 2006). Moreover, the value of the gravity on the ellipsoid at geodetic latitude ϕ can be written as (Van Dam et al., 2010).

$$g_s(\phi) = g_E \frac{1 + k_s\ sin^2(\phi)}{\sqrt{1 - e^2\ sin^2(\phi)}} \tag{4}$$

with $e^2 = 0.00669437999014$ is the first eccentricity squared of the WGS84 ellipsoid and $g_E = 9.7803253359m\ s^{-2}$ is the normal gravity at the Equator (Hofmann-Wellenhof and Moritz, 2006) and $k_s = 0.001931853$ (Van Dam et al., 2010).

Afterward, the expression of the pressure at the geopotential height (Z) with respect to a given reference level is (Van Dam et al., 2010)

$$p(Z) = p_0 \left(\frac{T_0 - \lambda\, \delta Z}{T_0}\right)^{g_0/R\lambda} \tag{5}$$

where T_0 and p_0 refer to the temperature and pressure values at a reference level, $R = 287.04\ J\ kg^{-1}\, {}^\circ K$ is the gas constant and $\lambda = 0.006499\ {}^\circ K\ m^{-1}$ is the lapse rate of the temperature, and δZ is the geopotential height difference between Z and the reference level.

Accordingly, given a Z_{GNSS} at each instant, we have to look for the immediate upper geopotential height level from ERA Interim among the 37 available levels. We should consider that at any time the pressure value of each level is constant but it does not necessarily happen the same with the geopotential height.

Let suppose that this level is 27 that corresponds to 750 hPa. Figure 3 illustrates the example. The value of IWV provided by ERA-Interim is the result of the numerical integration of the expression (Berrisford et al., 2011).

$$IWV_{ERA-Interim} = \frac{1}{g_0} \int_{p_1}^{p_s} q(p)\, dp \qquad (6)$$

where g_0 is the standard acceleration of the gravity at mean sea level, $q(p)$ is the specific humidity of the air at the pressure level p and the integral is calculated from the first level (p_1) up to the model surface level (p_s), i.e. up to the static geopotential height (Z_{model}) that corresponds to the station.

Therefore, by using temperature and specific humidity values given at the 2 layers above and below the point of interest, we have to interpolate T and q at the GNSS geopotential level (Z_{GNSS}). Because the pressure value at Z_{model} is not necessarily coincident with one of the given levels, we could also extrapolate T and q in the same way for Z_{model}.

Finally, the ΔIWV is computed as the numerical integral of Eq. (6) between the pressure values at Z_{model} and at Z_{GNSS}. This quantity could be additive if $Z_{GNSS} < Z_{model}$ or subtractive if opposite.

4 Results

The Table 2 shows the inter-annual IWV mean values for the 53 stations of the reduced subset that fulfill the station´s selection criteria by using the $|\Delta Z|$, i.e. ($Z_{GNSS} - Z_{NWM}$). IWV inter-annual averages were computed for GNSS ($\overline{IWV}_{GNSS}$) as well as for both NWM ($\overline{IWV}_{ERA-Interim}$ and $\overline{IWV}_{MERRA-2}$) . Note that MERRA-2 values could be a little more dispersive because of the coarser grid. However, the correlation coefficients between $\overline{IWV}_{GNSS}$ values and the respective ones for both NWM, are higher than 0.95 in most of the cases.

4.1 Analysis of the efficiency of the re-analysis models

In order to analyze the performance of ERA-Interim and MERRA-2, we compared both mean inter-annual averages of IWV ($\overline{IWV}_{ERA-Interim}$ and $\overline{IWV}_{MERRA-2}$) with respect to $\overline{IWV}_{GNSS}$.

Regarding Table 2 for Small $|\Delta Z|$ stations, and focusing on ERA-Interim, the subtractions of $\overline{IWV}_{GNSS}$ minus $\overline{IWV}_{ERA-Interim}$ have different signs but they are smaller than 3 $kg\ m^{-2}$ but RNNA station where it reaches 3.5 $kg\ m^{-2}$. On the other hand, the differences between ($\overline{IWV}_{GNSS} - \overline{IWV}_{MERRA-2}$) never surpass 3.5 $kg\ m^{-2}$. Moreover, generally $\overline{IWV}_{MERRA-2}$ resulted larger than $\overline{IWV}_{GNSS}$ and that overestimation of MERRA-2 can be seen despite the sign of $|\Delta Z|$.

In general for stations classified as Small, IWV mean values from ERA-Interim are closer to mean values from GNSS than MERRA-2. Moreover, the $\overline{IWV}_{NWM}$ disagreement from GNSS values is about a 7 % of $\overline{IWV}_{GNSS}$ for stations with $\overline{IWV} > 30\ kg\ m^{-2}$ and it remains in 7 % for stations with 12 $kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$. Furthermore, there is only one

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station that fulfill the condition $\overline{IWV} < 12\ kg\ m^{-2}$ and its maximum discrepancy is with MERRA-2 reaching $\backsim 6\%$ of the $\overline{IWV}_{GNSS}$.

Among Large $|\Delta Z|$ stations the situation also depends on the $\overline{IWV}$ expected. Thus, when $\overline{IWV} > 30\ kg\ m^{-2}$ the disagreement of MERRA-2 reaches $\backsim 15\%$ of $\overline{IWV}_{GNSS}$ while for ERA-Interim it is about 9 %. In the case of stations that fulfill the condition $12\ kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$, the discrepancies could reach up to $\backsim 35$ % and for stations with $\overline{IWV} < 12\ kg\ m^{-2}$ the disagreement of both models with respect to $\overline{IWV}_{GNSS}$ is below 40 % of this amount. For Critical $|\Delta Z|$ stations the discrepancies of the NWM with respect to GNSS can reach $\backsim 55\%$ of the $\overline{IWV}_{GNSS}$.

In general, we can observe that the percentages of model failures grow as the height differences (ΔZ) become larger. All of the above, we asseverate that the disagreement is the greatest for the stations classified as Critical.

Thus, provided that both models showed a very good representation of the IWV values for stations with a Small height difference, we will focus on such stations to analyze the seasonal behavior of each NWM with respect to IWV_{GNSS}. The objective is to distinguish a systematic lack of agreement between NWM and GNSS, if there are any.

Figure 4 shows the seasonal stacked ΔIWV for both models. Three cases among the Small height difference stations are shown as an example for $\overline{IWV} > 30\ kg\ m^{-2}$ (BELE), $12\ kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$ (LPGS) and $\overline{IWV} < 12\ kg\ m^{-2}$ (FALK). At BELE the differences from MERRA2 are always larger than the ones from ERA-Interim. Such differences also have a different sign indicating that ERA-Interim always underestimates $\overline{IWV}_{GNSS}$ but it hardly exceeds 3 $kg\ m^{-2}$, while MERRA2 always overestimate $\overline{IWV}_{GNSS}$ and the disagreement could reach 3.5 $kg\ m^{-2}$. For LPGS both NMW overestimate within 1 $kg\ m^{-2}$. Finally at FALK station both re-analysis models overestimate the inter-annual seasonal mean of IWV from GNSS although MERRA-2 values are always larger than ERA-Interim ones. As we said before, even though such a difference never exceed 1 $kg\ m^{-2}$, that represents about 10 % of the total amount because $\overline{IWV} < 12\ kg\ m^{-2}$.

4.2 Application of the integral correction

From the analysis of the behavior of the Small height difference stations, we can see that both NWM represent IWV from GNSS better than a 7% of the expected values in the worse case. Thus, we propose to compute a correction to the IWV values from ERA-Interim only for stations classified as Large and Critical. Such a compensation have to be added (or subtracted) to the given $IWV_{ERA-Interim}$ values considering the sign of the height differences. Accordingly, the proposed correction will be calculated as the numerical integration of the specific humidity (q) between the geopotential height from ERA-Interim and the geopotential height of the GNSS station (see Section 3.2).

Figure 5 shows the application of the before mentioned correction procedure on two Critical height difference stations: BOGT in Bogotá, Colombia, and SANT in Santiago de Chile, Chile. These stations are selected because their ΔZ is having a different sign. As expected both curves IWV_{GNSS} (blue solid line) and $IWV_{ERA-Interim}$ (green solid line) are not coincident. In the case of BOGT, ΔZ is positive, that means that GNSS station is higher to the location assigned by ERA-Interim. Accordingly, the model integrates a thicker layer of atmosphere and thus $IWV_{ERA-Interim}$ values resulted larger than ones from IWV_{GNSS}. The opposite can be seen in SANT. Figure 5 also shows us an improvement of the agreement with respect to IWV_{GNSS} when we add the correction to the values of the $IWV_{ERA-Interim}$ (red dashed line).

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Figure 6 shows the residuals with and without applying the integral correction. We can see that the differences ($IWV_{GNSS} - IWV_{ERA-Interim}$), which can reach up to 10 $kg\ m^{-2}$, are reduced to an order of magnitude of their respective value of $\overline{IWV}_{GNSS}$ (solid black line).

However, the application of this correction in the case of stations classified as Large should be more precautionary. This set of stations showed a heterogeneous behavior and include some cases where the application of the correction not only is unnecessary, but it can make the differences ($IWV_{GNSS} - IWV_{ERA-Interim}$) even larger. Effectively, in these cases different shortcomings of the model overlap the height problem and therefore the proposed correction does not work. As an example of this we can mention the case of coastal and/or insular stations where 2 or more grid points will be in the ocean. In all these cases the value of IWV calculated from the bilinear interpolation will be overvalued. Let's analyze in detail the case of stations near the seashore (for example PARC in Punta Arenas, Chile) where 2 of the 4 grid points are in the ocean (see Figure 7). Also ΔZ = -117.12 m in PARC indicating that the geopotential height from ERA-Interim is larger than the GNSS geopotential height and therefore the proposed correction will be additive. Besides this result, the $IWV_{ERA-Interim}$ resulted over-estimated by applying a bilinear interpolation that uses data points in the ocean. In conclusion, the value ($IWV_{ERA-Interim} + correction$) will result larger than the IWV_{GNSS} value that you intend to estimate. Thus, this is an example where applying the suggested correction may worsen the results.

5 Discussion and Conclusions

In this work, we analyzed the discrepancies between the vertically Integrated Water Vapor values provided by two re-analysis models (ERA-Interim and MERRA-2) with respect to the IWV_{GNSS} values taken as a reference in the South and Central American continent. We performed the comparison establishing a selection criteria according to the difference of static geopotential height (ΔZ) between GNSS and each reanalysis model at the station.

Several authors had been reported problems related to the elevation correction for data from the reanalysis models. The artificial bias in IWV introduced by this altitude difference was previously reported by Bock et al. (2007);Van Malderen et al. (2014);Bordi et al. (2014) and Bianchi et al. (2016a). Moreover, this effect can also affect other variables. For instance, Gao et al. (2012) studied the height corrections for the ERA-Interim 2m-temperature data at the Central Alps and they also found large biases that must be corrected in mountainous areas.

For the above, an integral correction was proposed that compensates the effect of the geopotential height difference between GNSS and the interpolated grid point in the reanalysis model and the results were tested with the respective ones from ERA-Interim. The correction is computed as the numerical integration of the specific humidity where the integral limit is a pressure difference at δZ (see Eqs. 5 and 6).

Before computing the correction, the set of GNSS stations was divided into 3 groups according to the differences ΔZ: Small height stations ($|\Delta Z| < 100m.$), Large height stations ($100m. \leq |\Delta Z| \leq 500m.$) and Critical height stations($|\Delta Z| > 500m.$).

For the Small height stations MERRA-2 mostly exhibits the larger discrepancies, i.e. $\left|\overline{IWV}_{GNSS} - \overline{IWV}_{MERRA-2}\right| > \left|\overline{IWV}_{GNSS} - \overline{IWV}_{ERA-Interim}\right|$, and this could be a consequence of a coarser horizontal grid used to the bilinear interpolation of data. Moreover, MERRA-2 generally overestimates IWV_{GNSS} because $IWV_{MERRA-2} > IWV_{ERA-Interim}$.

Both for Small and Large $|\Delta Z|$ stations the discrepancies between the NWM and GNSS can be analyzed depending on the $\overline{IWV}$ expected, but anyway the differences rise as the $|\Delta Z|$ grows. For $\overline{IWV} > 30\ kg\ m^{-2}$ the disagreement of the NWM with respect to GNSS is $\backsim$ 7% for Small $|\Delta Z|$ stations but it rise up to 15 % of $\overline{IWV}_{GNSS}$ for Large stations. If $12\ kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$, the disagreement of the NWM goes from $\backsim$ 7% for stations classified as Small up to $\backsim$ 35% for Large $|\Delta Z|$ stations. Finally, for $\overline{IWV} < 12\ kg\ m^{-2}$ the percentage of disagreement is always lower than 40 % of $\overline{IWV}_{GNSS}$ in the worse case,i.e. for Large $|\Delta Z|$ stations.

For Critical $|\Delta Z|$ stations the discrepancies of the IWV from NWM with respect to IWV from GNSS can reach $\backsim$ 55% of the expected values.

All of the above, we proposed the numerical correction only for the Large and Critical stations. The suggested improvement was successful reducing the differences between IWV_{GNSS} and $IWV_{ERA-Interim}$ from typical values of $10\ kg\ m^{-2}$ to an order of magnitude of their respective value of $\overline{IWV}_{GNSS}$. The correction is especially recommended for stations that were classified as Critical, most of them located in mountainous areas of South America.

Author contributions. L.I. Fernández led the study and contributed to data collection, analysis, and interpretation of the results; A.M. Meza and M.P. Natali co-wrote the paper. They also contributed to the statistical analysis and the interpretation of the results. C. E. Bianchi contributed to data collection. All authors read and approved the final manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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GNSS station	Geodetic coordinates			Classification		
	Longitude [°]	Latitude [°]	Height [m]	K-G	ERA-Interim	MERRA-2
BELE	-48.4626	-1.4088	9.1	Af	Small	Small
BYSP	-66.1612	18.4078	49.2	Af	Small	Large
CUCU	-72.4879	7.8985	311.2	Af	Critical	Critical
RIOB	-67.8028	-9.9655	172.6	Af	Small	Small
SAVO	-38.4323	-12.9392	76.3	Af	Small	Small
SSA1	-38.5165	-12.9752	-2.1	Af	Small	Large
MAPA	-51.0973	0.0467	-4.2	Am	Small	Small
ONRJ	-43.2243	-22.8957	35.6	Am	Large	Large
POVE	-63.8963	-8.7093	119.6	Am	Small	Small
RIOD	-43.3063	-22.8178	8.6	Am	Large	Large
RECF	-34.9515	-8.0510	20.1	As	Large	Small
RNNA	-35.2077	-5.8361	45.9	As	Small	Small
ACYA	-99.9030	16.8380	-4.9	Aw	Large	Large
BOAV	-60.7011	2.8452	69.5	Aw	Small	Small
BRFT	-38.4255	-3.8774	21.7	Aw	Small	Large
CEEU	-38.4255	-3.8775	21.7	Aw	Small	Large
CEFE	-40.3195	-20.3108	14.3	Aw	Large	Large
CHET	-88.2992	18.4953	3.0	Aw	Small	Small
CRO1	-64.5843	17.7569	-32.0	Aw	Small	Small
CUIB	-56.0699	-15.5553	237.5	Aw	Small	Large
MABA	-49.1223	-5.3624	79.8	Aw	Small	Large
MANA	-86.2490	12.1489	71.0	Aw	Large	Large
MSCG	-54.5407	-20.4409	676.5	Aw	Large	Large
PBCG	-35.9071	-7.2137	534.1	Aw	Large	Large
SALU	-44.2125	-2.5935	19.0	Aw	Small	Small
SCUB	-75.7623	20.0121	20.9	Aw	Large	Large
SSIA	-89.1166	13.6971	626.6	Aw	Large	Large
TAMP	-97.8640	22.2783	21.0	Aw	Small	Small
TOPL	-48.3307	-10.1711	256.5	Aw	Small	Large
VITH	-64.9692	18.3433	4.4	Aw	Small	Small

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Table 1: GNSS stations classified by $|\Delta Z|$

	Geodetic coordinates			Classification		
GNSS station	Longitude [°]	Latitude [°]	Height [m]	K-G	ERA-Interim	MERRA-2
BRAZ	-47.8779	-15.9475	1106.0	Aw	Large	Large
UBER	-48.3170	-18.8895	791.8	Aw	Small	Small
MARA	-71.6244	10.6740	28.4	BSh	Large	Small
MERI	-89.6203	20.9800	7.9	BSh	Small	Small
PEPE	-40.5061	-9.3844	369.1	BSh	Large	Small
MDO1	-104.0150	30.6805	2004.5	BSk	Critical	Critical
MZAC	-68.8756	-32.8952	859.9	BSk	Critical	Large
AREQ	-71.4928	-16.4655	2488.9	BWk	Large	Large
COPO	-70.3382	-27.3845	479.1	BWk	Critical	Critical
BRMU	-64.6963	32.3704	-11.6	Cfa	Small	Small
EBYP	-55.8922	-27.3689	139.8	Cfa	Small	Small
IGM1	-58.4393	-34.5722	50.7	Cfa	Small	Small
ISPA	-109.3444	-27.1250	112.5	Cfa	Large	Large
LPGS	-57.9323	-34.9067	29.9	Cfa	Small	Small
POAL	-51.1198	-30.0740	76.7	Cfa	Small	Small
PPTE	-51.4085	-22.1199	431.0	Cfa	Small	Small
SMAR	-53.7166	-29.7189	113.1	Cfa	Small	Small
UFPR	-49.2310	-25.4484	925.8	Cfa	Large	Large
UNRO	-60.6284	-32.9594	66.9	Cfa	Small	Small
AZUL	-59.8813	-36.7670	158.3	Cfb	Small	Small
BOGT	-74.0809	4.6401	2576.4	Cfb	Critical	Critical
CHPI	-44.9852	-22.6871	617.4	Cfb	Large	Large
POLI	-46.7303	-23.5556	730.6	Cfb	Small	Large
FALK	-57.8741	-51.6937	50.8	Cfc	Small	Small
PARC	-70.8799	-53.1370	22.3	Cfc	Large	Large
RIO2	-67.7511	-53.7855	32.0	Cfc	Large	Small
CONZ	-73.0255	-36.8438	180.6	Csb	Small	Small
GUAT	-90.5202	14.5904	1519.9	Csb	Large	Large
SANT	-70.6686	-33.1503	723.1	Csb	Critical	Critical
MGBH	-43.9249	-19.9419	974.8	Cwa	Small	Small

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Table 1: GNSS stations classified by $|\Delta Z|$

	Geodetic coordinates			Classification		
GNSS station	**Longitude** [°]	**Latitude** [°]	**Height** [m]	**K-G**	**ERA-Interim**	**MERRA-2**
UCOR	-64.1935	-31.4350	462.8	Cwa	Large	Large
LPAZ	-110.3194	24.1388	-6.9	Cwb	Large	Large
UNSA	-65.4076	-24.7275	1257.8	Cwb	Critical	Critical
OHI2	-57.9013	-63.3211	32.5	EF	Small	Large
PALM	-64.0511	-64.7751	31.1	EF	Large	Large
VESL	-2.8418	-71.6738	862.4	EF	Large	Large
AUTF	-68.3036	-54.8395	71.9	ET	Large	Large

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Table 2: Inter-annual mean of IWV ($\overline{IWV}^{*}$ in $[kg\, m^{-2}]$) for stations classified as Small, Large and Critical height difference. SD refers to the standard deviation. ΔZ [m.] refers to the difference between the geopotential height of the GNSS station and the bi-linear interpolated value of the geopotential height from each NWM.

		GNSS		ERA-Interim			MERRA-2		
	Name	$\overline{IWV}^{*}$	SD	ΔZ	$\overline{IWV}^{*}$	SD	ΔZ	$\overline{IWV}^{*}$	SD
SMALL	BELE	49.65	7.09	-39.88	49.25	6.83	-32.44	51.55	7.21
	RIOB	46.87	8.46	11.29	47.71	7.98	16.34	49.34	8.35
	SAVO	35.66	8.53	20.88	36.09	8.19	34.72	36.23	8.83
	MAPA	49.99	6.92	-60.84	49.65	6.79	-47.28	51.17	7.16
	POVE	50.37	8.80	33.71	46.61	8.66	35.91	51.27	8.33
	RNNA	40.41	8.72	-42.51	38.68	8.21	-4.14	39.76	9.16
	BOAV	50.19	5.80	-70.73	48.64	5.34	-49.38	51.59	5.49
	CHET	42.06	10.66	-37.16	41.43	10.17	-28.66	42.45	10.89
	CRO1	38.50	9.14	-73.65	39.30	8.97	-76.69	39.49	9.38
	SALU	47.86	7.07	-25.31	47.32	6.85	-21.79	48.92	7.63
	TAMP	36.64	11.90	5.49	37.28	11.61	-17.99	36.62	11.89
	VITH	39.11	9.17	-46.50	39.81	9.02	-43.11	39.75	9.56
	UBER	27.74	11.00	40.34	29.94	10.82	-14.81	30.32	11.41
	MERI	38.86	11.26	-28.17	38.96	11.02	-15.75	39.07	11.56
	BRMU	29.65	12.14	-44.30	29.98	11.84	-44.18	30.43	12.04
	EBYP	28.44	13.34	17.77	29.11	12.93	11.70	29.27	13.49
	IGM1	19.77	10.01	48.58	20.64	10.25	53.37	20.59	10.22
	LPGS	19.31	9.78	31.74	19.91	9.83	33.51	20.03	9.90
	POAL	26.61	11.62	-48.94	25.60	11.32	39.22	26.97	11.86
	PPTE	30.74	12.11	44.89	32.12	11.82	29.41	33.11	12.47
	UNRO	21.46	10.87	43.57	22.09	11.11	53.45	21.43	10.91
	SMAR	25.69	12.03	-83.77	25.20	11.57	-90.17	25.45	11.91
	AZUL	16.86	8.54	35.97	17.95	8.87	32.30	17.93	8.76
	FALK	10.98	4.50	57.56	11.41	4.56	46.53	11.70	4.60
	CONZ	14.15	5.84	33.72	13.95	5.51	84.21	14.38	5.92
	MGBH	26.55	10.10	70.90	27.54	9.76	16.00	28.48	10.32
LARGE	ONRJ	36.42	11.78	-117.45	34.64	11.36	-124.99	35.43	11.87
	RIOD	37.72	11.92	-211.95	34.35	11.33	-207.70	35.01	11.82

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		GNSS		ERA-Interim			MERRA-2		
	Name	$\overline{IWV}^{*}$	SD	ΔZ	$\overline{IWV}^{*}$	SD	ΔZ	$\overline{IWV}^{*}$	SD
	ACYA	41.39	11.78	-367.72	37.61	11.37	-340.88	38.42	11.73
	CEFE	37.43	11.02	-201.99	34.56	10.36	-217.97	35.21	11.00
	MANA	44.85	9.90	-113.84	42.40	10.09	-101.02	43.74	10.72
	MSCG	31.68	11.10	241.03	34.52	11.33	173.53	34.64	12.09
	PBCG	33.68	7.90	165.08	33.38	7.52	147.99	33.98	8.47
	SCUB	37.83	10.29	-138.75	37.88	10.03	-164.51	37.73	10.40
	SSIA	36.53	8.69	181.75	39.89	9.01	178.23	41.80	9.69
	BRAZ	26.25	9.89	125.69	28.26	9.73	126.97	29.22	10.80
	AREQ	11.02	6.71	-203.27	10.60	6.43	-341.84	11.88	6.13
	ISPA	26.35	7.68	107.18	25.75	6.85	106.23	26.23	6.98
	UFPR	23.69	10.03	243.15	26.66	10.17	153.10	27.06	10.57
	CHPI	29.48	10.51	-252.47	27.60	9.91	-323.87	27.51	10.32
	PARC†	10.21	4.51	-117.12	11.02	4.65	-59.50	11.61	3.43
	GUAT	22.85	7.56	443.91	30.00	8.31	328.58	30.98	9.10
	UCOR†	18.51	9.98	-145.30	19.44	9.56	-94.83	18.57	9.22
	LPAZ	25.34	15.37	-146.73	24.90	15.03	-165.53	25.08	15.31
	PALM	6.81	3.16	-132.37	6.34	2.77	-165.08	6.53	2.86
	VESL	3.14	0.94	106.15	1.91	1.19	241.94	2.25	1.36
	AUTF	10.18	3.79	-150.13	9.75	4.06	-228.66	9.51	3.89
CRITICAL	CUCU	43.14	5.80	-842.18	32.87	5.22	-645.50	34.46	5.79
	MDO1	10.20	7.64	688.88	15.42	10.13	630.23	15.34	10.36
	COPO	11.94	5.37	-748.63	8.89	4.58	-532.69	9.88	4.28
	BOGT	19.61	3.29	736.63	26.79	3.26	643.76	28.36	3.75
	SANT	12.52	5.09	-1698.36	6.93	3.49	-577.70	7.98	4.11
	UNSA	19.08	10.07	-706.68	16.69	8.01	-707.45	15.43	8.78

† Stations with $|\Delta Z|$ between GNSS and the four MERRA-2's grid points > 100 m.

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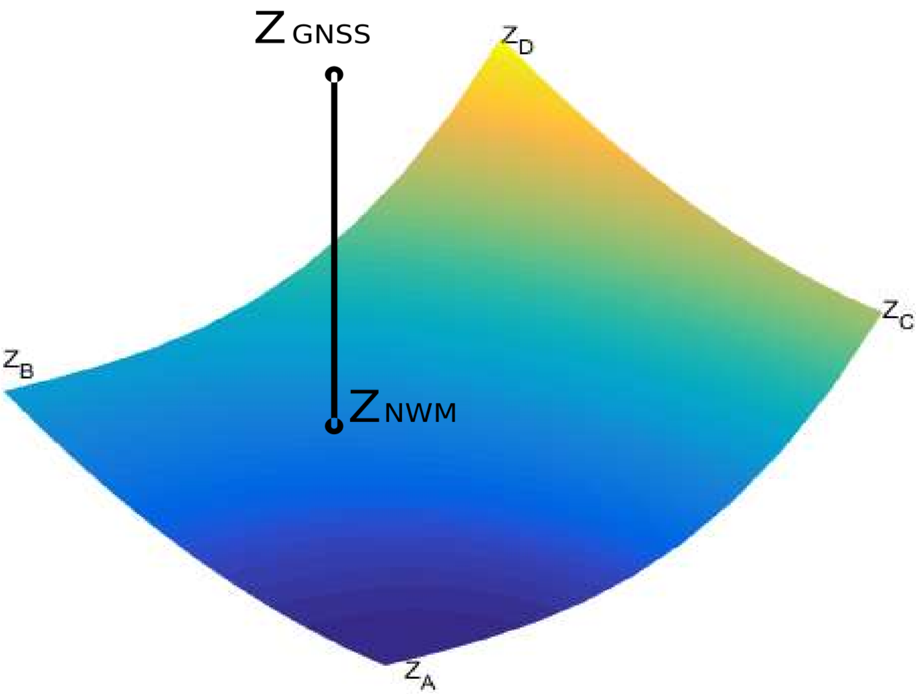

~~**Figure 1.** Example of geopotential height differences used to classify GNSS stations. Z_{NWM} results from a bi-linear interpolation of the gridded data. A, B, C and D are the four grid points of the NWM around the GNSS station.~~

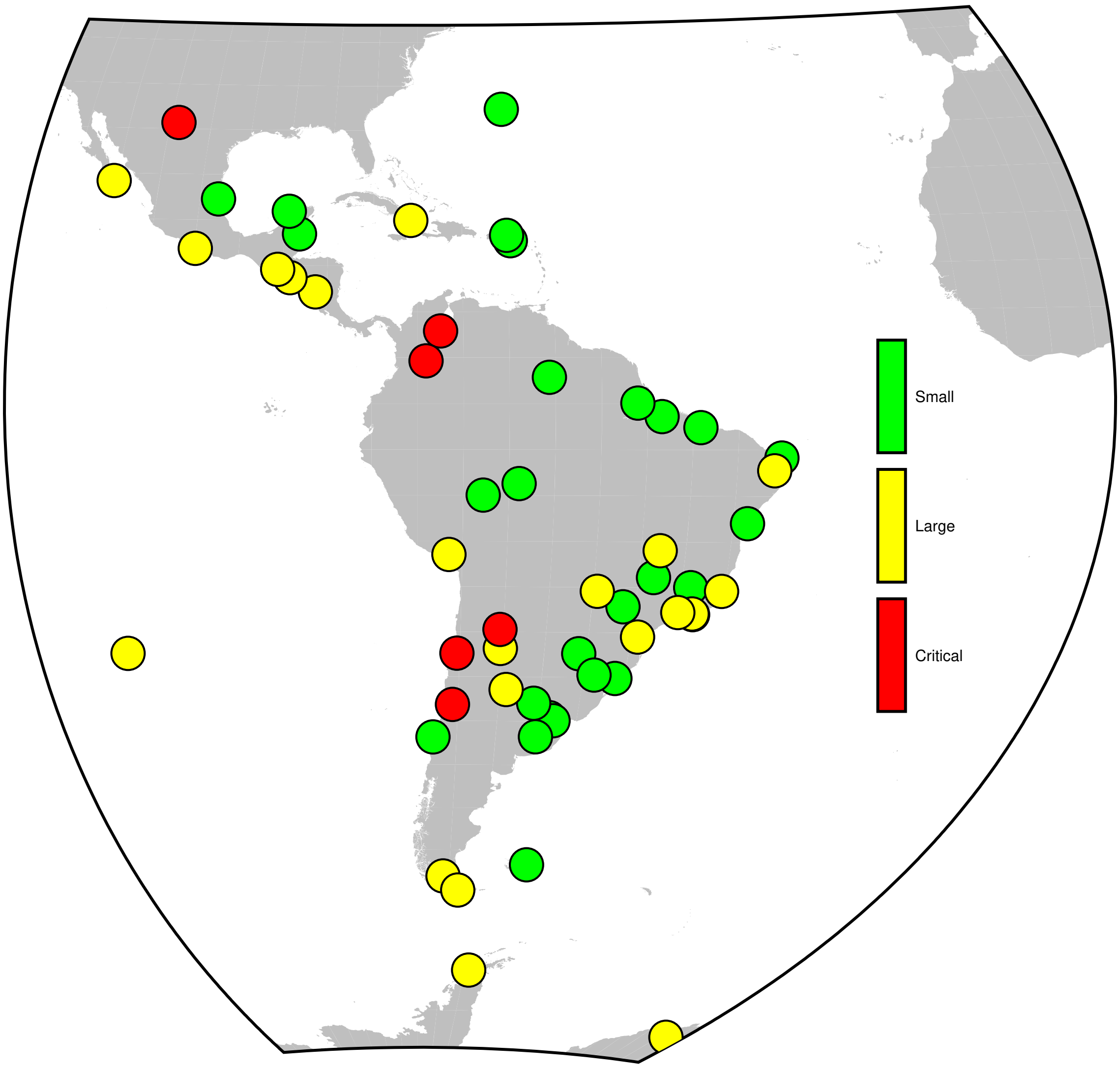

Figure 2. Station classification according to the difference between GNSS geopotential heights and the static geopotential heights from ERA-Interim ($Z_{GNSS} - Z_{ERA-Interim}$).

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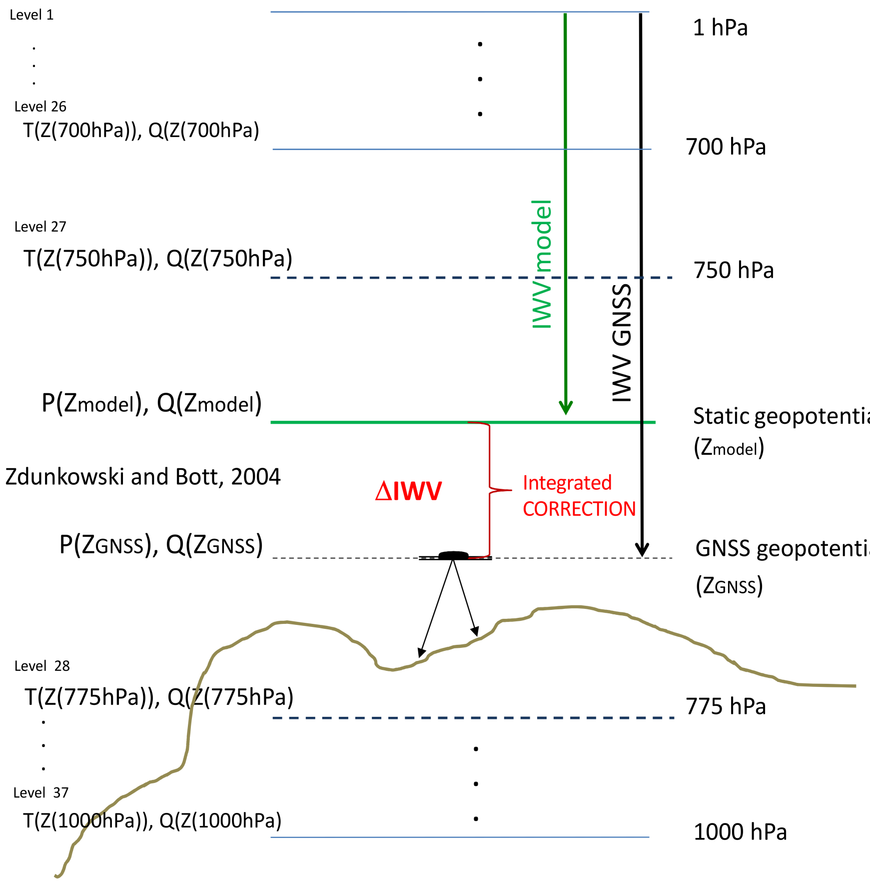

Figure 3. Scheme of the applied correction to the IWV from ERA-Interim reanalysis.

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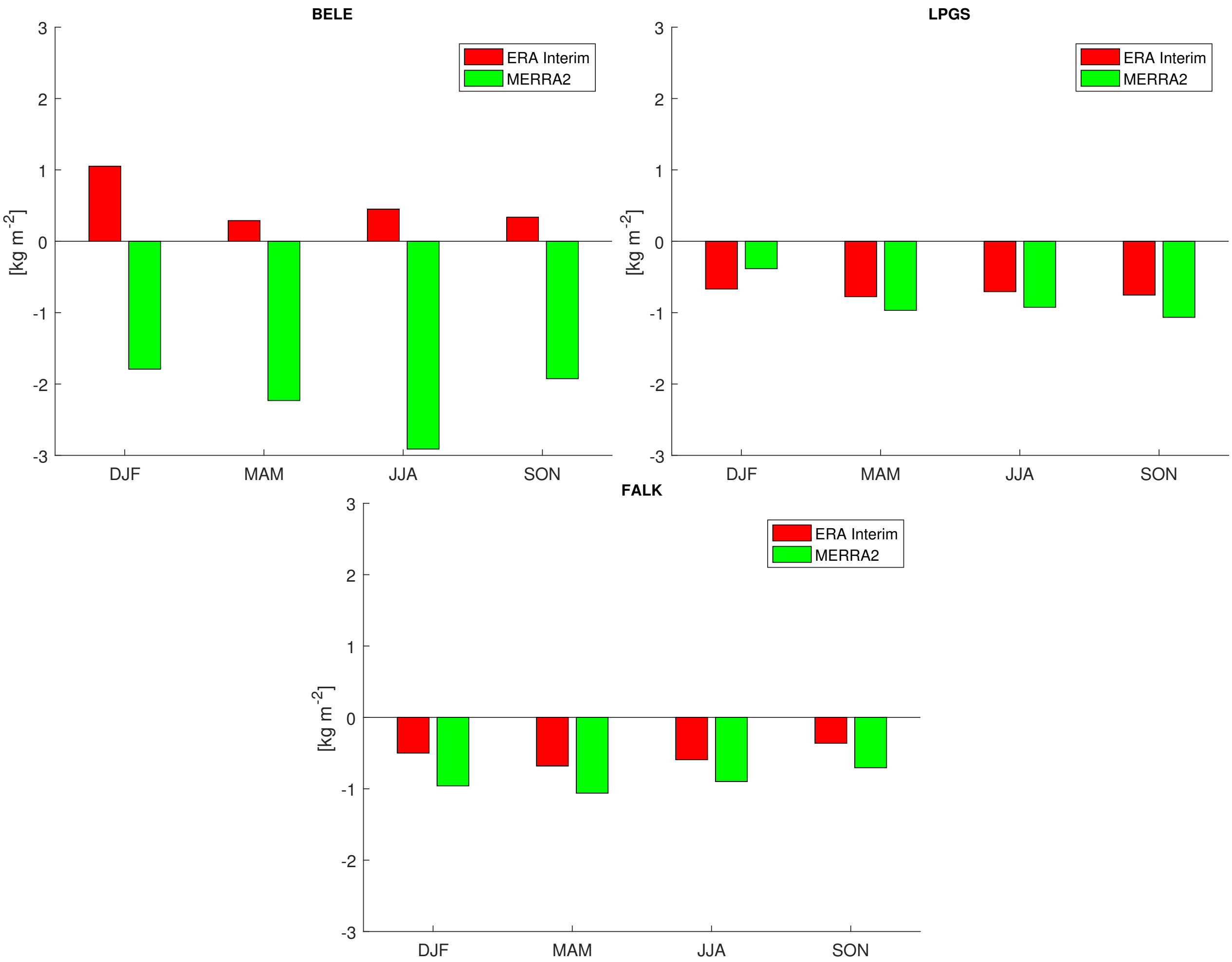

Figure 4. Differences of $(IWV_{GNSS} - IWV_{NWM})$ seasonally stacked for Small height difference stations. Both reanalysis models are shown: ERA-Interim in red and MERRA-2 in green. (from left to right and up to down) Examples for $\overline{IWV} > 30\ kg\ m^{-2}$ (BELE), $12\ kg\ m^{-2} \leqslant \overline{IWV} \leqslant 30\ kg\ m^{-2}$ (LPGS) and $\overline{IWV} < 12\ kg\ m^{-2}$ (FALK)

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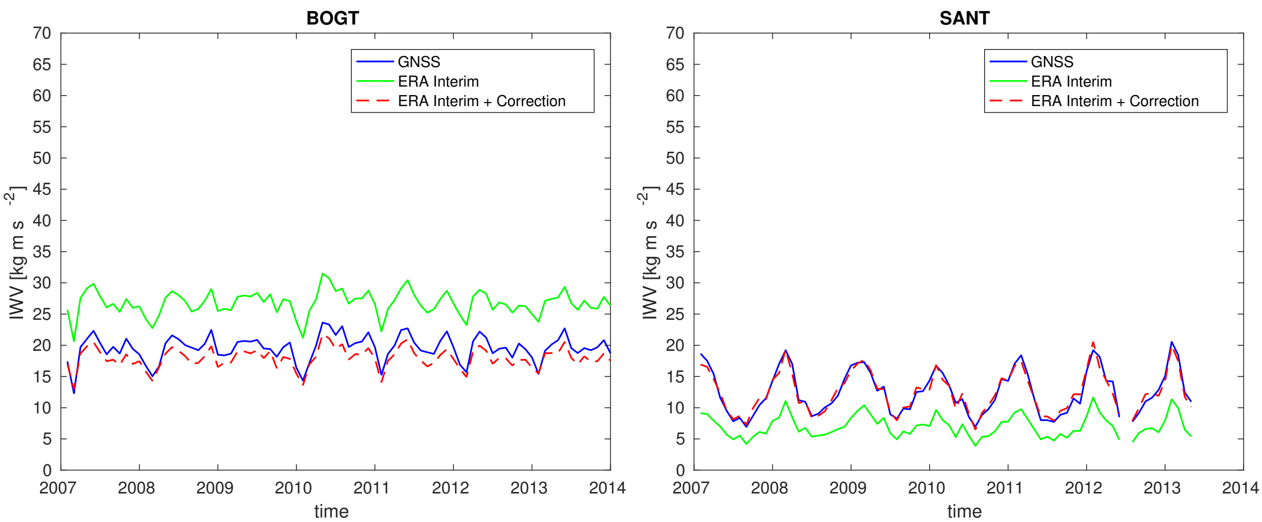

Figure 5. GNSS IWV (blue, solid line) and ERA-Interim IWV (green, solid line) data time series for 2 critical stations shown as an example: BOGT in Bogotá, Colombia (ΔZ = 736 m.) and SANT in Santiago de Chile, Chile (ΔZ = -1037 m.). The IWV values as a result of the addition of the computed correction plus IWV values from ERA-Interim are also shown (red, dashed line)

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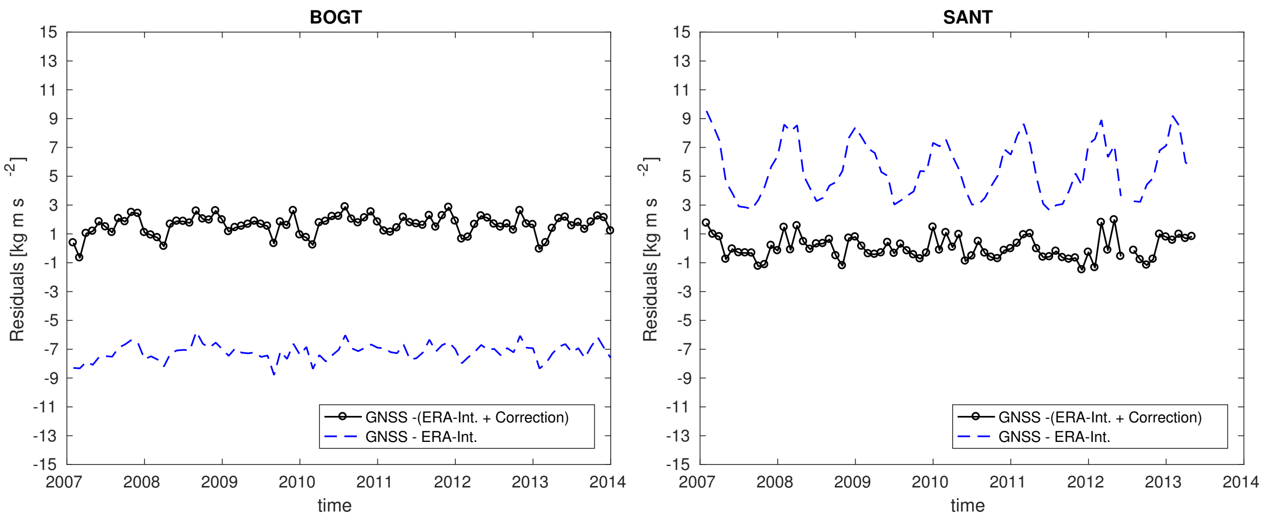

Figure 6. Residuals of the difference $(IWV_{GNSS} - IWV_{ERA-Interim})$ (blue, dashed line) along with residuals of the difference $[IWV_{GNSS} - (IWV_{ERA-Interim} + correction)]$ (solid black line)

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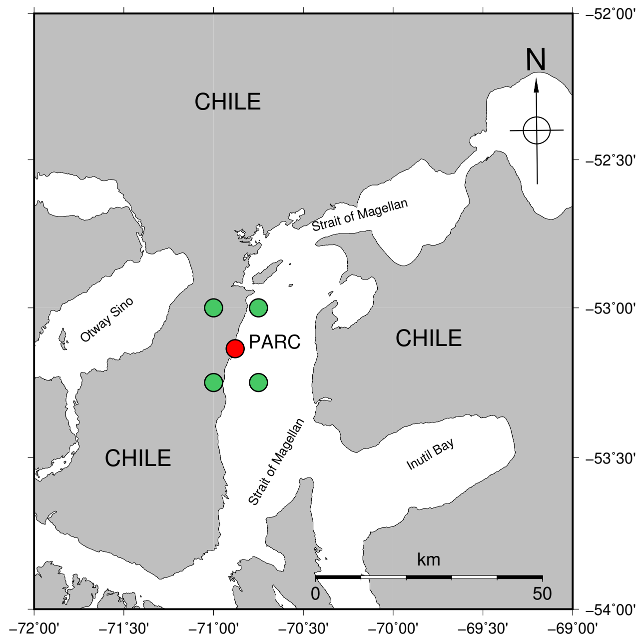

~~Figure 7~~. Location of GNSS station PARC along with the 4 grid points around the station. The grid points correspond to ERA-Interim.