Precision estimation in temperature and refractivity profiles retrieved by GPS radio occultations

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2013JD021016

Abstract. The Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) is a six satellite Global Positioning System (GPS) radio occultation (RO) mission that started in April 2006. The close proximity of these satellites during some months after launch provided a unique opportunity to evaluate the precision of GPS RO temperature and refractivity profile retrievals in the neutral atmosphere from nearly collocated and simultaneous observations. In order to work with nearly homogeneous sets, data are divided into 5 groups according to latitude bands during 20 days of July. For all latitude bands and variables, the best precision values (about 0.1 %) are found somewhere between 8 and 25 km height. In general, we find that precision degrades significantly with height above 30 km and its performance becomes there worse than 1 %. Temperature precision assessment has been generally excluded in previous studies. Refractivity has here in general a precision similar to dry temperature, but worse than wet temperature in the lower atmosphere and above 30 km. However, it has been shown that the better performance of wet temperature is an artificial effect produced by the use of the same background information in nearly collocated wet retrievals. Performance in refractivity around 1 % is found in the Northern Hemisphere at the lowest heights and significantly worse in the Southern polar zone above 30 km. There is no strong dependence of the estimated precision in terms of height on day and night, on latitude, on season or on the homogeneity degree of each group of profiles. This reinforces the usual claim that GPS RO precision is independent of the atmospheric conditions. The roughly 0.1 %

precision in the 8-25 km height interval should suffice to distinguish between day and night average values, but no significant differences are found through a Student *t*-test for both populations at all heights in each latitude band. It was then shown that the present spatial density of GPS RO does not allow to analyze smaller latitudinal bands, which could lead to smaller dispersions associated with the day and night means, where it would then be potentially possible to detect significant statistical differences among both categories. We studied the uncertainties associated with the background conditions used in the retrievals and found that their contribution is negligible at all latitudes and heights. However, they force an artificial improvement of wet temperature precision as compared to the dry counterpart at the lowest and highest altitudes studied. In addition, we showed that there is no detectable dubious behavior of COSMIC data prior to day 194 of year 2006 as warned by the data providers, but our result applies only to the precision issue and cannot be extended to other features of data quality. Regarding accuracy, we estimated an average bias of 0.1 K for GPS RO temperature between about 10 and 30 km height and somewhat larger at lower altitudes. We expect a roughly -0.5 K bias above 35 km altitude. Regarding refractivity, a -0.2% bias of the measurements was estimated below about 8 km height.

1. Introduction

A Global Positioning System (GPS) radio occultation (RO) occurs whenever a transmitting satellite from the global navigation network at an altitude about 20,000 km rises or sets from the standpoint of a low Earth orbit (LEO) receiving satellite at a height of about 500 km and the signal traverses the atmospheric limb. The Doppler frequency alteration produced through the refraction of the ray by the Earth's atmosphere in the trajectory between the transmitter and the receiver is detected and then may be converted through a sequence of established procedures into profiles of diverse variables in the neutral atmosphere and ionosphere [see e.g., *Kursinski et al.*, 1997]. The technique has a typical measurement time in the neutral atmosphere of 1 min (as compared to the much longer dynamical processes), it has global coverage, all-weather and all-time capability, no recurrent need of instrumental drift or bias corrections (observations are stable in the long-term due to permanent self-calibration). A vertical resolution of about 0.1 km may be reached at the lowest heights and it gradually increases to about 1.5 km in the upper troposphere or lower stratosphere.

In April 2006, the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) launched six LEO satellites. The aim of the mission was to produce up to 2500 GPS RO daily with global distribution. The orbital characteristics of the LEO probes imply that most RO soundings occur at mid-latitudes. Immediately after launch, all the LEO satellites orbited very closely to each other for a few months, so during this period the geographical distribution of data was particularly clustered [e.g., *Liou et al.*, 2007]. This offers an excellent possibility to assess the precision of the retrieved profiles through the inter-comparison of nearly collocated and simultaneous observations with respect to a given GPS satellite, whereby the RO occultation planes (each one defined by the emitting and receiving satellites and the Earth's center) are almost coincident. The corresponding soundings therefore included nearly the same covered atmospheric portions and time.

The precision (level of "reproducibility") of an instrument or an observational technique may be evaluated by the root-mean-square (RMS) difference between a large number of pairs of independent observations. In the case of GPS RO retrievals of neutral atmosphere data, we apply this procedure to assess the temperature and refractivity at altitudes within the observable range. It must be stated that even under the most favorable conditions, measurements usually cannot be repeated under exactly the same experimental conditions. In our study we put a constraint on the separations in time and space of pairs of retrievals to make them acceptable for comparison. The methodology of this work is not new. There have already been some GPS RO error comparison studies for different missions that focused on precision and representativeness aspects in the neutral atmosphere [e.g., *Hajj et al.*, 2004; *Schreiner et al.*, 2007; *Anthes et al.*, 2008; *Staten and Reichler*, 2009; *Alexander et al.*, 2010a]. However, these works used earlier data which were later corrected or reprocessed or they did not divide the global data into sets with some degree of homogeneity. Some of these works established inter-comparisons between GPS RO stemming from different missions. However, these stuides used much laxer conditions regarding separation in distance and time of both retrievals of each pair than those that can be accomplished with the initial COSMIC data (typically 200 km and 30 min against 10 km and 1 min).

Accuracy (level of "exactitude") cannot be analyzed at the same depth in this study as we have no simultaneously collocated global and reliable reference measurements available. Accuracy of the GPS RO retrieval method has been theoretically evaluated [e.g., *Kursinski et al.*, 1997] and experimentally assessed by contrast with other observational data [e.g., *Kuo et al.*, 2004]. However, it must be taken into account that any such a comparison encompasses not only the measurement but also the representativeness errors of both observational methods being compared. Also, other platforms do not possess the global and permanent features of GPS RO, so comparisons can only be established in some space and time bounded cases [e.g., *Kuo et al.*, 2005]. Representativeness errors, for example for radiosonde observations, have been evaluated by *Kitchen* [1989]. Representativeness errors for GPS RO in the neutral atmosphere have been evaluated in some works [e.g., *Staten and Reichler*, 2009; *Alexander et al.*, 2010a]. This type of error is mainly associated with the fact that the observations are not point measurements, but line integrals of about 200 km [*Kursinski et al.*, 1997]. Nevertheless, they are treated as point values located in the tangent point to the Earth of the ray traveling from the GPS to the LEO satellite. Different but simultaneous RO observations of the same tangent point could be sampling different zones of the atmosphere, depending on the line of sight between both satellites and the corresponding path integral. Therefore, significant differences may appear in atmospheric properties assigned to a given point and time from diverse RO measurements. This does not happen in our study, as nearly collocated and simultaneous retrievals are sampling similar areas. We may therefore assume that representativeness errors do not strongly interfere with our results and can therefore disentangle in our analysis the issues of precision and representativeness error. In general, the horizontal inhomogeneity affecting the assumption of spherical symmetry is considered a significant representativeness error source in the GPS RO retrievals in the lower troposphere [e.g., *Kursinski et al.*, 1997; *Foelsche and Kirchengast*, 2004]. Taking all these precautions, we qualitatively assessed GPS RO accuracy, a quite elusive quantity, by comparing the profiles with those from the ECMWF (European Centre for Medium-Range Weather Forecasts) operational model, following similar ideas by *Steiner and Kirchengast* [2005]; *Gorbunov et al.* [2011]. Our procedure possesses a good statistical strength and allows to evaluate its merit by comparing the results with substantiated expectations according to the geographic location of the data. However, the results should not be considered a high standard estimation but just a qualitative assessment of GPS RO accuracy.

In section 2, we present the GPS RO data analysed in this study. In addition, we describe the selection process used to obtain acceptable pairs of profiles through a space and time proximity criterium, their classification in groups according to latitude localization, and the analysis method applied. In section 3, we present the results assessing the precision and accuracy of GPS RO temperature and refractivity profiles in the neutral atmosphere. Section 4 discusses the meaning of the results, establishes comparisons with previous works on the subject and presents our conclusions.

2. Data selection and analysis method

This study uses the latest post-processed data (product version 2010.2640) from the COSMIC mission provided by CDAAC (COSMIC Data Analysis and Archive Center). We statistically evaluate the precision of the GPS RO measurements in the neutral atmosphere by using the COSMIC level 2 refractivity and temperature profiles, where the former variable is equivalent to density by a simple transformation. We considered days 194-213 of year 2006, which implied processing 13951 profiles. It has been reported that early mission data, gathered before day 194 of year 2006, are not high quality due to receiver tracking issues, so it is strongly recommended that users focus their efforts on products starting on that day (cdaac-www.cosmic.ucar.edu/cdaac/products.html#cosmic). The recently reprocessed data offer an opportunity to check the validity of previous results which partly used the dubious period. We used only 20 days in order to avoid any seasonal variation of data, starting on day 194. This time period corresponds to winter in the Southern Hemisphere (SH) and summer in the Northern Hemisphere (NH). There is a delicate balance between narrowing the acceptable separation standard in space and time of both GPS RO of every nearly collocated pair (to ensure that we are measuring the "same" observable) and keeping a large number of cases, so as to be able to perform satisfactory statistics. We chose to examine all pairs with a time and horizontal separation of respectively up to 1 min between both soundings and less than 10 km between the corresponding tangent points at every altitude. This criterium yielded 847 pairs and thus allowed us to obtain an acceptable statistical power. A similar analysis was performed by *Schreiner et al.* [2007]. Their data were produced with the initial processing algorithms and firmware configurations of COSMIC and in addition belong to a period of time (days 111-277 of year 2006) that is partially considered dubious (see above). As the authors themselves acknowledged, issues related to receiver tracking may impact accuracy and precision of the retrieved profiles. Therefore, we also wanted to check whether this fact produced any bias in their analysis, so we included in our study data from another 20 day interval within the dubious period: days 174-193 of year 2006 (6824 soundings). In addition, our study separates the data according to latitude bands, so that each group shows some degree of similarity or homogeneity among the profiles (with the optimal group exhibiting a very low dispersion). Homogeneity aims to measure the degree of variability against height of each group of profiles through a dispersion index. By this procedure, we try to see if already unseen precision issues emerge clearly, as they could be masked when all data are assembled, i.e. we try to uncover any possible hidden association between precision and specific typical latitudinal characteristics of the profiles. For example, the basic general features of the vertical representations of temperature in a given time of the year depend essentially on latitude. Most of the temperature profiles at low latitudes have a clearly defined acute tropopause, whereas at high latitudes the opposite happens, and if the tropopause in the latter case can be detected, it is usually located at much lower altitudes than in the former case. Moreover, multiple tropopauses often occur in the polar regions. In addition, grouping the profiles in terms of latitude also leads to a smaller dispersion of their values for each height. It is expected that profile groupings from very large latitude bands or from all over the globe should be quite non-homogeneous (large dispersion indices). The present GPS RO density does not allow us to use latitude bands of the order of 10^o or less, in order to approach nearly zero variability in every group and thus be able to obtain a measure of precision in terms of profile types. Taking into account the limited amount of RO, we divide the profiles in only five latitudinal groups and evaluate the degree of homogeneity in each set in order to quantify how similar they are.

Due to the vapour ambiguity at low altitudes, temperature and humidity information can be then derived from GPS RO refractivity only if a priori (or background) data are incorporated. This is done in a statistically optimal way by using one-dimensional variational (1DVar) techniques with the combination of measurements and first-guess background information (e.g. analyses), addressing the issues of noise in the former and uncertainty in the latter [*Healy and Eyre*, 2000; *Poli et al.*, 2002]. The wet temperature profiles presented here were obtained at CDAAC using a 1Dvar approach, and they nearly coincide with the dry counterparts above about 8 km height, where the water vapor is negligible. We have analyzed the following three post-processed level 2 data products: atmPrf files contain among others a vertical profile of dry temperature, where no moisture effects have been separated, wetPrf files include the wet (”true”) temperature obtained using a 1DVar technique, whereas ecmPrf files hold the collocated background data used in deriving the wet temperature, which are a product generated from gridded analysis provided by the ECMWF every day for 0000 UTC and 1200 UTC against 21 pressure levels between 1000 and 1 hPa. According to the data product, CDAAC provides profiles for diverse altitude intervals and vertical resolutions. Often, there are some missing values at the lowest heights, which may be caused, for example, by GPS RO signal multi-path propagation or its reduction below the noise level [e.g., *Sokolovskiy et al.*, 2010]. In addition, we removed the lowest 3 km to avoid any possible planetary boundary layer effect.

All the pairs detected belong to satellites 3 and 4, so we were not able to find triads of close RO. Within days 194-213, there are no data from satellite 4 during days 201, 204 and 209, so no pairs could be found during that time. There were no profiles available from satellite 5 during days 198 and 199, whereas satellite 2 provided observations only during day 213. In Figure 1 we show the number of RO retrievals per day for satellite 4 (as a proxy for the potential number of nearly collocated and simultaneous cases) and the number of pairs found. Both amounts show a decreasing trend with time. A linear fit to the number of pairs against time in the same figure evidences the decreasing tendency (about 1 pair loss per day, roughly a reduction from 60 to 40 daily cases from day 194 to day 213). It is therefore expected that the statistical significance of additional time intervals will decline after day 213 (from the values in Figure 1, it may be inferred that about 40 % less pairs are expected for the following 20 days). The eventual inclusion of additional days could also reduce the data homogeneity degree (quantified by the dispersion index), as seasonal effects could start to leave visible imprints of variability in the profiles.

We classified the pairs in 5 groups, according to the geographical location of RO: low (L), middle (M) and high (H) latitudes in the Northern (N) and Southern (S) Hemispheres. The boundaries that define the zones HN, MN, L, MS and HS correspond to ± 20^o and ± 55^o. In Table 1, we show the number of pairs per group within days 194-213, including their occurrence during day or night. This table reflects an imbalance of 6 % between day and night pairs with respect to the mean (a surplus of the latter cases). It can also be observed that as expected, during July there is a prevalence of day and night events respectively in the NH and SH. In particular, almost all RO at high latitudes occur during the night and day respectively in the southern and northern halves. It is also well-known that due to the configuration of the constellation, most RO are found at middle latitudes and much less close to the poles. If we exclude the RO at low latitudes, then there are 17 % more pairs with respect to the mean in the SH (527) than in the NH (488). This difference between both amounts of RO is the ultimate cause for the overall night surplus. However, we do not know the reason for the slightly better coverage of the southern half in our data-set.

For each of the 5 groups, we calculated the average temperature and refractivity profiles against altitude. In order to check the homogeneous degree of each group, we also computed the standard deviation of the profiles against altitude. Thereafter we calculated the RMS difference of all close pairs in each group against height to evaluate precision. We also statistically assessed the significance of eventually separating each group into night and day subgroups. We finally evaluated accuracy by comparing GPS RO retrievals against collocated numerical model results.

3. Results

Mean wet temperature T_w and refractivity N profiles against height within days 194-213 for the five groups are shown in panels a of Figures 2-6. Panels b indicate the number of pairs to evaluate the statistical strength of the calculations, in panels c we show the ratio of T_w standard deviation σ and mean to assess the homogeneity of the group, whereas in panels d we plot the ratio of the RMS difference of the pairs and the mean T_w. Panels e and f display the same as c and d but for N instead of T_w. The RMS difference addresses the issue of the precision of the profiles of a given group in terms of altitude. However, when evaluating its relevance it should not be considered separately from the other panels. A short note to avoid confusions: the well-known relation

$$x_{RMS}^2 = \overline{x}^2 + \sigma_x^2$$

where $\bar{}$ and σ represent mean and standard deviation should not be wrongly applied here. The RMS values refer to the collocated differences, whereas the means and the standard deviations correspond to the profile values.

Well-known typical features of temperature profiles are exhibited by the averaged RO retrievals in panels a of Figures 2-6: the absence of a clear unique tropopause at high latitudes but instead a broad feature between about 10 and 25 km altitude, a better defined elbow around 18 km height at mid-latitudes and a sharp kink at a similar altitude in the equatorial region. Refractivity curves show the typical exponential decrease with height. Panels b show that significant statistics have been obtained at all studied heights for the 5 groups. Panels c and e show that profiles are quite homogeneous, usually with a variability below 5 %. In the tropical region there is a small degradation around the tropopause and a noticeable lack of homogeneity at low altitudes in N, possibly due to the significant effect of moisture. At middle latitudes the profiles also exhibit a lower homogeneity degree close to the tropopause, but a significant effect is also observed for T_w around 10 km altitude, and in the SH also at about 30 km height. N becomes less homogeneous at low altitudes with the only exception of HS, but in this zone a significant effect appears above 30 km height. In HN the profiles exhibit less homogeneity around the apparent first tropopause and in refractivity also at low altitudes. HS exhibits an atypical behavior with a larger/lower homogeneity degree in T_w/N around the first apparent tropopause, and lowest profile uniformity in T_w around 20 km and 35 km height and in N above 20 km. These clear differences in homogeneity between both high latitude bands should be ascribed to their very different conditions: summer and nearly 24 hour day vs winter and nearly 24 hour night. According to all panels d and f, in general precision is seen to be at its best between about 8 km and 25 km height (around 0.1 %). This may just reflect some known difficulties of the RO retrieval process: below about 8 km there is uncertainty associated to the so-called water vapor ambiguity and above about 30 km the

RO profiles often harbor spurious fluctuations that are attributed to upper initialization issues that propagate and shrink downwards and there is also ionospheric residual phase noise [*Kursinski et al.*, 1997; *Hajj et al.*, 2004]. In addition, possible strong water vapor gradients give even lower validity to the spherical assumption of the retrievals in the lower atmosphere. In general, while precision in terms of altitude exhibits a quite consistent behavior for the 5 latitude bands, homogeneity is more varied. Moreover, we can see that the precision estimation at given height ranges (roughly 0-8 km, 8-25 km, 25-40 km) is not significantly affected by the homogeneity degree, the latitude bands or the season, so it seems to be quite independent of the atmospheric conditions.

We now compare T_w and T_d profiles and then try to find out whether the precision differences in N and T_w in the lower and upper 10 km are due to the effect of background data precision issues. [*Healy and Eyre*, 2000] have already established that the GPS RO observations have a dominant role on the retrievals only between approximately altitudes 9 and 22 km. Panels a of Figures 2-6 show that below about 10 km height T_d is notably smaller than T_w, most importantly in the NH (summer during July) and zone L. Above 30 km altitude there is a small but not negligible difference between T_d and T_w in the NH, which cannot be due to upper initialization, because both profiles in each RO stem from the same conditions. This is a consequence of the different dry and 1DVar procedures and their sensitivity to observational data. In panels c there is a significant difference in the assessment of the variability of T_d and T_w in all cases below about 10 km height, most appreciably in MN and L, whereas SH and L also exhibit some differences above about 30 km. When comparing panels d and f, in all cases the lower 10 km difference in precision between T_w and N may be explained by the difference in precision between

T_w and T_d, or the same may be checked directly in panels d and f in Figures 8-12. The same happens with the difference in the upper 10 km for L and MS, but only partially in the remaining 3 latitudinal regions, so in those cases the use of the same background information in each pair may be artificially forcing a reduction in the estimated retrieved temperature uncertainty. Variability peaks in the 10-20 km height zone are mainly due to the sensitivity of the calculation to the position of the tropopause in each profile (compare panels c and e with a). In order to assess the influence of the background differences in each collocated pair on the precision estimate of the dry and wet profiles we repeated the RMS calculations for the background data used. In panels d and f of Figures 2-6 it can be seen that the corresponding uncertainty is rather limited, which has some consequences which are described below on T_w precision in the height intervals where background data is relevant for the retrievals. It should be stressed that here we are assessing the influence of the background differences due to nearly collocated pairs, but not the impact of the background (and measurements) through the 1D-Var process on the final profiles, which has been evaluated by *Healy and Eyre* [2000]. In the calculation of the background data RMS, due to anomalous differences in temperature and refractivity around 16 km height, we had to eliminate a collocated pair corresponding to day 198 and time 02:04 for satellite 3 and 02:03 for satellite 4.

In 3 of the 5 wet groups, we also assessed the statistical significance of putting together day and night profiles and tried to determine if there is a clear separation between day and night temperatures. The tests were not performed in the high latitude zones as there were very few night/day RO in HN/HS as expected during July, which would render low statistical power to the comparisons. However, small differences may be presumed in both zones between day and night profiles because each minority subgroup belongs to a very short time period embedded within the almost 24 hours of the majority subgroup (there is nearly permanent day or night). For each of the 3 latitudinal bands we computed the mean and standard deviation of day and night values in terms of height. At each altitude, we tested whether the averages of day and night had significant differences. We previously checked that each subgroup resembled a normal distribution. The differences between night and day means were evaluated through a two-tailed Student t-test. In the 3 groups and at all heights, the null hypothesis that day and night averages are equal was accepted at a 5% statistical significance level. Relative differences between day and night averages were not significant and we may conclude that the relative difference between day and night values is too subtle. Ideally, we should have used much smaller latitudinal bands, as the profiles may exhibit significant variability if broad latitudinal extensions are used, but the limited amount of GPS RO soundings prevented us from doing so. This means that the dispersion in the data of each of both categories was probably produced by a (for the moment) unmanageable factor. If a much larger set of cases (GPS RO or any other method) is available in the future, we may be able to define much smaller latitude bands, and if the calculations result in smaller variances, we may be able to show that it is adequate (or not) to separate day and night temperatures. In the hope of a positive answer to this issue in the future, we include in Figure 7 the relative day and night temperature differences and our assessment of relative GPS RO precision. It is worth noting that even if the above differences between day and night mean values were statistically significant, the threshold given by the precision estimate (which is always positive) is smaller than the absolute value of the differences between day and night mean values only between 8 and 25 km heights approximately. Moreover, as the RMS calculation is a gross evaluation of precision, we should establish a demanding criterium, e.g. the absolute value of day and night differences should be at least double the precision estimate, which then reduces further the vertical ranges where day and night values could be distinguished. Therefore, we cannot for the moment answer the question whether GPS RO precision is good enough to discriminate between day and night values in a given location and height and any further discussion will require a much higher density of soundings in the future. The present amount of retrievals is too low to perform calculations on small global latitude bands, which would naturally exhibit much smaller dispersion and could eventually lead to the compliance with a discrimination criterium between day and night values in some latitudinal bands and altitude intervals. We consider that the time interval used (20 days) does not introduce a significant dispersion due to seasonal variations.

In panels a of Figures 8-12 we try to assess whether there are significant seasonal changes in each latitudinal group between the profiles of days 174-193 (which are part of the dubious period) and of days 194-213. If we conclude that the general characteristics of both time intervals remain quite similar, then we may analyze if precision issues emerge in the earlier group after a warning issued by the COSMIC data providers. We can see subtle changes in the mean profiles, typically in N below 10 km and in T_d above 30 km. Band L is a different case, which exhibits some differences below and close to 20 km height, which are not due to changes in the shape of the profiles but rather a small but non-negligible descent in the position of the acute tropopause with time (the profiles for days 174-193 are not shown here in order to avoid the repetition of similar graphical material) and a possible real descent of temperature with time in the lowest altitudes or induced by background information. Notice that the refractivity profile (there are no dry and wet versions) of each group is the same as in Figures 2-6 and is included for reference only. In panels b it can be seen that the statistical power is lower in the earlier set, as there are roughly half as many RO and about 40 % less collocated pairs. In Table 2 we show the distribution in terms of latitudinal band. The amount of available GPS RO (cdaac-www.cosmic.ucar.edu/cdaac/DBif/cdaac_highlevel.cgi) shows a significant rising trend around day 194, so the earlier group has less soundings. However, the ratio of pairs to number of total RO in the earlier data-set (526/6824) is larger than in the later period (847/13953), as the probability of collocated COSMIC cases tended to decrease with time due to the progressive separation of the satellites [*Liou et al.*, 2007]. In panels c-f we see in general differences in the lower or upper 10 km and in some cases around 10-20 km attributable to changes in the altitude of the tropopause rather than changes in the shape due to seasonal factors. There is no clear evidence of precision problems in the earlier data. No outstanding situations can be outlined below 25-30 km. Above these altitudes there is some noticeable precision difference in panels d and f for N and T_d between both time periods in latitude bands L, MS and HS. However, when going back to panels d of Figures 2-6 it becomes clear, as already indicated for T_d (and therefore also for N), that precision degrades at the highest altitudes in those 3 latitude bands, which then implies that precision differences may become large. In brief, no remarkable precision problems as given by COSMIC data providers come out plainly in this analysis of days within the dubious period. No negative effects or particular biases become clearly evident. However, this conclusion only refers to the precision and cannot be extended to other aspects of data quality. In panels e and f the refractivity ratio profiles of each group are the same as in Figures 2-6 (the same explanation as for panel a applies) and are included just for reference.

In general, it may be seen that the precision of N is quite stable between about 8-25 km and there is a degradation further upwards. However, for T_w and T_d (see Figures 2-6 and 8-12) this deterioration starts lower. N is a byproduct of the Abel inversion, whereas T_d and T_w result from a further step which is the hydrostatic integration (additional errors become introduced). Both procedures propagate profile upper initialization (decreasing) uncertainties downward. Numerical simulations have shown that appreciable temperature biases due to high altitude initialization may be found up to 15 km lower than those of refractivity, reaching the lower stratosphere [*Steiner and Kirchengast*, 2005]. It is also worth mentioning that N and to some degree T_d tend to exhibit larger biases than T_w at the highest altitudes. This may be related to the fact that the same background information used on T_w for close pairs artificially forces better precision values for it. A similar effect may be noticed at the lowest altitudes. Both extreme height ranges are the zones where the background conditions have a significant effect on the retrieved T_w. Although dry profiles are usually provided up to about 60 km height, according to *Das and Pan* [2014] they may be reliable up to an altitude about 50 km. However, they compared means from COSMIC against means from other sources, which does not imply that good quality in individual profiles may be still found at 50 km. Moreover, in our Figures 2-6 it may be clearly seen that precision around 40 km height is always definitely above 1 %. The deteriorating trends in precision for increasing heights around 40 km are quite clear.

We finally assessed accuracy by comparing GPS RO T_w and N profiles with collocated ECMWF analyses. We have chosen a region over the Pacific Ocean (160-200W,30-50N), where assimilated observational data (mainly radiosonde) into the operational model are sparse, and a region in the same latitude range including the USA (80-120W,30-50N), well covered with in situ measurements. We may assume that the ECMWF data are closer to reality over the USA than over the Pacific Ocean (largely model-driven due to lack of data). The degraded model data over the Pacific Ocean should lead to less reliable comparison statistics between GPS RO and the ECMWF analysis (the ”truth”). ECMWF started assimilating GPS RO data after December 2006, so there is no risk in this assessment of artificially improving the comparison performance through the model assimilated data. Accuracy has been evaluated here from the GPS RO data minus the reference values given by the ECMWF model. The results in Figure 13 show similar characteristics regarding both regions and both variables. No significant general feature implying a better performance above the USA comes out clearly. There are just a few salient aspects. There is an average bias of about 0.1 K for GPS RO temperature in both geographic regions between about 10 and 30 km height (roughly the interval where retrievals are less dependent on background data) and somewhat larger at lower altitudes. As the USA region is more reliable, we infer a roughly -0.5 K bias above 35 km altitude, whereas regarding refractivity, a -0.2% bias of the measurements is expected below about 8 km height.

4. Discussion and conclusions

Immediately after launch, the satellites of the COSMIC mission were closely collocated in space and time, which allowed to evaluate the precision of neutral atmosphere variables retrieved by GPS RO against height. We studied wet and dry temperature and refractivity in 5 different latitudinal zones during 20 days of July 2006. Regardless of the 5 groups and the 3 variables, the best precision (about 0.1%) was found between approximately 8 and 25 km height. This altitude interval is less affected by the water vapor ambiguity, by upper initialization issues of the retrievals and by ionospheric residual phase noise. Waves inferred from temperature profiles in the upper troposphere and lower stratosphere [e.g., *Alexander et al.*, 2010b] are therefore reliable if amplitudes lie above about 0.2 K. In general, precision degrades with height above 30 km and performs worse than 1 %. Refractivity and dry temperature exhibit in general similar precision features in terms of latitude bands and heights, but wet temperature apparently performs better in the lower atmosphere and around the top heights of this study. However, it has been shown here that this is an artifact induced by the background information. GPS RO 1DVar retrievals are a weighted combination of the original measurements and a priori, background model or climatological data, where according to *Healy and Eyre* [2000] the former have a dominant role approximately between altitudes 9 and 22 km. Well outside of this altitude interval true precision might be underestimated, as nearly the same background information is used in each collocated pair, which particularly holds for wet temperature profiles. Otherwise, uncertainties related to background conditions used in the retrievals make in general small quantitative contributions to precision issues. There are no clear hemispheric or latitude band differences; only in the polar zones a worse precision in refractivity was found, in NH at the lowest heights and in HS at the largest altitudes. There is no strong dependence of the estimated precision on day and night, on latitude, on season or on the variability degree of the profiles within each group. Therefore, RO exhibits a precision which seems to be roughly independent from the atmospheric conditions. We show that due to insufficient present GPS RO sounding density, it is not possible to evaluate if the nearly 0.1 % precision in the 8-25 km height interval is in general sufficient to resolve day and night average differences in each latitude band. A future larger spatial density of GPS RO may allow us to analyze smaller latitudinal bands, which could lead to smaller dispersions associated to the day and night means, and then it might be possible to detect significant statistical differences among both.

Our initial idea of classifying data into diverse non-overlapping latitude bands was related to the expectation of separating possible emerging precision issues related to the different typical characteristics of the profiles. The payoff was however quite modest: only in the polar zones a worse precision in refractivity was found in NH at the lowest heights and in HS at the largest altitudes (the differences may be due to seasonal effects). Homogeneity and precision were shown to be quite unrelated. Homogeneity exhibits a significant variation among the latitude bands and altitude ranges, while precision against height shows a consistent behavior among the 5 latitudinal sectors. According to some claims found in the literature, GPS RO has in general a good precision against height regardless of the atmospheric conditions, but we are not aware of a supporting study that encompasses the variety of factors contemplated here: variability of the used profiles, latitude, day-night and season (winter or summer).

We show that available COSMIC RO data prior to day 194 of year 2006 have apparently no negative effect on precision estimates or produce no visible impact on average profiles or their variabilities. A possible bias stemming from the use of the dubious period does not emerge clearly. However, this does not imply that other aspects of data quality have not deteriorated. There is a significant increasing trend of available daily sounding somewhat after day 194. However, data providers have suggested the avoidance of earlier data. After a request to the COSMIC staff, we were informed that before about day 194 there were problems with RO L2 phase data (some soundings would be cut off too high or have bad ionospheric correction applied near the bottom), there were difficulties with open loop data (RO might not have penetrated as deeply as they could and there might have been a bias at the bottom) and there was lower amount of retrievals due to obstacles in processing rising events (Doug Hunt 2013, personal communication).

We evaluated accuracy by comparing GPS RO with collocated ECMWF analysis data. We estimated an average bias of 0.1 K for GPS RO temperature between about 10 and 30 km height and somewhat larger at lower altitudes. From our results we expect a roughly -0.5 K bias above 35 km altitude. As to refractivity, a -0.2% bias of the measurements is expected below about 8 km height.

Schreiner et al. [2007] globally evaluated refractivity precision with COSMIC RO pairs that were less than 10 km and 1 min apart between days 111 and 277 of year 2006 (data before day 194 are dubious). They did not evaluate temperature precision because refractivity should be less affected by initialization. In our results, no clear drawback emerges in temperature. They found differences of less than 0.2 % between 10 and 20 km altitude [also outlined by *Anthes et al.*, 2008] and up to about 0.7 % at 30 km. Precision was about 0.8 % at 2 km altitude and decreased to about 0.2 % near 7 km altitude. However, they were not able to see precision degradation above 1 % in the lower atmosphere in the NH and equatorial region and at 30 km and above in HS. The separation of observations according to latitudinal bands, the avoidance of possible seasonal effects due to the use of a short period and the inclusion of temperature profiles may have unmasked in our work some of the features not observed in earlier studies.

Acknowledgments. Manuscript prepared under grant CONICET PIP 11220090100649. P. Alexander, A. de la Torre, P. Llamedo and R. Hierro are members of CONICET. Data downloaded from cdaac-ftp.cosmic.ucar.edu. We thank unknown referees for very helpful suggestions.

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Table 1. Number of pairs of close RO between days 194 and 213 in the five latitudinal bands including their occurrence during day or night.

Latitude band	Day	Night	Total
55^o to 90^o	104	2	106
20^o to 55^o	144	57	201
-20^o to 20^o	58	49	107
-55^o to -20^o	85	246	331
-90^o to -55^o	5	97	102
Total	396	451	847

Table 2. Number of pairs of close RO between days 174 and 193 in the five latitudinal bands.

Latitude band	Number of pairs
55^o to 90^o	60
20^o to 55^o	145
-20^o to 20^o	64
-55^o to -20^o	198
-90^o to -55^o	59
Total	526

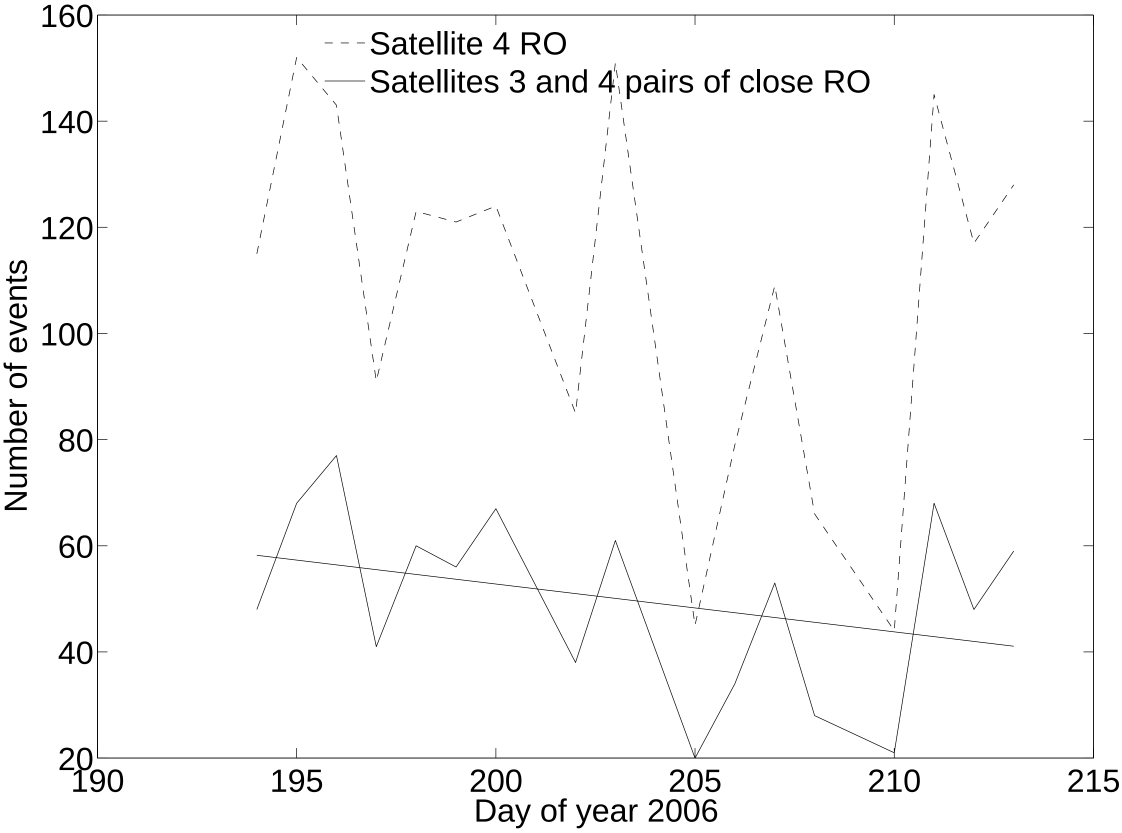

Figure 1. Number of RO retrievals for COSMIC satellite 4 and the number of pairs found with satellite 3 (both per day of year 2006).

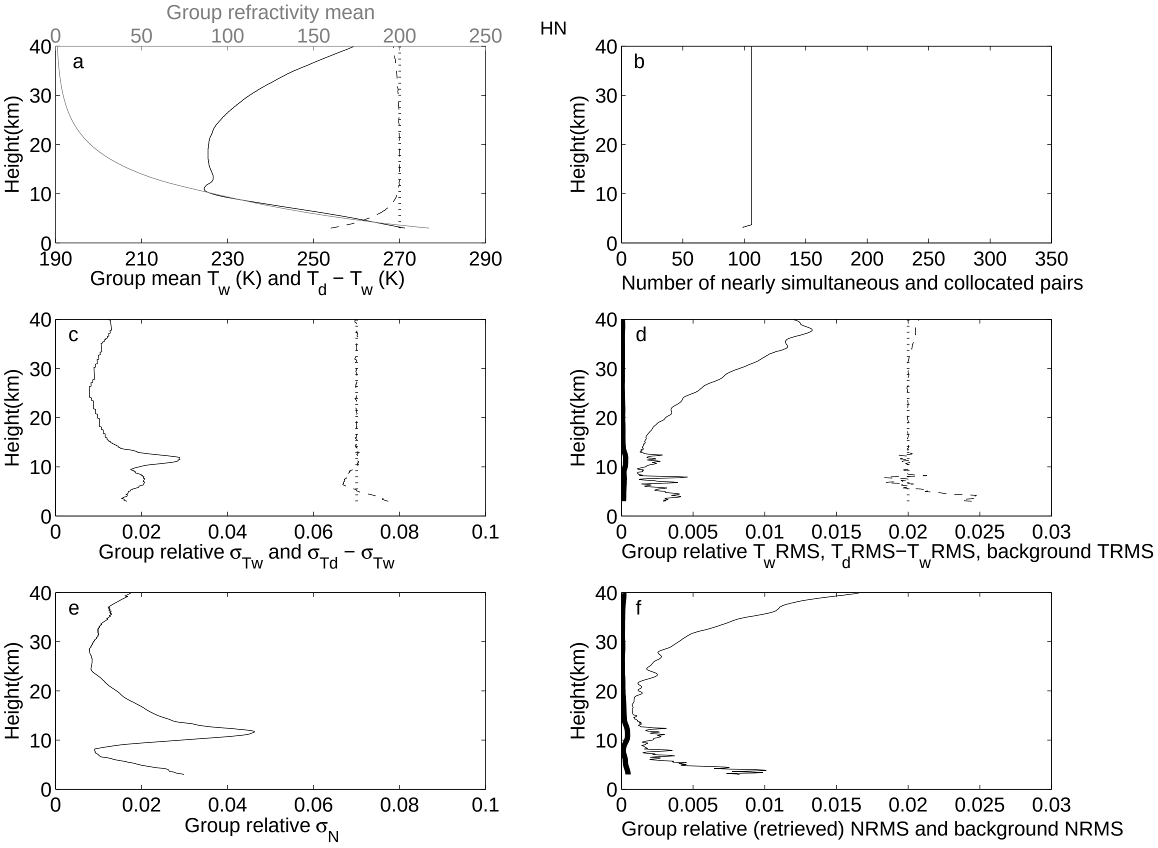

Figure 2. Profiles for group HN against height between days 194 and 213 of a) mean T_w (solid black), mean N (solid grey) and mean $T_d - T_w$ (dashed; zero is represented by the vertical dotted line above 270 K), b) the number of pairs for days 194-213, c) the ratio of the standard deviation and the mean temperature for the wet profiles (solid) and the ratio for the dry profiles minus the ratio of the wet profiles (dashed; zero is represented by the vertical dotted line above 0.07), d) the ratio of the RMS difference of the pairs and the mean temperature for the wet profiles (solid) and the ratio for the dry profiles minus the ratio of the wet profiles (dashed; zero is represented by the vertical dotted line above 0.02), e) the ratio of the standard deviation and the mean refractivity, f) the ratio of the RMS difference of the pairs and the mean refractivity. In panels d and f the bold lines represent the RMS difference in the background fields for the collocated pairs (background N is not used in the 1DVar).

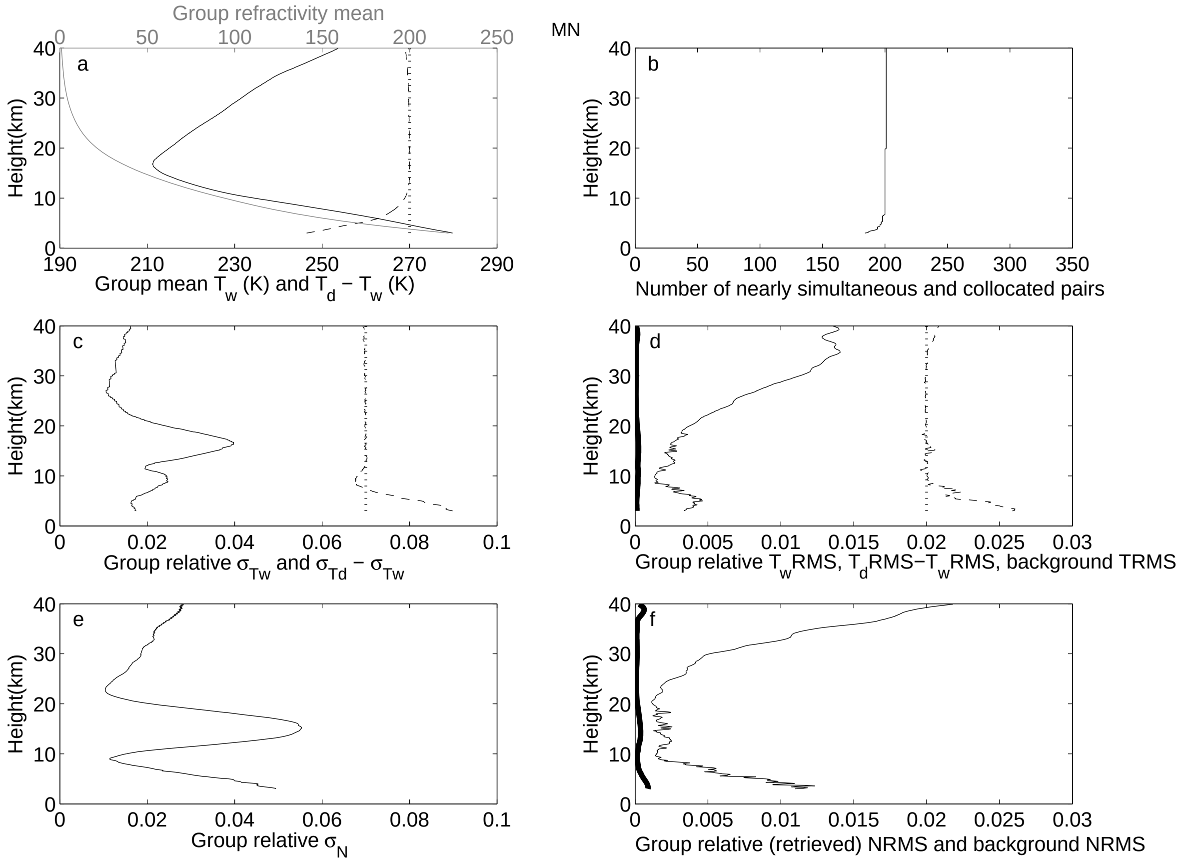

Figure 3. Same as Figure 2 for group MN.

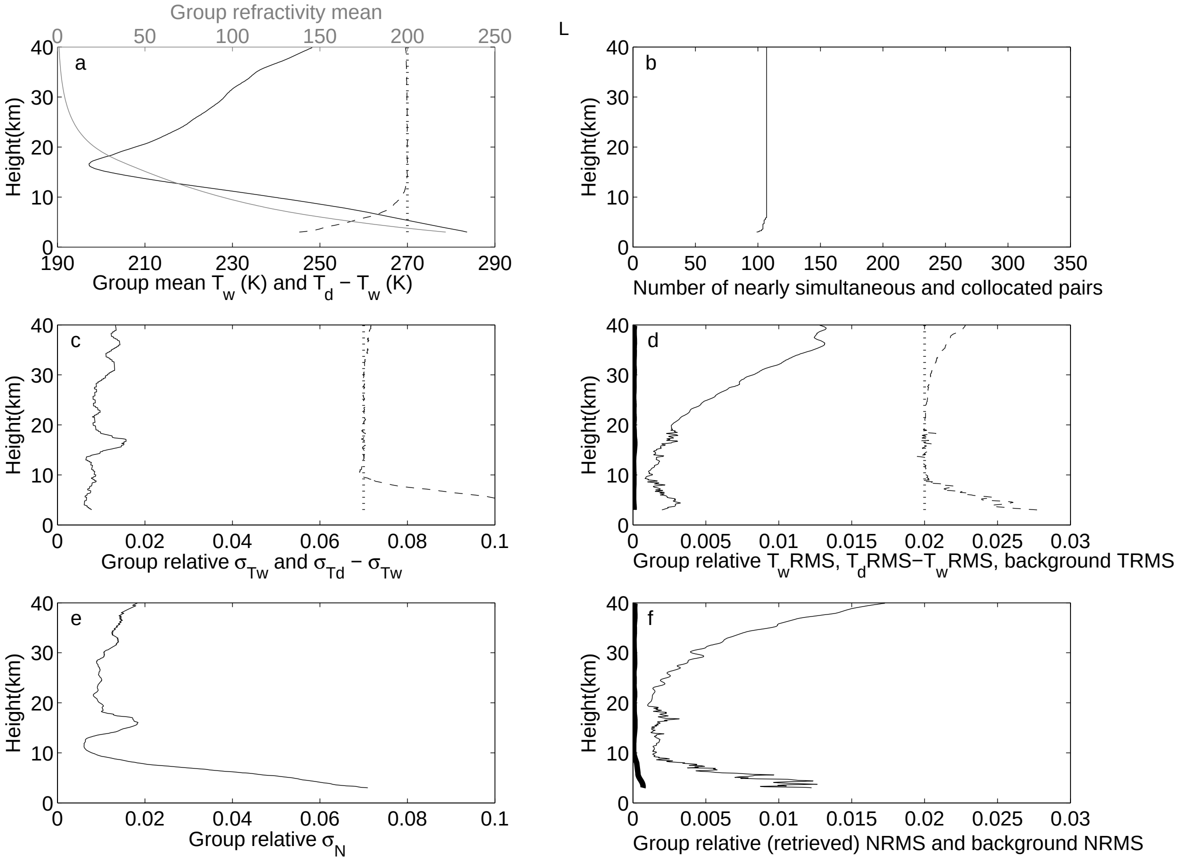

Figure 4. The same as Figure 2 for group L.

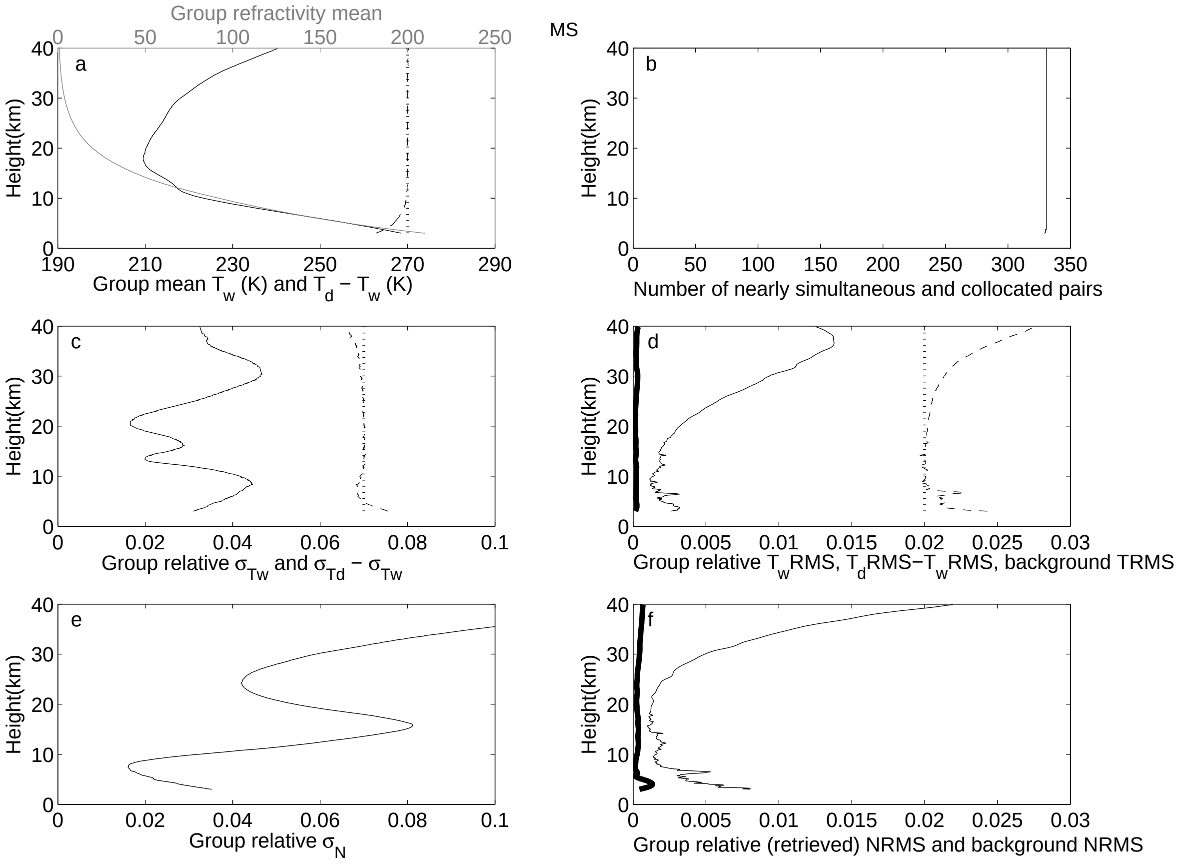

Figure 5. The same as Figure 2 for group MS.

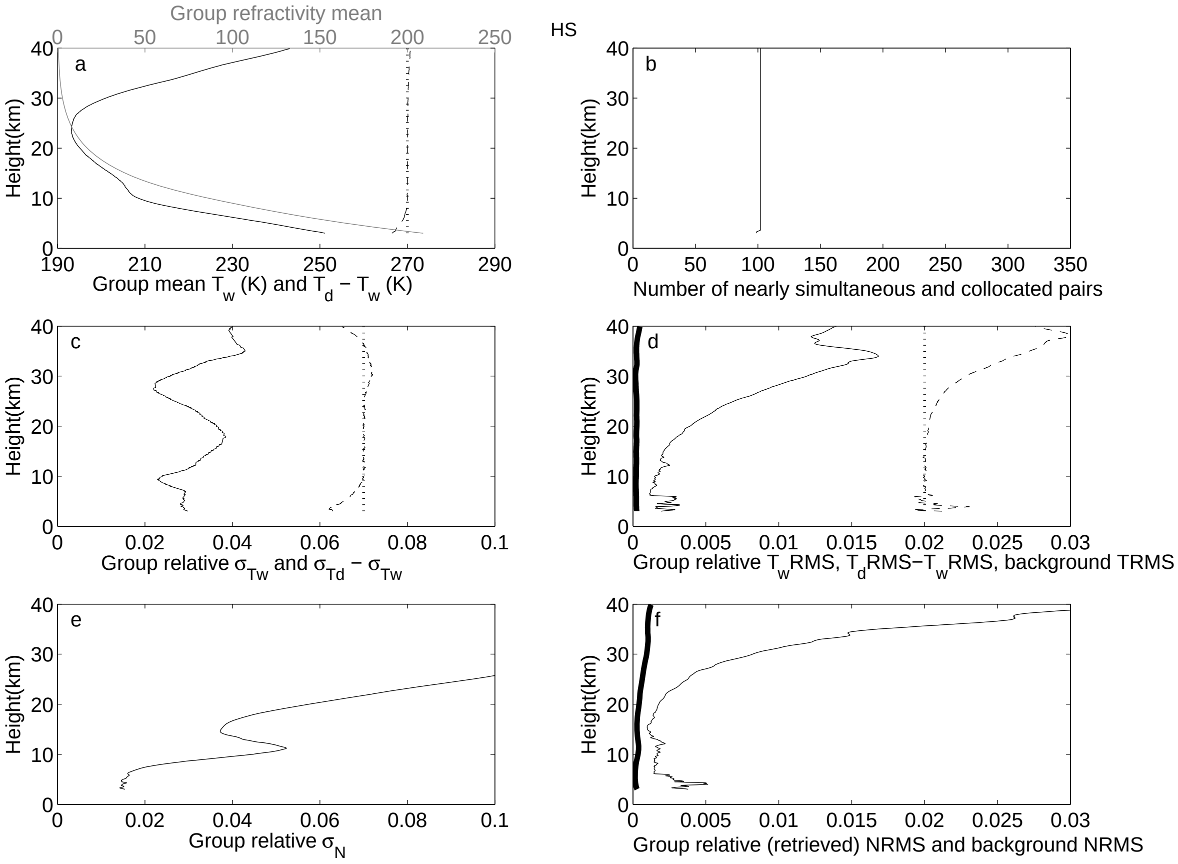

Figure 6. The same as Figure 2 for group HS.

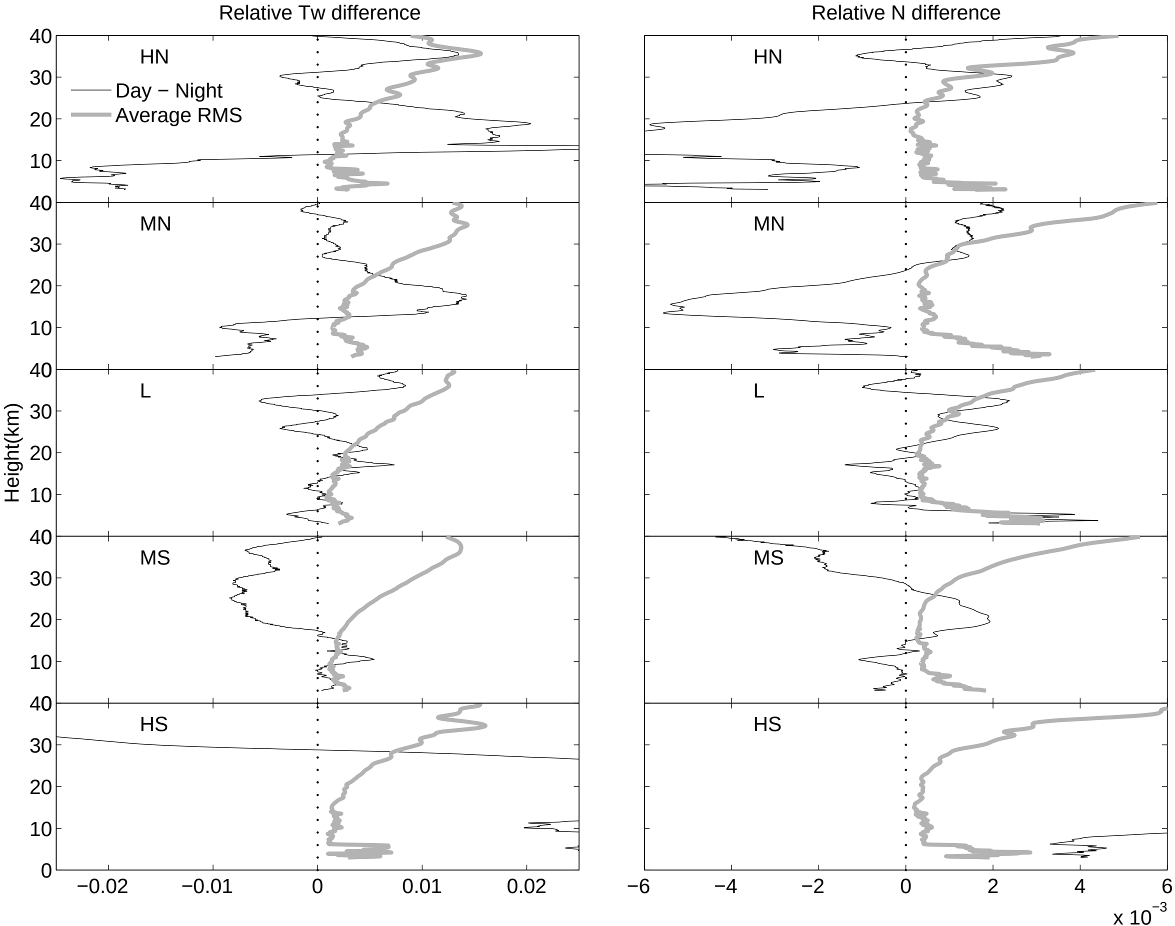

Figure 7. Relative difference between day and night average values and precision (day and night average RMS) against height for the 5 latitudinal bands between days 194 and 213.

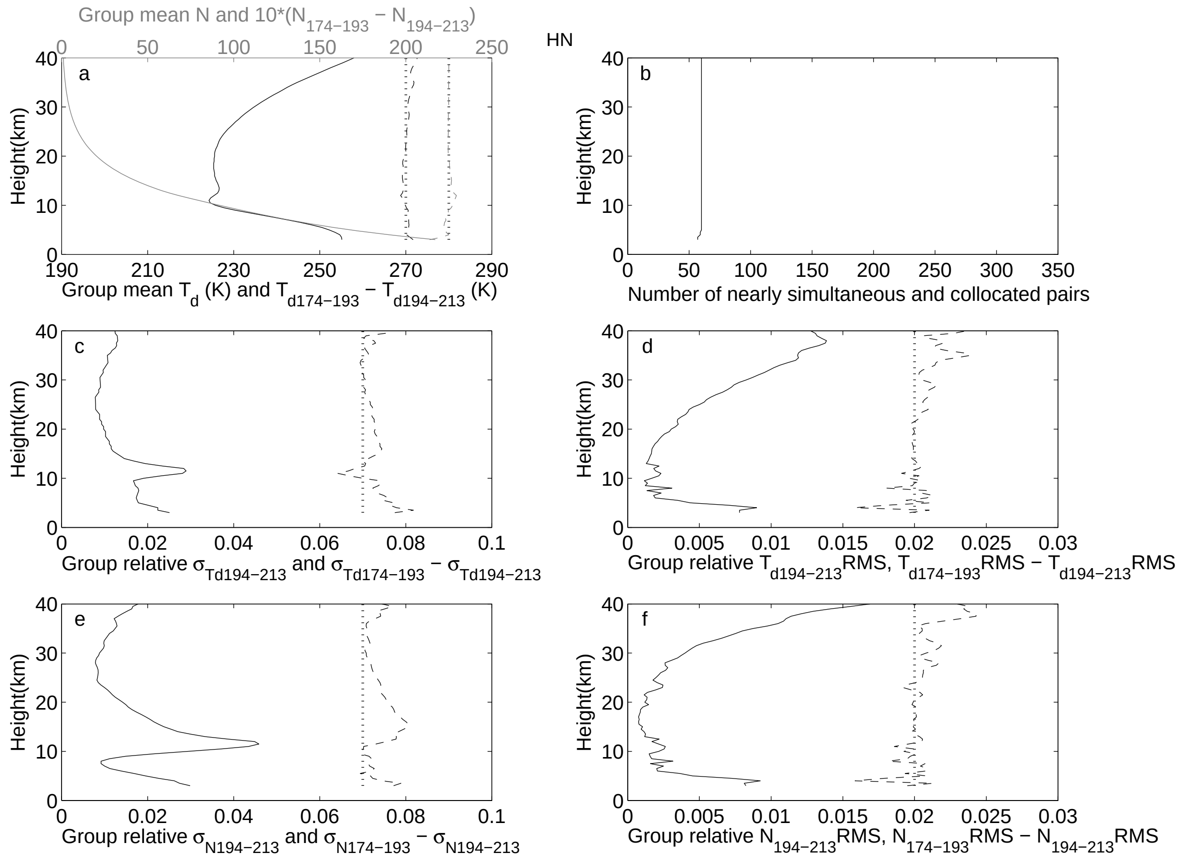

Figure 8. Profiles for group HN against height between days 194 and 213 of a) mean T_d (solid black), mean N (solid grey) and the differences in T_d (dashed black) and $10 * N$ (dashed grey) corresponding to days 174-193 minus 194-213 (in the former zero is represented by the vertical dotted line above 270 K and in the latter below 225), b) the number of pairs for days 174-193, c) the ratio of the standard deviation and the mean temperature for the dry profiles between days 194-213 (solid) and the ratio for the dry profiles between days 174-193 minus the ratio for the dry profiles between days 194-213 (dashed; zero is represented by the vertical dotted line above 0.07), d) the ratio of the RMS of the pairs and the mean temperature for the dry profiles between days 194-213 (solid) and the ratio for the dry profiles between days 174-193 minus the ratio of the dry profiles between days 194-213 (dashed; zero is represented by the vertical dotted line above 0.02), e) the ratio of the standard deviation and the mean refractivity (solid) and the difference between days 174-193 minus 194-213 (dashed; zero is represented by the vertical dotted line above 0.07), f) the ratio of the RMS of the pairs and the mean refractivity (solid) and the difference between days 174-193 minus 194-213 (dashed; zero is represented by the vertical dotted line above 0.02).

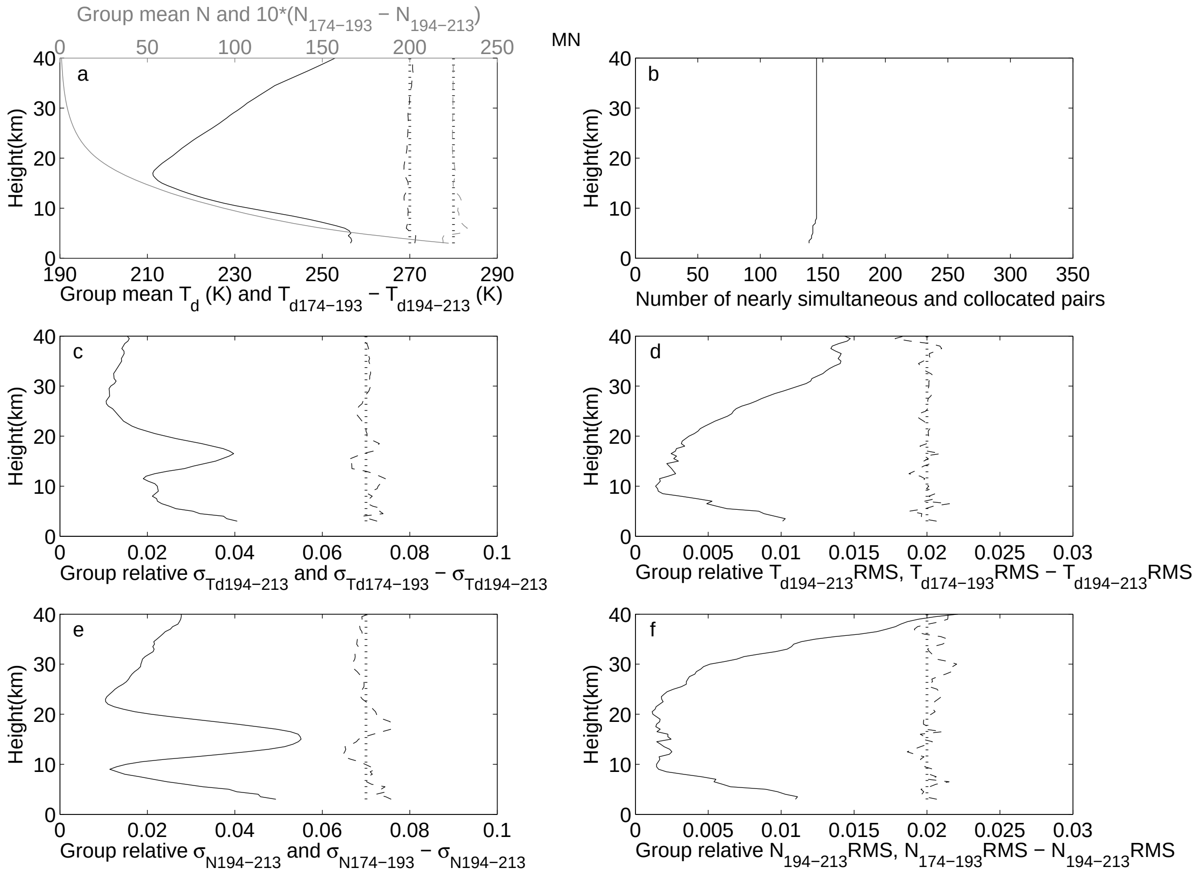

Figure 9. Same as Figure 8 for group MN.

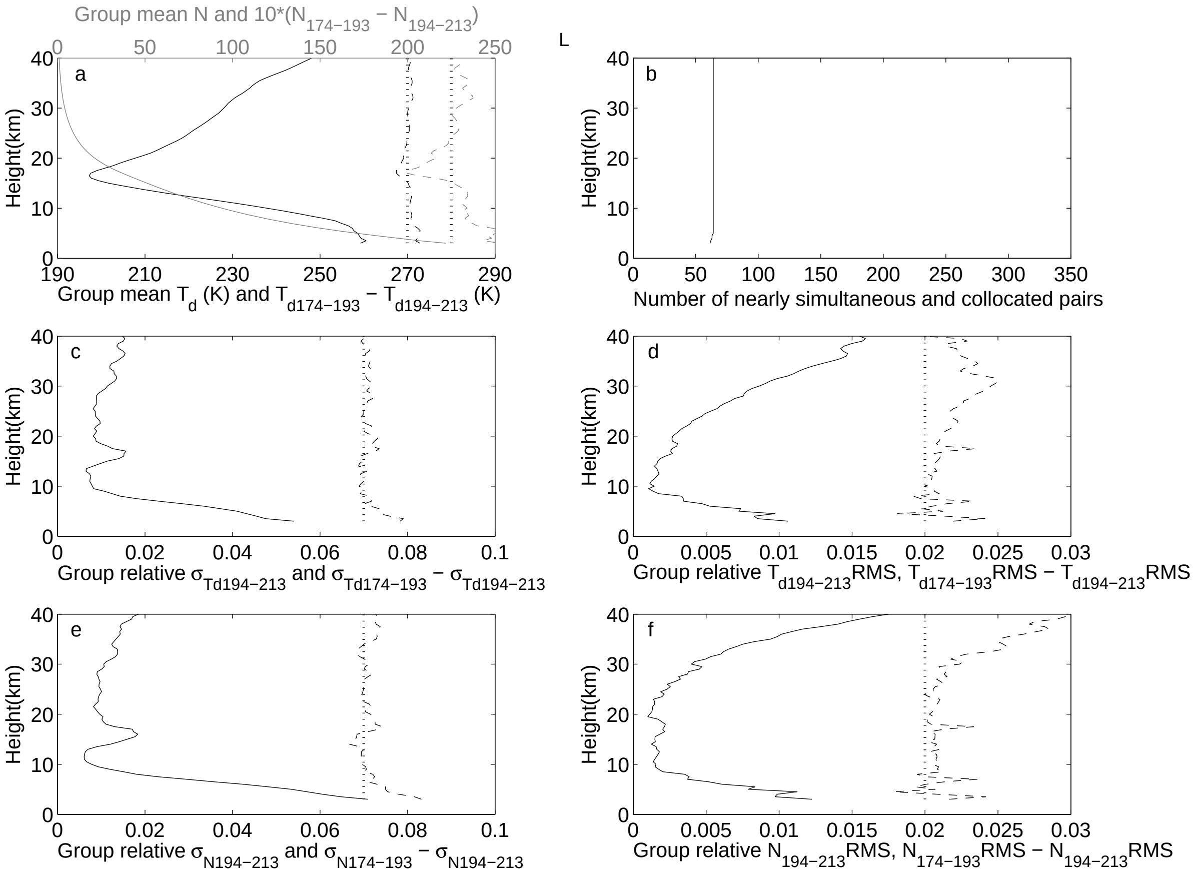

Figure 10. The same as Figure 8 for group L.

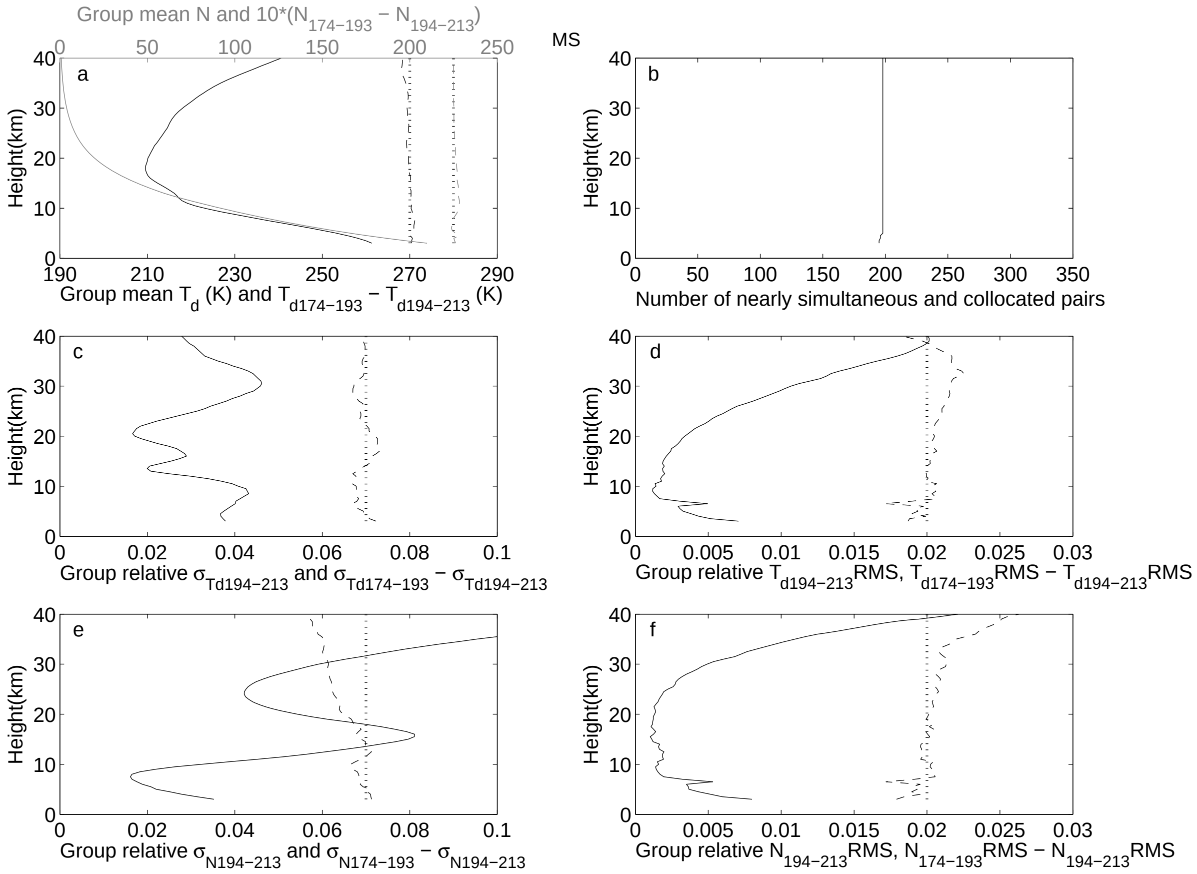

Figure 11. The same as Figure 8 for group MS.

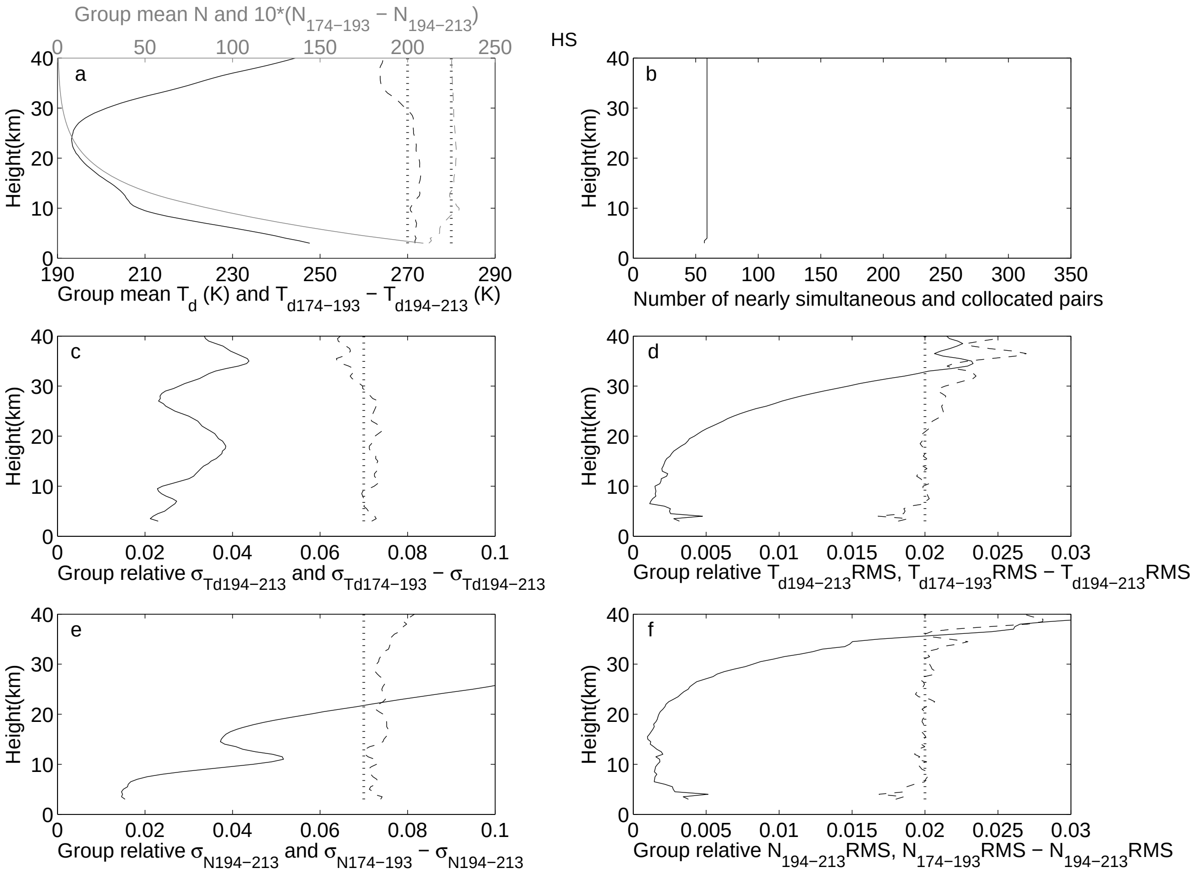

Figure 12. The same as Figure 8 for group HS.

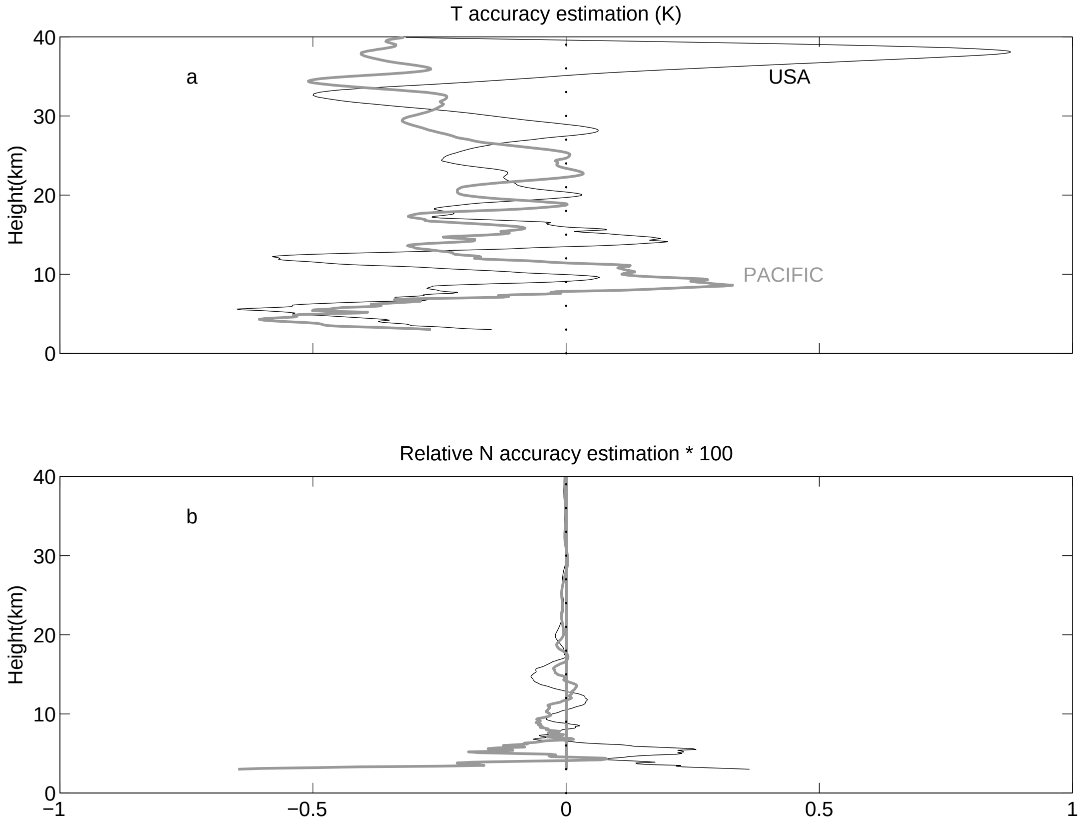

Figure 13. Estimation of accuracy of GPS RO against height in two different geographic regions for a) temperature, b) refractivity (percentage).