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Atmospheric Measurement Techniques Discussions

Interactive comment on "Tropospheric dry layers in the TropicalWestern Pacific: Comparisons of GPS radio occultation with multiple data sets" *by* Therese Rieckh et al.

Therese Rieckh et al.

rieckh@ucar.edu

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We thank the anonymous referee for the thorough review and all comments. We will implement the following changes according to the referee's suggestions. We have answered all comments below (for easier comparison the referee comments are included in italic).

Page 3, Line 1 (P3, L1): The reference to Randel 2016 is vague. Is this paper in preparation, submitted, etc.?
The complete reference has been provided.

P5, L19: The instrument resolution is not the same as the retrieved product resolution for AIRS. The authors should quote the horizontal resolution of the retrieved temperature and humidity Level 2 products, not the instrument resolution.
We changed the sentence to:

"The AIRS Level 2 products are reported on 28 standard pressure levels between 1100 hPa and 0.1 hPa. They have a horizontal resolution of 50 km[1], and a vertical resolution of ∼1 km for temperature and ∼2 km for humidity[2]."

P5, L28: I believe it is incorrect to suggest that the in-situ measurements have large sampling errors by comparison. Sampling error is the difference between a measurement value and the actual atmospheric state given the sampling volume.
We should have used "representativeness error" or "representativeness difference" rather than "sampling error". We modified the sentence beginning with "As such....." in line 26 to:

"AIRS, RO, and models, on the other hand, represent averages over much larger horizontal and vertical scales of observation (larger horizontal and vertical footprints). Thus different volumes of air are sampled and compared, leading to representativeness errors or differences due to their different horizontal and vertical footprints, especially when measuring fields with high temporal and spatial variability such as water vapor and relative humidity."

P6, L11: This reads as follows: the time and space criteria consist of three pairs of values. What is meant by "closest" in time and space? Given the pairs, it is ambiguous. Which pair represents the maximal degree of collocation?
We clarified this discussion as follows:

[1] http://disc.gsfc.nasa.gov/uui/datasets/AIRS2RET_V006/summary
[2] http://airs.jpl.nasa.gov/data/physical_retrievals

"Note that the shortest time windows in these criteria correspond to the longest spatial intervals; this is done to ensure enough pairs in sets matching each of the criteria. Using a criterion of the shortest time and space separation would not yield enough pairs to make the results as meaningful. As shown in Section 5 below, all three of our criteria gave similar results; thus we only show results for the 3 h and 600 km criteria."

We also show the statistics showing the similar results (see response to the comment P11, L30 below).

P6, L19: It's not clear that the GFS and ERA profile shapes are limited by "lower vertical resolution" (Figure 2). How many levels are there between 0 and 2.5 km? It may be more subtle factors such as model physics, or limited observations, that account for the profile shape.
P10, L7: I agree that AIRS vertical resolution cannot capture the transition, but the number of levels of GFS or ERA may be able. Please state the number of levels in these models for the different lower troposphere altitude ranges.
P16, L3: I need to be convinced (based on the number of levels) that resolution is what limits GFS and ERA, versus other factors such as physics, or assimilation data set and method, etc.
Since both reviewers commented on the vertical resolution of ERA and GFS, we provide a response here adressing all concerns of both reviewers:

Vertical profiles from the ERA and GFS analyses interpolated to RO locations are provided by COSMIC CDAAC for pressure levels (while the RO physical profiles are given on a 100 m grid). GFS is given on the following pressure levels: from 1000 hPa to 250 hPa every 50 hPa, and additionally on 975 hPa and 925 hPa (plus additional levels above 250 hPa which are not relevant here). ERA is given on the following pressure levels: from 1000 hPa to 750 hPa at 25 hPa steps, and from 750 hPa to 250 hPa at 50 hPa

steps (plus additional levels above 250 hPa which are not relevant here). Assuming a scale height of 8 km, this yields a total of 18 levels for ERA and 15 levels for GFS where RO provides reliable moisture information (below 8 km, about 375 hPa). There are 80 RO levels between the surface and 8 km. Thus the vertical resolution of the ERA and GFS analyses provided by CDAAC is much lower than that of the RO observations.

CDAAC does not provide RO-collocated model profiles on model levels. Thus we downloaded an example day of the ERA fields for both pressure and model levels and converted model levels to pressure levels ourselves. Assuming a scale height of about 8 km, ERA provides 18 pressure levels below 8 km (corresponding to about 375 hPa) and 25 model levels. A few of these extra model levels are at very low altitudes (near the surface, at altitudes with pressure greater than 1000 hPa, which is the lowest given pressure level for ERA on a pressure grid). Consequently, this leaves only a few more extra model levels that would increase the vertical resolution when compared to pressure levels.

Assuming again a scale height of 8 km, a pressure of 750 hPa corresponds to 2.4 km. This yields 8 pressure levels for GFS and 11 pressure levels for the ERA between 1000 hPa and 750 hPa (surface to 2.4 km). The vertical separation between levels increases further when going to higher altitudes. The smoothness (lack of vertical detail) of the GFS and ERA profiles compared to the RO and CONTRAST profiles is an indication of the lower vertical resolution of these models compared to RO and CONTRAST. The important point is that the overall shape of the GFS and ERA profiles is similar to the overall shape of the higher-resolution profiles (RO and CONTRAST). Other factors such as model physics or limited observations could not increase the vertical resolution of the GFS and ERA profiles, but they could change the overall shape.

The bottom line: increasing the vertical resolution of the GFS and ERA profiles by adding a few more levels in the vertical would not change the overall shape nor the conclusions. We are confident in our comments on P6 L18 and P10 L8 that the less

sharp vertical gradients in moisture at the top of the moist layers in the model analyses are "partly due to lower vertical resolution".

P11, L10: Please provide reference(s) to the previous work mentioned.
The "narrow dry tongues" actually refer to stratospheric intrusions on the rear of strong extratropical cycles (as in Young et al. (1987), Browning and Dicks (2001), and Keyser and Shapiro (1986)) and not the large-scale sinking air that is studied here. Thus we removed the entire paragraph (P11, L9-11) and instead edited the paragraph starting at P10, L14:

"Fig. 4, top right, shows the ERA RH fields at 500 hPa for the whole region. The large-scale region of very dry air extends from 110°E to 180°E with a width of 1600 km to 2200 km. It also shows the high horizontal variability of moisture."

P11, L30: Given the similarities mentioned, is there a compelling reason not to show the aggregate statistics for all the collocation criteria?
In the revised paper we now present the aggregate statistics for relative humidity differences between RO and CONTRAST, ERA and CONTRAST, and GFS and CONTRAST for the three collocation criteria. We added the following sentence at page 11, line 30 (after "..profile statistics and scatter plots"):

"To illustrate the similarities, we show the mean, root mean square (RMS), and Pearson R correlation coefficient for relative humidity RH for RO-CONRAST, ERA-CONTRAST and GFS-CONTRAST differences for all three criteria in Table 2. We chose RH due to our focus on tropospheric moisture in this paper. Furthermore, RH is the only parameter without some inherent vertical correlation due to a general decrease with altitude (i.e. N, T, and q)."

Furthermore, we accidentally included data above 10 km in the scatter plots, but

Table 2. Mean, RMS, and Pearson R coefficients for differences in relative humidity RH of RO-CONTRAST, ERA-CONTRAST, and GFS-CONTRAST for 3 different collocation criteria.

		3 h 600 km	**12 h 300 km**	**24 h 200 km**
		644 points	687 points	419 points
	mean	-4.0	-6.5	-0.2
RO-CONTRAST	RMS	21.3	23.4	22.5
	Pearson R	0.782	0.758	0.751
	mean	-3.9	-5.4	0.6
ERA-CONTRAST	RMS	20.0	20.5	21.8
	Pearson R	0.807	0.807	0.760
	mean	-5.0	-6.3	-0.1
GFS-CONTRAST	RMS	20.7	21.4	21.9
	Pearson R	0.799	0.798	0.757

discarded some of the data below. In the revised paper all data points below 10 km are included in the scatter plots. This does not change the results or the conclusions we can draw from them. The corrected scatter plots are included in the revised manuscript.

P12, L5: Figure 6 as presented has limited value because the contribution of collocation error to RH scatter is completely unconstrained, thus compromising the value of this information in assessing RO. An attempt should be made to assess the contribution of collocation error (e.g. vary collocation criteria in time and space to assess scatter growth with collocation distance, or use reanalyses to assess – in a lower-bound sense – the contribution from collocation).
Comparisons using 8 years of radiosonde (2 stations) and RO data using very tight collocation criteria (1 h, 100 km) still showed highly scattered data for RH (Figure 1). Thus the collocation errors are not the dominant factor in the large scatter between RO and CONTRAST relative humidities. Relative Humidity is a highly variable parameter, even if comparisons are made that close in time and location. Tighter criteria are

Fig. 1. Scatter plot of RO relative humidity and radisonde (RS) relative humidity for pairs of RO and RS data located within 1 h and 100 km.

maybe possible using a long radiosonde record, however, with the very limited number of collocations of CONTRAST and RO, that is not possible. The point of Fig. 6 lower right and Fig. 7 left is that RH is a highly variable parameter and that small differences in temperature and/or specific humidity make large differences in relative humidity. These differences occur when the scale (footprint) of the different observations vary, as they do between RO and CONTRAST and ERA and CONTRAST. The scatter is less when the footprints of the two correlated RH values are similar, as in GFS vs. ERA (Fig. 7, right), but the scatter is still large compared to the scatter of temperature, refractivity, and specific humidity (Fig. 6).

P15, L16: Appendix A has limited value, as it represents a single profile, but the difference between 1DVAR and "simple" depends critically on the accuracy of the temperature used in simple. Additional factors affect 1DVAR accuracy. A simulation or analytical treatment of the technique differences would be more useful, that spans a range of temperature errors (among other factors). It would seem more useful to quote the literature on errors of the simple method (e.g. Vergados et al. publications) and compare these errors to what is expected in the 1DVAR. I recommend removing or strongly modifying Appendix A to take these factors into account. If Appendix A is removed, the literature should be consulted as to how 1DVAR and simple might differ, and the appropriate references included and quoted.
We rewrote Appendix A and added figures that further explore the differences in moisture resulting from applying the simple retrieval versus the 1D-Var and included references to the work of Vergados and colleagues. Appendix A now contains statistics of many comparisons of the simple and 1D-Var retrievals in addition to the one example:

Appendix A: RO Water Vapor Retrievals:
The two common techniques to retrieve physical temperature and water vapor profiles from RO are the so-called simple retrieval (Kursinski and Hajj, 2001) and the 1D-Var retrieval. For the simple retrieval, e is derived via Eq. 1 using the RO observed N, and T from an independent source (e.g. radiosonde, model, or analysis). Advantages of the simple retrieval are its simplicity and ease of calculation, and its independence of model moisture (and thus independence from errors in model moisture). Vergados et al. (2015) used the simple method for this reason, using ECMWF temperatures for the independent temperatures. Ware et al. (1996) (Eq. 3 and 4 in their manuscript) noted that for a perfect N and p, the error (difference) in e related to an error (difference) in T can be approximated by:

$$\Delta e \approx \frac{2TN - 77.6p}{3.73\times10^5}\times\Delta T A1 \tag{1}$$

The simple method provides good results ($\Delta e < 0.25$ hPa) in the lower troposphere if the ancillary temperature data are reasonably accurate ($\Delta T < 1$ K). In the 1D-Var procedure, a-priori (first guess or background) profiles of T and e are obtained from independent observations and adjusted toward the RO measurements by a statistical optimization procedure (Poli et al., 2002; COSMIC, 2005). The 1D-Var procedure considers the statistics of errors in the RO observations as well as the statistical errors in the a-priori information, to achieve a consistent temperature and water vapor profile that minimizes, in a statistical sense, the errors in T and e.

Because both the 1D-Var and simple method are used in different studies to estimate water vapor, it is important to understand how the results from the two methods compare. In this Appendix we compare the two methods using the data in our study by first showing an example and then statistics using a large number of data pairs. Fig. 2 shows the parameters RH, T, q, and e for the first guess (ERA, solid) and retrieved

Fig. 2. T, RH, q, and e profiles for ERA (solid, a-priori), RO 1D-Var (dashed), and RO simple retrieval (dotted).

from RO with the 1D-Var (dashed) and the simple retrieval (dotted) for an example profile.

The RH (top left) is very low between 4 km and 9 km. The simple retrieval and the 1D-Var agree very well up to 4 km. At 4.2 km and 6 km to 9 km, the simple retrieval produces a negative RH (due to negative e values). In the simple retrieval, any error in T will produce an error in e, and for dry air (e close to zero), this error may lead to an unphysical negative value for e, q, and RH. The 1D-Var can theoretically also reach negative values in these situations, but it is artificially set to a very small positive value (10^{-6} hPa) in the COSMIC CDAAC 1D-Var retrieval.

The RO 1D-Var and first guess (ERA) T (top right) agree very well; temperature differences are within 1.5 K throughout the profile. (The RO T in the simple retrieval assumes ERA T to be the truth, so it is identical to the ERA T in this figure.)

The bottom panels show q and e. Both parameters become negative above 4.2 km in the simple retrieval.

Generally, the moisture profiles derived from both the simple retrieval and the 1D-Var show much more vertical structure than the ERA profile; this structure comes from the vertical structure of the RO refractivity profile. The above example shows that the simple and 1D-Var methods give very similar results for temperature, specific humidity, water vapor pressure, and even relative humidity up to the bottom of the very dry layer (a little above 4 km) where the water vapor pressure becomes less than 0.1 hPa. The close agreement in this example is typical, as shown by a comparison of the simple and 1D-Var method over a large number of cases.

We compared values of T, q and RH computed from the two methods, using ERA

Fig. 3. Specific humidity from the RO 1D-Var retrieval (left) and simple retrieval (right) versus radiosonde data. Collocation criteria: 2 h 200 km, altitude range 1000 hPa to 200 hPa.

Fig. 4. Specific humidity from the RO 1D-Var retrieval compared to the RO simple retrieval, using the same profiles as in Fig 3. Points from profiles for which the collocated radiosonde profile experiences super-refraction are marked by an X.

T directly for the simple retrieval and ERA T and q as the first guess for the 1D-Var estimates, against radiosonde data from Vacoas, Mauritus (20.3°S, 57.5°E), which is located in a region that frequently contains very dry layers. We used the period 2006 to 2014, using collocation criteria of 2 h and 200 km. Because of large uncertainties in radiosonde humidity measurements above 10 km (Miloshevich et al., 2006), we focus on comparisons over 1000 hPa to 200 hPa.

Scatter plots of q from the 1D-Var retrieval (left) and the simple retrieval (right) versus the independent radiosonde observations are shown in Fig. 3. The results are very similar with a correlation of 0.914 for the 1D-Var retrieval and 0.908 for the simple method.

Fig. 4 uses the same data as above, but shows the scatter plot of specific humidities from the 1D-Var versus simple retrieval. The retrieved values from the two methods are very similar with a correlation of 0.994. Approximately 15 points (blue, i.e. pressure altitudes of about 800 hPa) show 1D-Var values that are significantly higher than the simple values. We suspected that these points were from profiles where super-refraction occurs. In the case of super-refraction, N is biased negatively (Sokolovskiy, 2003) and e from the simple retrieval, which uses an accurate estimate of T, will be too low. In 1D-Var, the negative RO N bias will be mitigated to some extent and the resultant 1D-Var temperature will be too high and the water vapor pressure too low, but not as low as in the simple retrieval. Thus e from the simple method will be significantly

lower than the e from the 1D-Var method under conditions of super-refraction.

To test this hypothesis, we checked all radiosonde profiles in the pairs for the criterion for super-refraction (dN/d$z < -157$ N-units km^{-1}). If a profile contained this critical value at some pressure level, we marked all data points of that profile with an X in Fig. 4. Indeed, most of the points with strong differences between 1D-Var and simple appear to occur with super-refraction.

We note that neither the 1D-Var nor the simple method for computing water vapor pressure at high altitudes (p <200 hPa) from observed RO refractivity N will provide reliable estimates, because at these altitudes water vapor contributes very little to the refractivity; i.e. the so-called "wet" term in Eq. 1 is less than 1% of the first, or "dry" term as noted by Wang et al. (2013). There is simply not enough information on water vapor pressure in refractivity at these altitudes to retrieve accurate estimates of water vapor. For example, the mean hurricane-season tropical atmosphere (Dunion and Marron, 2008) gives the following value of T at 200 hPa (about 12.4 km altitude): $T = -54.6\,^{\circ}$C (218.6 K). The saturation vapor pressure at this temperature is 0.04 hPa; thus for 100% relative humidity, the dry term for N is 71.0 and the wet term is 0.31, or 0.4% of the refractivity value. For the above values, the relationship between errors in e and T (Eq. 1) gives $\Delta e = 0.042\Delta T$ (hPa). So a temperature error (difference) of 0.5 K gives a difference in e of 0.021 hPa, which is more than 50% of the saturation vapor pressure at this temperature. This example illustrates the difficulty in calculating water vapor pressure and relative humidity in the upper troposphere. Vergados et al. (2014) estimated the retrieval errors in specific humidity at different pressure levels (925, 850, 700, 500, and 400 hPa). They estimated that in the lower troposphere (925, 850 and 700 hPa) the percentage error in specific humidity for a temperature uncertainty of 1 K was less than 3 % in the tropics, 6 % in middle latitudes, and 10 % in high latitudes. At 400 hPa, the percent errors grew to 18 % in the tropics, 45,% in middle latitudes, and 67 % in high latitudes.

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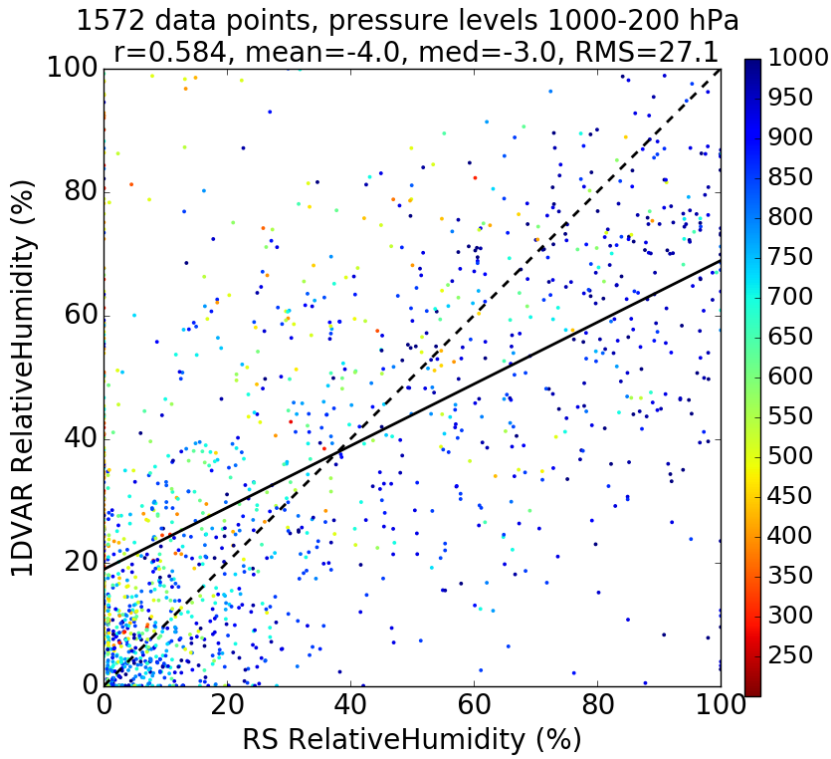

Fig. 5.

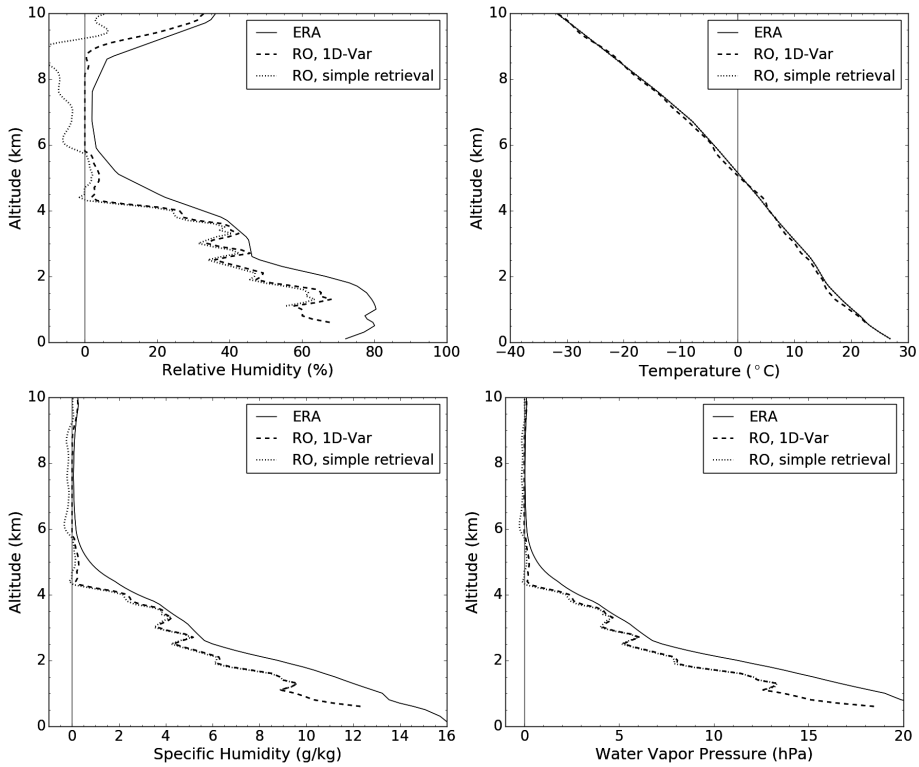
ERA
RO, 1D-Var
RO, simple retrieval
Altitude (km)
Relative Humidity (%)
Temperature (°C)
Specific Humidity (g/kg)
Water Vapor Pressure (hPa)

Fig. 6.

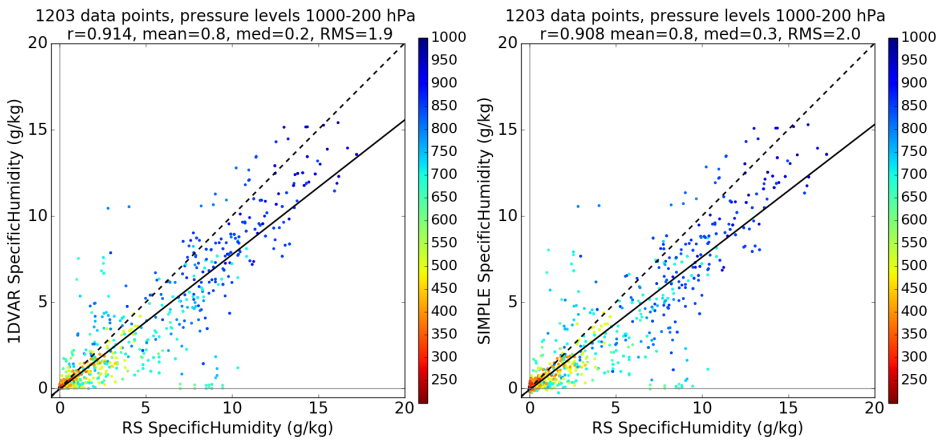
1203 data points, pressure levels 1000-200 hPa
r=0.914, mean=0.8, med=0.2, RMS=1.9
1DVAR SpecificHumidity (g/kg)
RS SpecificHumidity (g/kg)
1203 data points, pressure levels 1000-200 hPa
r=0.908 mean=0.8, med=0.3, RMS=2.0
SIMPLE SpecificHumidity (g/kg)
RS SpecificHumidity (g/kg)

Fig. 7.

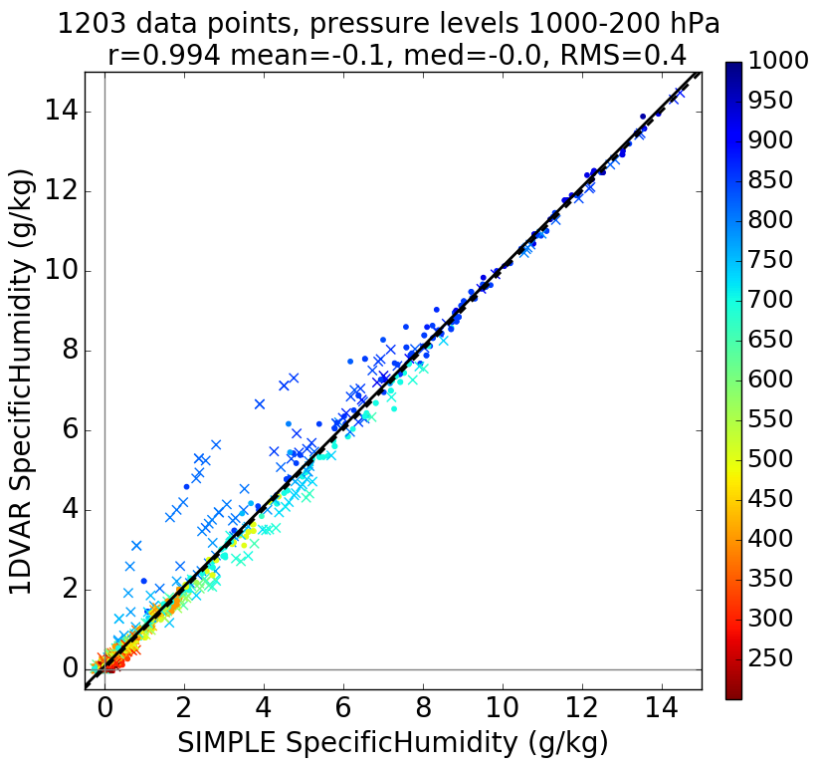
1203 data points, pressure levels 1000-200 hPa
r=0.994 mean=-0.1, med=-0.0, RMS=0.4
1DVAR SpecificHumidity (g/kg)
SIMPLE SpecificHumidity (g/kg)
0
2
4
6
8
10
12
14
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250

Fig. 8.