

Interactive comment on “A microwave satellite water vapour column retrieval for polar winter conditions” by C. Perro et al.

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1 Response to Referee 2

Referee: The manuscript presents a new algorithm (PLDC15) for the retrieval of Arctic column water vapor from measurements by microwave instruments deployed on operational meteorological weather satellites. Monitoring water vapor in this climate sensitive region is both challenging and important.

The algorithm is only a slight update of previous ones, i.e. Melsheimer and Heygster (2008; called MH08) retrieval. However, the incorporation of a priori information is shown to provide a major benefit in a synthetic study and in the assessment using

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ground-based observations (GVR) at Barrow as a reference. Several other water vapor products are also evaluated providing an interesting add-on. In general the paper provides an interesting contribution though the relation of the study to previous work (see below point 1) and the uncertainty analysis (2) need to be improved. The latter also includes the formulation of statements in respect to algorithm quality.

Authors: We thank Referee 2 for their overall positive view of our manuscript and for making helpful suggestions on how to improve it.

Referee: 1. In the introduction I am missing background information on the need of algorithm, e.g. see Serreze et al. (2012), motivating the evaluation of the new algorithm and its relative performance to various water vapor products from reanalysis and satellite. Further, the introduction should include an overview of other sources of information/ground truth for water vapor like the classical radiosonde profiling and many more – see also the GEWEX water vapor assessment (G-vap; <http://gewex-vap.org/>) to motivate that the GVR is especially suited. In my view the introduction should already name the challenges of satellite retrievals and intercomparisons, namely the problem of varying surface emissivity (nowhere the variation with surface type is quantified) and spatio-temporal variability of water vapor (Bühler et al., 2012, Tobin et al., 2006).

Authors: We have split the first paragraph and expanded upon it to help better motivate our study:

“The polar winter troposphere is very dry, with water vapour columns typically near 3 kg m^{-2} (Serreze et al., 1995). Climate change is expected to increase absolute humidity and alter the polar radiative balance (Stamnes et al., 1998) with consequences for sea ice and global climate. Accurately monitoring polar humidity variations is difficult owing to the small water

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vapour concentrations and the few ground-based stations from which observations may be conducted. Infrared and visible satellite measurements have better spatial coverage but are challenged by scattering and absorption from clouds and the lack of solar radiation during polar winter.

Microwave satellite measurements overcome many of the difficulties. Microwaves have strong water vapour absorption lines that are useful for dry conditions, and their emissions can be observed during any part of the diurnal cycle. Microwaves are less affected by scattering and absorption, allowing for water vapour measurements in most weather conditions (Miao et al., 2001). Microwave instruments aboard a series of polar-orbiting satellites since 1991 (F11 to 19, NOAA-15 to 19, MetOP-A and B, FY3-A to C, and NPP) already provide a substantial data set for water vapour studies. Planned missions include JPSS-1 and 2, MetOP-C, and DMSP-S20."

The Serreze et al. (2012) paper provided by the Referee proved helpful, and we now reference it in our manuscript in the new Sect. 4.4 (see response to the Referee's point 2).

We have added the following to the Introduction to emphasize the reasons we chose the GVR as ground truth:

"The continuous measurements, relatively low uncertainties, and availability of complementary measurements (most notably a micro pulse lidar) make the GVR an ideal instrument against which to test satellite retrievals."

The lidar measurements available at the ARM site were used in our response to the second paragraph of the Referee's point 2.

With respect to surface emissivity, we added the following to the end of the Introduction:

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"Complications arising from varying microwave surface emissivity are not treated in this paper, which only examines the retrieval at a single location. A follow-on paper that applies the retrieval in a pan-Arctic context will explore this important topic."

The issue of spatio-temporal variability is now addressed in the new Sect. 4.4, including addition of references to the papers by Buehler et al. (2012) and Tobin et al. (2006). See the response to the Referee's point 2.

Finally, we amended the Conclusions to emphasize the clearer picture the new retrieval brings:

"A new retrieval based on the microwave formulation developed by Miao was introduced. Simulations show that the new technique reduces errors compared to earlier approaches if a priori information for the atmospheric conditions is used. In a comparison with ground-truth measurements, the new PLDC16 retrieval provides more accurate water vapour columns than other satellite measurements having a standard deviation of 0.39 kg m^{-2} and a bias of 0.08 kg m^{-2} , and better resolution than atmospheric analysis data products. Given the benefits of a priori information, optimal estimation techniques (Rodgers, 2000) may further improve water vapour retrievals.

Maps of water vapour can be created that reveal fine structure that conventional reanalyses are unable to discern. Pan-Arctic water vapour charts can be created twice per day using the combination of overpasses from NOAA-18 and MetOP-A alone. Temporal resolution may be further improved by including additional instruments. Given historical satellite data sets and planned launches, microwave water vapour measurements may provide new insights into the changes in Arctic climate."

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Referee: 2. The authors are sometimes too optimistic with their statements (see detailed description in my minor comments). In its current form I can (yet) not share the view of the authors on their algorithm as expressed in the abstract: "The errors are shown to be significantly less than for other satellite measurement systems." or on p9970, l17 "The results indicate that the PLDC15 retrieval is more accurate." In section 4 the performance of the algorithm (PLDC15) in comparison to MH08 is tested on a synthetic data set. Here Case 1 (ideal) and Case 2 (addition of noise) represent self tests of the PLDC15 algorithm and only Case 3 is a realistic application. For Case 1 and 2 MH08 can not perform better as the coefficients are not tuned to the specific situation. For the realistic application (Case 3) for most regimes MH08 is superior to PLDC15 (see Table 3)? This proves that the major benefit of PLDC15 arises from the incorporation of the a priori. Therefore the question is: how good does the a priori have to be that PLDC15 becomes superior to MH08 and other methods? BTW, it is irritating that for Case 3 – in contrast to Cases 1 and 2 the scatter plot is shown only for PLDC15 and not for MH08. This synthetic study (Case 2) should be extended to not only test the effect of noise but also to test the assumptions in respect to emissivity and cloud liquid/ice to estimate the associated uncertainties. I appreciate section 5.3 which includes a comprehensive list of uncertainties (but I would like to see more in depth attempts to estimate the relative contribution (see above). There are also additional points of uncertainty: Both GVR and MHS use the same spectral range and therefore any uncertainties in the spectroscopy are cancelled. Also both would suffer from liquid water emission and/or scattering. To address this issue a comparison of satellite estimates with Barrow radio soundings could further validate the algorithm. With the strongly overlapping orbits there are hopefully sufficient data point.

Authors: We have changed the abstract to be more precise about the comparisons:

"The retrieval errors at Barrow are less than for data products from the Atmospheric Infrared Sounder (AIRS), Japanese 55 year Reanalysis (JRA-55), and National Centers for Environmental Prediction (NCEP) reanalyses.
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Although the uncertainties are comparable to ECMWF-Interim and Arctic System Reanalysis(ASR) products, the MHS data have much higher horizontal resolution (< 40 km) and are shown to reveal more structure."

We also adjusted the sentence on pg. 9970 to say

"The results indicate that the PLDC16 retrieval is more accurate if there is perfect a priori information."

It is expected that users of our retrieval will always have reanalysis data available to serve as the a priori. As such, Case 2 is the most realistic of the simulations. The Case 3 results are meant to provide a worst-case scenario for when the reanalyses are no better than a climatology. Real data provide a good test of the retrievals, and such tests are provided in Sect. 5. To further clarify the situation for the reader, we have added a new subsection (4.4 Discussion), which says:

"Three test cases were given to theoretically evaluate the PLDC16 and MH08 retrievals. Case 1 tests their intrinsic accuracy for noiseless brightness temperatures and perfect a priori information. Both retrievals performed as expected, with the PLDC16 retrieval faithfully reproducing the model water vapour data. Case 2 included randomized noise as found in the MHS instruments. Given perfect a priori information, the PLDC16 retrieval more accurately reproduced the model water vapour. Case 3 employed a climatological a priori, which represents a worst-case scenario for PLDC16. The test yielded comparable errors for the two retrievals for most regimes.

We expect that reanalysis data will always be available as the a priori. As such, the most realistic retrieval comparison is given by Case 2. Notwith-

standing, there are errors in the reanalyses (Serreze et al., 2012), spatio-temporal variations (Bühler et al., 2012, Tobin et al., 2006), and systematic errors which are difficult to treat quantitatively in simulations. To address these concerns testing in real-world conditions is appropriate, and our results are given in Sect. 5."

It is unclear how to quantify "how much better" the reanalyses have to be for an improved retrieval. We do show, however, that existing reanalyses result in major benefits.

The manuscript has been updated to include the MH08 plot in the figure for Case 3. Note that it is the same plot from Case 2.

The concerns raised about the errors introduced by clouds, the impact of the similar spectral range between GVR and MHS, and the use of radiosonde data are addressed in response to the next Referee comment.

Referee: Supercooled liquid cloud layers occur frequently in the Arctic. They absorb microwave radiation strongly increasing in strength with frequency. Thus, I am not convinced by the statement on p 9964, l19. Here the authors refer to Miao et al. (2001) but since this time more detailed measurements on Arctic mixed phase clouds have revealed their complicated nature. As shown by Xie et al. (2015) liquid and snow significantly effect microwave brightness temperatures for ground- and spaceborne geometry and also the relative layering of liquid and ice leads plays a role. The authors should at least provide a quantitative estimation of the effect of hydrometeors.

Authors: The point made by the Referee about liquid water clouds resulted in a significant improvement to this paper. We used the micro pulse lidar backscatter and depolarization data available at Barrow to separate MHS measurements into cases with and without clouds of different types. We found that that the presence of liquid

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water or ice clouds caused a minor increase to the standard deviation with little change in the bias. As such, we added the following paragraph to Section 5.3:

"For (iv), MHS measurements at Barrow were separated into cases with liquid water clouds, ice clouds, and clear skies by using micro pulse lidar (MPL) backscatter and depolarization data. The PLDC16 retrieval was applied to each set of measurements and then compared to radiosonde measurements that came within 1 hour of the MHS measurements. Radiosonde measurements were used instead of the GVR as it could suffer from similar effects due to scattering and absorption of liquid water and ice clouds as it measures in the microwave spectrum. The liquid water and ice cloud cases had 0.06 kg m^{-2} and 0.04 kg m^{-2} increases in the standard deviation, respectively, when compared to the clear sky cases. The bias did not change significantly between the three cases. This analysis indicates that clouds do not present a large source of error in the retrieval."

Referee: 3. For potential users of the algorithm detailed information how to apply it would be highly desirable – for example in an appendix ?

Authors: We have included all of the information needed in Section 2. There are no missing details that we can think to add.

Referee: Abstract: "The errors are shown to be significantly less than for other satellite measurement systems." Here you need to be more specific. I guess it concerns Table 5 so it is important to name the ones used there and say which satellite products perform better/worse? And are you sure that this is true everywhere in the Arctic?

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Authors: We have adjusted the abstract to be more specific, and in particular to make clear that we are only talking about a comparison at Barrow:

“The retrieval errors at Barrow are less than for data products from the Atmospheric Infrared Sounder (AIRS), Japanese 55 year Reanalysis (JRA-55), and National Centers for Environmental Prediction (NCEP) reanalyses. Although the uncertainties are comparable to ECMWF-Interim and Arctic System Reanalysis(ASR) products, the MHS data have much higher horizontal resolution (< 40 km) and are shown to reveal more structure.”

Referee:P9961, line 20: explain acronym “ARM”

Authors: Done.

Referee: Introduction: In fact I would have liked a separate section on the GVR rather than having processing details in the introduction. This could also address some more details on the intercomparison with radiosondes. Of that period? relative error? Humidity correction of radiosondes?

Authors: The details about the GVR are given in a separate paper that we reference. We found that including the details in the Introduction worked best.

Referee: P9962, 1st paragraph need to explain acronyms, make clear that MIRS is not an instrument!

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Authors: Done.

Referee: Section 2: The title of section 2 is misleading as “Microwave signal formulation” also includes the GVR. I suggest to reformulate or have the GVR as a separate subsection.

Authors: We renamed the Section to "Satellite microwave signal formulation and retrieval techniques".

Referee: P9962, Eq(1): It is very important to mention that this is already a reduced form of the RT equation! The sentence “.. satellite-borne microwave instrument is given ..” needs to be changed as it includes simplifications and assumptions. For example the detailed atmospheric vertical structure is parameterized in the factor m. What is exactly $T_0 - T_{atm}$ at the surface or at 2m? Please change the word “given” to “parameterized” or “simplified” and provide the reference (Guissard and Sobiewski, 1994) right in the beginning. What do you mean with “solar contribution to the microwave background”? Is this for the rather rare occasions that the sun is in the field of view?

Authors: To indicate that a reduced form of the radiative transfer equation is being used, we changed the word "given" to "parameterized" and refer to Guissard and Sobiewski (1994) up front. We indicate the T_0 is the surface air temperature. The confusing statement about solar radiation has been removed. Here is the updated paragraph:

quote “The brightness temperature T_i measured at frequency ν_i by channel i of a satellite-borne microwave instrument is parameterized by (Guissard and Sobieski, 1994)

$$T_i = m_p(\nu_i)T_s - (T_o - T_c)(1 - \varepsilon_i) e^{-2\tau_i \sec \theta}$$

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where T_s is the skin temperature, T_o is the surface air temperature, T_c is the cosmic background temperature, ε_i is the surface emissivity, $\tau_i \equiv \tau_i(0, \infty)$ is the total optical depth, θ is the zenith viewing angle of the satellite, and m_p is a factor incorporating the vertical structure of the atmosphere. Equation (1) is a combined form of the upwelling and downwelling brightness temperature equations that includes a contribution from cosmic microwave background radiation. Microwave contributions are assumed to be identical in both polarizations. The surface is also assumed to be a perfect specular reflector."

Referee: P9963, I19: "Notice that the dependence on surface emissivity is eliminated due to the assumption constant conditions across the spectrum."

Authors: We included the addition to that sentence.

Referee: P9967, I1: M08 -> MH08

Authors: Done.

Referee: P9969, I24: The sentence "The results indicate that the error f or PLDC15 is lower than for MH08. The PLDC15 results also demonstrate the utility of using a priori information for regime selection." should be eliminated. Case 1 is just a self test for the algorithm. Something would be wrong if it moves away from the a priori. As mentioned above (I 10) there is no chance for MH08 to be superior. What might be mentioned instead is that here only cloud free cases are tested and perfect knowledge of emissivity is assumed.

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Authors: We eliminated the sentence as requested. We also changed L12 P9968 to say "cloud-free brightness temperatures", and L2 P9969 to say:

"All three cases assume perfect knowledge of the surface emissivity."

Referee: p9970, I17: "The results indicate that the PLDC15 retrieval is more accurate." see the previous point. This should be eliminated. Why don't you use same regime classification or quantify the effect?

Authors: We changed the sentence to say the following:

"The results indicate that the PLDC16 retrieval is more accurate if there is perfect a priori information."

We chose to use a new regime classification because of artifacts created in the MH08 classification due to variations in temperature profile structure as seen in Fig. 3. It is difficult to meaningfully quantify the effect as it depends on temperature structure.

Referee: p9970, I19: Exchange "worst-case" scenario to "realistic".

Authors: This issue has been addressed in response to the Referee's point 2.

Referee: P9971, I2-2: "The results show that when the a priori is degraded our retrieval can be expected to perform comparably to MH08." In my opinion this is only true for the low and mid regime.

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Authors: We change the sentence to say the following:

“The results show that when the a priori is degraded our retrieval can be expected to perform comparably to MH08 for the low and mid regimes.”

Referee: Section 4.4: Why don't you use case 2 which is much more suitable as the effect of Interactive measurement noise is included? How much do the results of changing emissivity ratios depend on the atmospheric situation?

Authors: We added the following point about why Case 1 was chosen:

“Case 1 simulations were performed so that we could completely isolate the effects of each assumption.”

We have also changed the text to note that it is the "maximum random error" we quote, and have added:

“The error is largest for the low-humidity end of each regime.”

Referee: Section 5: Suggest to change title to “Assessment of water vapor column using GVR

Authors: Done.

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Referee: Section 5.1: What about the elevation difference between ERA-Interim, MHS pixels, Barrow and other products? What is its impact on water vapor column? How does surface emissivity / land surface type vary around Barrow?

Authors: We investigated this issue and have added the following paragraph to Sect. 5.1:

“We tested the impact of elevation differences at Barrow for the various data products using the Case 3 simulations. The terrain around Barrow ranges from 7 to 20 m height with small amounts of vegetation. Our calculation indicate differences in precipitable water of less than 1 percent.”

Referee: P9973, I15: To make you point you could also plot the standard deviation (or rel. error) as a function of water vapor column (binned).

Authors: As requested, we modified Figure 6 to include a binned standard deviation plot.

Referee: P9974, I15: Noise in AMSU-B in Table 1 might be underestimated as in flight degradation probably has occurred for some instruments. Did you see dependence on satellite?

Authors: We do not see a dependence on satellite. We examined the data from Figure 6 and find that for satellite MetOP-A and NOAA-18 there is only a 0.01 kg m^{-2} difference in the standard deviation and a 0.02 kg m^{-2} difference in the bias.

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Referee: P9974, I16: I would move the following paragraph to 5.3 as it is a study on the uncertainty due to the choice of a priori.

Authors: Done, with slight modifications:

“For (iii), Table 6 provides a statistical comparison for using different data sets as the a priori for the PLDC16 retrieval compared with the GVR at Barrow. GVR water vapour columns of less than 6 kg m^{-2} are considered. The results from Table 6 show the standard deviation only slightly changing depending on the data set used for the a priori. The ECMWF a priori provides the smallest standard deviation while the NCEP a priori gives the largest. To use the ECMWF climatological profiles as the a priori, the daily ECMWF reanalysis was used for the regime selection.”

Referee: P9977, I3: Note the strong meridional convergence of the orbits. In fact in 6 hours the whole Arctic is covered – therefore it is important to know how good PLDC15 performs elsewhere in the Arctic.

Authors: Agreed. This is the topic of a paper we have under preparation. It is a considerable body of work in its own right, and is beyond the scope of the current manuscript.

Referee: P9977, I7: Typically microwave brightness temperatures are directly assimilated into NWP models and reanalysis. Therefore I see the production of water vapor climatologies and budget studies as most important applications. Please formulate a bit more careful.

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Authors: Agreed. We have removed the poorly-formulated statement from the Conclusions.

Referee: General: A single sentence can not be a paragraph.

Authors: We have eliminated single-sentence paragraphs.

Referee: Table 5: The specification of the relative error would also be helpful.

Authors: Done.

Referee: Table 6: say that comparison is with GVR.

Authors: Done.

Referee: Figure 5: PLD15 -> PLDC15.

Authors: Done.

Interactive comment on Atmos. Meas. Tech. Discuss., 8, 9959, 2015.

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