Replies to Reviewer #1's comments

First of all, the authors gratefully acknowledge the reviewer for his/her comments and suggestions. The reply to each reviewer's comment is given in blue below the comment.

Interactive comment on "The Advanced Infra-Red WAter Vapour Estimator (AIRWAVE) version 2: algorithm evolution, dataset description and performance improvements" by E. Castelli et al.
Anonymous Referee #1
Received and published: 27 July 2018

General Comments

This paper outlines updates made to the AIRWAVE algorithm that exploit the dual view of the ATSR series of IR radiometers to retrieve TCWV using the split window technique. The authors present seasonal maps of TCWV and present results from inter- comparisons with an established SSM/I TCWV product and ARSA radiosondes. The general comments were written after completing the specific and technical comments. When reviewing the results section the reader is redirected to a previous paper by the same group from 2018 for comparison of results. After downloading Papandrea et al. (2018) it becomes immediately apparent that the 2 manuscripts are very similar in layout and appearance. The results from the earlier manuscript have practically identical figures, in the same order, with the only difference being Papandrea et al. (2018) validates the version 1 product whereas this study uses the new version 2 data. This study fails to show enough independence from the previously published work to warrant a new publication at this stage.

The main concern of the reviewer is related to the fact that the present paper seems not enough independent from Papandrea et al., 2018, that contains AIRWAVEv1 validation. He/she says that this is due to the fact that the lay-out of figures is the same in the two papers.
The reviewer is correct about the style of the figures regarding the validation. However, this is not true for the content of these figures! The use of the same figures layout is meant to produce a benefit for the reader, who can easily appreciate the differences between the two versions of the algorithm. Furthermore, the present paper contains the description of AIRWAVEv2 algorithm and a climatology of the dataset in addition to validation. We think that all these elements guarantee enough independency from previous work and that the improvements of version 2, are relevant and deserve publication.
In order to clarify the relevance of these improvements, also considering the other reviewer's comments, we add information on the comparisons between AIRWAVEv1 and AIRWAVEv2 (see specific comments below and reply to reviewer #2).

Also, missing from the analysis/discussion is a quantification of the improvements between version 1 and 2 of the algorithm.

In the revised version of the paper we report directly the comparison of performances of AIRWAVE version 1 and version2 adding in Table 2 the results of AIRWAVEv1 validation from Papandrea et al., 2018. This allow the direct comparison and the quantification of the improvements between the two version of the algorithm. The results of the comparisons and the improvements obtained with AIRWAVEv2 are also reported in session "Discussion and Conclusions".

Overall the study is of value due to the legacy of the ATSR series, and the FCDR the radiances represent. I would recommend this for publication only after all the issues that I have highlighted are addressed.

Specific Comments

1. Introduction lines 24-39: You mention microwave and near-infrared sensors, but what about water vapour from infrared sensors? TCWV estimates using the split window technique have been done with HIRS, AVHRR and MODIS to my knowledge. There is also no mention of chal-

lenges of ocean vs. land retrievals using IR window channels. What are the benefits of using the ATSR series?

To cover this point, in the revised version of the paper we add:

“TCWV retrievals from infrared spectral regions were performed from Advanced Very High Resolution Radiometer (AVHRR; Emery, 1992) measurements, using the split window technique, (Sobrino et al., 1991) and from MODIS (Seeman et al., 2003). TCWV retrievals from infrared channels over land suffer of the limited knowledge of the temperature and the emissivity of land surfaces (Lindstrot et al., 2014)”

before “The Along-Track Scanning Radiometer (ATSR, Delderfield et al. (1986)) instrument series had as main objective the accurate ...”

In line 37 we also add, following the reviewer’s suggestion “Due to the legacy of the ATSR series, and the fact that the radiances are a fundamental climate dataset record, the AIRWAVE dataset is an important resource for water vapor studies.”

Consequently, we add the following references:

Lindstrot, R. M. Stengel, M. Schröder, J. Fischer, R. Preusker, N. Schneider, T. Steenbergen, and B. R. Bojkov.“A global climatology of total columnar water vapour from SSM/I and MERIS”,Earth Syst. Sci. Data, 6, 221–233, 2014 www.earth-syst-sci-data.net/6/221/2014/ doi:10.5194/essd-6-221-2014

Seemann, S., J. Li, W. P. Menzel, and L. Gumley (2003), Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances, J. Appl. Meteorol., 42, 1072–1091.

Sobrino, J. A.; Coll, C.; Caselles, V. Atmospheric corrections for land surface temperature using AVHRR channel 4 and 5. Remote Sens. Environ.1991, 38, 19-34.

2. Introduction line 42: Quantify ’general good quality’ from previous assessment of version 1.

Done. we add “(average correlative bias of 0.72 kg/m2 vs SSM/I and 0.80 kg/m2 vs ARSA)” after “general good quality of AIRWAVEv1 dataset”.

3. Section 2.1: Equation 1 it is unclear how lambda 1 & 2 are being used here. Is it referring to the 10.8 and 12 micron channels? How is it being used in the superscript notation? What is being multiplied with the optical depths? Also what is F? Further clarity is needed here.

Yes, lambda 1 refers to the channel at 10.8 um, while lambda 2 is for the channel at 12 um. In the superscript it is the exponent of the term. The optical depths are multiplied by the values of the frequencies. F is now explicitly described and in the revised version of the paper we clarify all these points.

4. Section 2.1 Line 96: Can you state the accuracy? Has this already been shown with AIRWAVE-v1?

In Casadio et al., 2016 Appendix A we evaluate the accuracy of geometric correction to the AMF for the TIR channels of ATSR. In this paper we evaluate the accuracy of the whole retrieval procedure (not only the linear dependence between TCWV and optical depths).

5. Section 2.1 Line 136: Do the reported effects have an equal impact on retrieval precision for scan angles in the swath?

The estimates reported in the paper are given for along track configuration only. In the revised version of the paper we specify this in the text. However, we can also give an estimate of the improvement for extreme across track points: In worse cases, the precision has at maximum 1% higher value in the extreme across track of the swath with respect to the sub satellite points. We add this information at the end of Section 2.1.

6. Section 2.2 line 156: So what year do you use and why?

We use the 2010 (we added this information in the revised version of the paper). As stated in the text, the year to year variability has globally no impact on the spectra apart from some species whose impact has been assessed in the appendix.

7. Section 2.2 line 165: Why do you use ECMWF SSTs instead of the ARC/ESA CCI SST data products which are from the same instruments?

The SST used to calculate the retrieval parameter should be just representative of average conditions in a given season and latitude band. For this scope average SSTs obtained from the easily accessible ECMWF monthly means are suitable. ARC/ESA SSTs would have been suitable too.

8. Section 3 line 194: Do you also retrieve TCWV over lakes?

Yes, we clarify this in the revised version of the paper. We add “surfaces (sea and lakes)” after “over water”

9. Section 3 line 198: Are the uncertainties aggregated to the 0.25x0.25 grid? If so how are they propagated?

No, As specified in lines 199-200 the SSMI group contains also the values of standard deviations for each 0.25x0.25 grid points. In the revised version of the paper we rephrase in order to clarify this point.
We replace :”The SSM/I group, in addition, contains the value of the standard deviation and the number of elements aggregated within the SSM/I grid cell. ”
with
“The SSM/I group, in addition, contains the value of the number of elements aggregated within the SSM/I grid cell and the standard deviation of the TCWV value associated to each cell. ”

10. Figures 1-4: Too many sub-figures with replication of information. These should be combined into a single figure, removing either the 1b, 2b, 3b and 4b plots or the standard deviation maps to allow the reader to compare them side-by-side.

Following also the comments by Reviewer #2 we combine in one single figure figures 1,2,3 and 4 a and 1,2,3,4 c, now it is Figure 2.
Figures b) were moved in a separate figure, now it is Figure 3. We changed the text and the captions accordingly.

11. Section 3 line 223: Is this the RSS or HOAPS SSM/I product?

RSS as in Papandrea et al. 2018. This information has been added into the revised version of the paper where we describe with version of the SSM/I dataset was used for the comparison.

12. Section 3 line 234: Figure 7 is introduced before figure 6. Also you switch between Fig and Figure - please be consistent.

In the revised text we have switched the order of figures 5 and 6. We use Figure when it is at the beginning of a sentence and Fig. in all other cases as specified in AMT guidelines.

13. Figure 5: There is approximately 3 orders of magnitude more collocations with SSM/I than there are with ARSA. What impact does this have on the reported biases? Also the legends have different labels, the right-hand figure has bias while the left-hand figure says mean. Which is it? Ideally these should also be labelled a) and b).

About the different number of collocations: The reviewer is right when he says that the satellite has 3 orders of magnitude collocations than the radiosondes. However the number of collocations is very high (order of 10^5) and thus the impact on the bias is not related to that. However, the positions of the ARSA stations, that are not equally distributed worldwide as the satellite measurements (the majority of sites is based at mid-latitudes), may result in a small displacement of the TCWV values that are compared w.r.t. satellite (i.e. less relative amount of very high TCWV, characteristic of tropical conditions).
Done. We add a) and b) in figures and use “bias” in both panels (now it is Figure 5).

14. Figure 6: If using colour filled regions that sit on top of one another then the alpha value needs to be lowered to add transparency so that both regions can be seen. Alternatively replace one with error bars.

Done. In the revised version AIRWAVEv1 has blue error bars (now it is Figure 4).

15. Section 3 line 250: Do you require the reader to physically compare the table from Papandrea et al. 2018 with table 2 in this paper? From looking at the publication there is no table 2 but a table 1 and is this paper the validation of AIRWAVE-v1? This should be added to the discussion section if you want to make this comparison and discuss the improvements rather make the reader search them out.

Done.We added the values of bias and standard deviations of the differences between AIRWAVEv1 and SSM/I , ARSA extracted from Table 1 of Papandrea et al., 2018 in Table 2. We also change Table caption and text accordingly.

16. Section 4: This section seems very empty especially as results from what assume to be the AIRWAVE-v1 product were only published earlier this year. There is a lack of quantified improvements in the algorithm discussed or shown, especially as this is key to the title of the paper. Reads like a summary at best.

In the revised version of the paper we add here a quantification of the improvements obtained from version 1 to version 2.
We added:
As expected also from the analysis of synthetic retrievals, the most significant AIRWAVEv2 improvement is achieved at polar latitudes. In polar regions the bias versus SSM/I improves of 4.2 kg/m2 and of 3.2 kg/m2 versus ARSA. In both cases the standard deviations are reduced of about 1.6-1.9 kg/m2 .However, improvements at mid-latitudes are also found. The average bias with respect to SSM/I improves of about 0.7 kg/m2 and the standard deviation is reduced of about 1 kg/m2. In case of validation against radiosondes the bias in AIRWAVEv2 is reduced of about 0.6 kg/m2 with respect to AIRWAVEv1 and the standard deviation is reduced of 1.6 kg/m2.”

Technical Comments
1. Abstract line 1: First sentence doesn’t read well. Suggested change to: "Total Column Water Vapour (TCWV) is a key atmospheric variable which is generally evaluated at global scales through the use of satellite data."

Done.

2. Introduction line 19: Remove the word ’the’ after ’Actually,’

Done.

3. Introduction line 20: Full stop after Allen et al (2014) reference, begin new sentence with ’For this reason, …’

Done.

4. Introduction line 44: Incorrect spelling: ’theese’ (1 to many ’e’)

Done.

5. The AIRWAVE v2 line 55: Delete the ’general’ from ’general high quality’

Done.

6. The AIRWAVE v2 lines 55-63: You switch between AIRWAVE-v1, AIRWAVEv1 and v1

In the revised version of the paper we use AIRWAVEv1 everywhere.

7. Section 2.1: Inconsistency in how AIRWAVE is referenced between v1 and v2 throughout section.

In the revised version of the paper we use AIRWAVEv1 everywhere.

8. Section 2.1 Lines 95-96: ’is envisaged’ suggests an aspirational future outcome. If this was done in AIRWAVE-v1 then it should be known whether this is true. The 2 sentences don not read well as the second sentence states that the known linear dependence allows for accurate retrievals. This is a little confusing to read, needs rewording.

Done. In the revised version of the paper “is envisaged” is removed and the two sentences were rephrased: ”This equation shows that a linear behavior exists between the water vapour optical depth and the TCWV.
The linear dependence is exploited to solve the AIRWAVE equation and to retrieve TCWV. “

9. Section 3 Line 192-193: Inconsistency in how AIRWAVE is referenced, here it is AIRWAVE V2 rather than AIRWAVE-v2 or V2. Need to settle on a single style.

In the revised version of the paper we use AIRWAVEv2 everywhere.

10. Section 3 line 201: Same as above but now you use AIRWAVEv2 11. Section 3 line 224: DMSP already defined in Introduction

In the revised version of the paper we use AIRWAVEv2 everywhere. DMSP Done.

12. Section 3 line 239: incorrect spelling: ’radiosoundes’ (no ’u’)

Done.

13. Introduction & section 3: Acronym SSMI should be SSM/I.

Done.

Replies to Reviewer #2's comments

First of all the authors gratefully acknowledge the reviewer for his/her comments and suggestions. The reply to each reviewer's comment is given in blue below the comment.

Interactive comment on "The Advanced Infra-Red Water Vapour Estimator (AIRWAVE) version 2: algorithm evolution, dataset description and performance improvements" by Castelli et al., 2018
Anonymous Referee #2

General comments

This paper describes a new version of the AIRWAVE algorithm and the retrieved Total Column Water Vapour (TCWV) product from the Along-Track Scanning Radiometer (ATSR) instruments. TCWV is obtained from the thermal infrared channels at 10.8 and 12 µm, the nadir and oblique views, and over sea surfaces. Validations are carried out based on aggregated products at 0.25 deg resolution and worldwide.
Overall, the reading of this paper leaves me in two minds. On the one hand, the value is principle very high due to the legacy of the very long time series of dataset provided by the ATSR series and the importance of deriving TCWV. The retrieval approach seems interesting too with the decomposition of the inverse model into a linear analytical equation. And the apparent evaluation results given at the end seem encouraging for this product and associated retrieval approach. But on the other hand, the added value and independency of this new manuscript w.r.t the requirements of the AMT journal and work already done and presented in the pre-existing studies, on which this manuscript relies, seem relatively little. I cannot at this stage recommend publication in AMT, and would like first to encourage the authors to address the major comments listed below:

- As emphasized by Referee #1, figures and layout of this manuscript are almost identical to the paper of Papandrea et al. (2018). The main difference is the evaluation of the v1 dataset, while here the focus is on v2. Apart of the generation of v2 (and associated new simulations), the present paper does not provide new works and innovations compared to the mentioned previous works.

As replied to reviewer #1, it is true that the figures have the same outline of Papandrea et al 2018. This was done to ease the comparison between the two dataset versions. However, the content of the figures is totally different! and also the layout of the paper is not the same. In this paper we present the new version of the algorithm with all the new calculations used to improve the retrieval performances. Then we show the performances of the new dataset against the AIRWAVEv1 and we present the climatology from AIRWAVEv2 dataset. In addition, we provide a quantification of major error sources. Due to the entity of the improvements of the TCWV AIRWAVEv2 dataset we think that the paper presents new work with respect to the previous ones.

- In several parts of this manuscript, the writing is a bit too qualitative, and even sometimes a bit ambiguous. Efforts shall be made to add more quantitative elements.

Done. Following the reviewer's suggestions, we add more quantification of the results and clarified the points raised by the reviewer.

- The reader is sort out invited to check the improvements between AIRWAVE v1 and v2 by himself with the few lines given on Page 9. This is a bit unusual. A direct and explicit inter- comparison shall be provided here, with an explicit estimation of the bias reduction and precision improvements worldwide, per areas, and for different conditions.

Done. We report the results of the validation of AIRWAVEv1 in Table 2 together with AIRWAVEv2. Then we add a discussion on that and a direct comparison in Section 4.

- One of the expected improvements is the across-track variability. However, this element is not quantified in terms of uncertainty reduction on the TCWV. Same regarding the latitude dependency. Also please clarify sometimes if you are talking about bias, precision, overall uncertainty, etc...

In the revised version of the paper we clarify when we talk about bias or precision. Regarding the across track variability a more extensive reply is given below. In Appendix A we give an estimate of the accuracy of the new parameters using simulated values. When applied to real data, due to the nature of the algorithm and to the used interpolations, is not easy to decouple the single effects on the retrieval. However, in the paper we report the results (in terms of bias and standard deviation) of the validation against other instruments also for latitude regions in order to highlight the impact of the new algorithm in different latitude bands.

- To warrant a new publication and invite the use of this new dataset, I think this manuscript should go beyond the previous ones by providing more validation exercises with new additional TCWV dataset instead of repeating similar work: from other satellite instruments: e.g. MODIS (Diedrich et al., 2015), MERIS (e.g. Lindstrot et al., 2012), ENVISAT Radiometer, MSG SEVIRI, and / or ground-based sensors (AERONET, GNSS, or other radiosondes), and / or ECMWF reanalysis. The approach proposed by AIRWAVE shall critically be analysed and compared with more "classically achieved" with other thermal infrared sensors to be in line with the ambitious title. Furthermore, what about the different sensitivities to the atmospheric layers of the different spectral ranges (i.e. thermal infrared and microwave). Does it allow, prevent, or limit in a certain range the comparison of the associated total columns?

The main scopes of this paper is to describe the algorithm evolution, the dataset and performance improvements. For these reasons we repeat the validation exercise using the same validation dataset used for AIRWAVEv1. Furthermore, the validation is performed using satellite microwave data and radiosondes data, thus two very different datasets (platforms, sensitivity …) allowing to evaluate the AIRWAVEv2 performances under two very different point of view. In future, additional validation exercises will be performed (e.g. with MWR on ENVISAT), however this is out of the scope of the present paper.
Regarding the different sensitivities of TIR and microwave, in the validation exercise we compare SSM/I data in coincidence with AIRWAVEv2 ones. Since AIRWAVE is applicable only to clear sky measurements this is a method to filter out SSM/I "cloudy" TCWV and thus to avoid biases due to different sensitivity related to the used spectral range. When comparing to radiosondes, the small bias we found demonstrate that AIRWAVE TCWV are sensitive also to low atmospheric levels.

In the revised version of the paper we added a sentence about the different sensitivity of TIR, microwave and radiosondes reported above.

• The evolutions in the AIRWAVE equations in Sect. 2.1., i.e. "latitude dependencies and across-track variations", do not explicitly appear. It is quite hard for the reader to be able to make the link between these, the given variables, and their physical meanings. The authors shall better help the reader to establish these connections. Furthermore, I am a bit surprise that across- track and along-track viewing angles were not already considered in the previous version. And adding this in the update seems quite natural I think. As far as I can see, every atmospheric retrieval approach based on satellite sensors always needs to consider the sensor geometries to characterize accurately the average light path followed by the detected photons. Given how the air mass thickness varies with the geometry, the consideration of the viewing angles does not sound as very innovative to me, but rather quite natural. Other (precipitable) water retrieval from ATSR2, e.g. Li et al., 2003, although over land, Ren et al. (2015) or even from SEVIRI (e.g. Sobrino et al., 2007) already considered the variations of zenith angle at the surface for both nadir and forward views.

In the revised version of the paper we follow the reviewer's suggestion reported also in the specific comments and tried to clarify the quantities in the equations, their link with viewing geometries and physical quantities.

Regarding the across track angles: possibly there is a misunderstanding here. In Casado et al., 2016 : ”To account for the variability of the nadir view angle (0–25°), the TCWV evaluated through Eq. (29) are corrected using an empirical correction factor, dependent on the across track index position of the ATSR measurements. This across-track correction has been evaluated through radiative transfer simulation and provides a sufficiently accurate but extremely fast solution (in terms of CPU efficiency) to this problem. In the next version of the AIRWAVE algorithm, the retrieval parameters will be extracted from pre-calculated look-up tables, in which the angular dependence will be considered.” And what we present in this paper is exactly the calculation of angular dependent retrieval parameters.

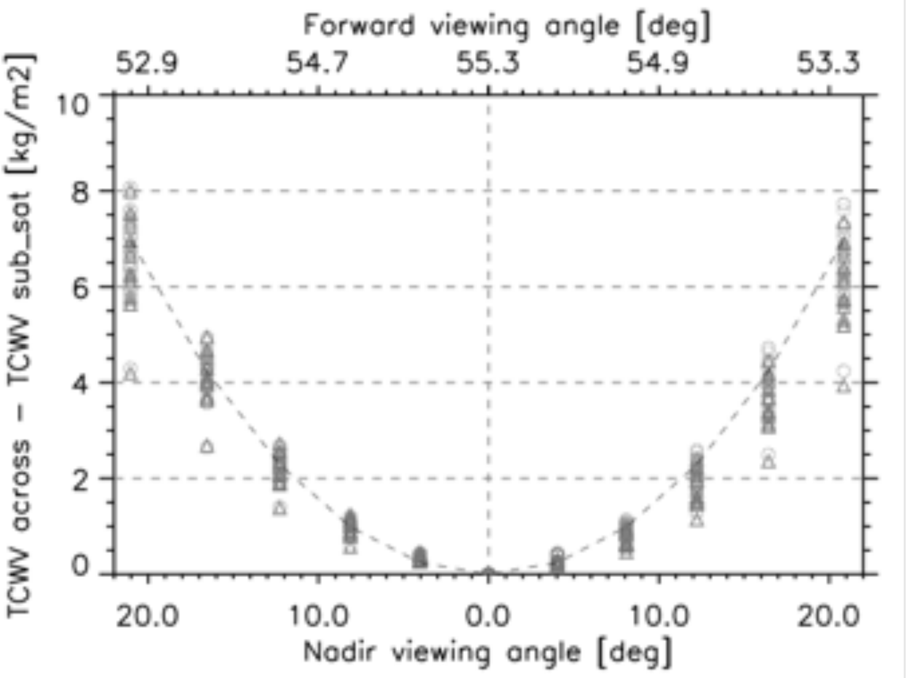

Figure 0: Differences between TCWV calculated from across pixels and TCWV calculated sub-satellite track as a function of across track position calculated for different atmospheric scenarios and for AATSR. Black dotted line corresponds to AIRWAVEv1 parametrization.

Figure 0 shows the absolute difference between TCWV from across track pixels and sub-satellite pixels calculated for AATSR in different atmospheric scenarios (tropical and mid-latitude) from synthetic measurements. To produce these retrievals, we simulated ATSR(s) radiances at the eleven tie points for the nadir and forward views considering also the surface emissivity variations with viewing angles. The atmospheric scenario, the TCWV and the SST were kept constant and they were exactly the same used for the sub-satellite track case. Then we retrieved the TCWV for each of the 11 couples of BTs and computed the difference with respect to the value obtained at the sub-satellite track position (that coincide with the TCWV reference value). The dotted line in Fig. 0 mimics the correction term adopted within the AIRWAVEv1 algorithm. As can be seen the dotted line well mimic the general behavior of the across track TCWV dependence. This is confirmed by the comparison made between AIRWAVEv1 TCWV and SSMI or ECMWF TCWV (see Casadio et al., 2016): on average we did not found any across-track bias, thus confirming the general validity of this correction. However, as can be seen in Fig. 0, in specific cases this approximation can generate differences depending on the used atmospheric scenario. Furthermore, a slight asymmetry with respect to the along track position is also visible. This behavior is expected as the ATSR instruments are tilted of about 4 respect to the flying direction of the satellite. In order to properly account for these variations, in AIRWAVEv2 we replace the a-posteriori correction by directly calculating the retrieval parameters for each of the 11 tie points of the nadir and forward swaths and interpolating the results at each position of the ground pixels. We also use in the solving equations the correct emissivity values, in order to properly take into account the angular dependence of the sea surface emissivity.

In the revised version of the paper we add some details to clarify this (see replies to specific comments # 8,18 and 23).

Specific comments

1. Abstract line 4: “performs the TCWV retrieval” => Please rephrase more direct e.g. “retrieves TCWV”

Done.

2. Abstract line 5: “combining nadir and forward observation geometries”: The verb “combine, here and elsewhere in the manuscript, sounds overstated for me. Both geometries are not considered strictly combined in a way it helps to retrieve 1 single TCWV value, But both views are considered individually and independently for deriving TCWV per observation geometry…

We remove “combining” in the abstract. Then we use “using” in other part (line 31 of the discussion version of the paper).

3. Abstract line 7: “almost no bias” => Please be more quantitative and less qualitative. What does it mean “no bias”? I do not know any retrieval with an exactly null bias.

We rephrase “very good agreement with almost no bias all over the ATSR missions, with the exception of the polar and the coastal region where AIRWAVE underestimate the TCWV amount.” —> “very good agreement with an overall bias of 3% all over the ATSR missions. A large contribution to this bias comes from the polar and the coastal region where AIRWAVE underestimate the TCWV amount.”

4. Abstract line 9: “these problems” => Which ones?

The underestimation of TCWV in coastal and polar areas. We change “to overcome these problems” with “to reduce the bias in these regions”.

5. Abstract line 14: “significant improvements...” => Again, be quantitative. How much is the improvement overall? RMSE not defined previously. Clarify overall that AIRWAVE is over sea, no land!

Done. Now it is: “Results show significant improvements in both biases (from 0.72 to 0.02 kg/m2) and standard deviations (from 5.75 to 4.69 kg/m2 versus SSM/I)”. We add “over sea” in the fourth abstract sentence: “The algorithm was used to produce a TCWV database over sea from the whole ATSR mission”.

6. Introduction line 36: Why AIRWAVE v1 is only available aggregated at the coarse resolution of 2x2 deg, and not for all the individual retrievals?

AIRWAVE is included into the G-VAP at this resolution. Contacting the authors, the complete dataset can be obtained. Actually on the G-VAP only monthly means from 2003-2008 are available.

7. Introduction line 38 “good results” & line 42 “good quality”: again, please be more specific and quantify. What the range of bias and precision for which you consider this is a good result?

Done. We added: ”(average correlative bias of 0.72 kg/m2 vs SSM/I and 0.80 kg/m2 vs ARSA, below the 1 kg/m2 indicated in the GlobVapour project (Lindstrot et al., 2010))” after This exercise demonstrated a general good quality of AIRWAVEv1 dataset
In the PVR of the GlobVapour project report they use as goal 1kg/m2 for bias. Results from both AIWAVEv1 and AIRWAVEv2 are below this threshold.

8. Introduction line 44: “by accounting for latitudinal and angular variations of the retrieval”: Not clear, retrieval estimations always vary with respect to geometry and latitude variation of the airmass. You probably mean the dependency of your forward & fitted model?

First of all we want to clarify that AIRWAVE does not make direct use of a forward model, but uses pre-computed parameters (retrieval parameters) to solve equation 13 of the revised version of the paper. In AIRWAVEv1 we used fixed parameters along the globe, in addition, “to account for the variability of the nadir view angle (0–25°), the TCWV evaluated through Eq. (29) are corrected using an empirical correction factor, dependent on the across track index position of the ATSR measurements.”(Casadio et al., 2016). In AIRWAVEv2 we use latitudinal dependent retrieval parameters calculated for each of the 22 (11 nadir and 11 forward) tie angles. To clarify this,in the revised version of the paper we add :
“AIRWAVEv1 use fixed retrieval parameters along the globe and TCWV are corrected for viewing angles variability in nadir and slant by using an empirical correction factor.” in line 39 after “ For this reason, in the V1 algorithm several approximations were made.”

9. Introduction line 48: “spread” => Do you mean precision? Or uncertainty? Or spread of the differences with respect to another dataset?

Spread of the differences with respect to another dataset. We modified the text accordingly.

10. Section 2 line 58 “average retrieval parameters”: Which ones are you talking about here? Please be more specific. At this stage, the read haven’t read it the equations in Sect. 2.1…

We reformulate:” AIRWAVEv1 makes use of retrieval parameters calculated though RTM simulations of tropical and mid-latitude atmospheric scenarios then averaged and used for the whole globe.”

11. Section 2 line 66: again please clarify. Retrievals always vary with seasons and latitudes (water vapour properties). Do you mean that you explicitly consider the spatial and temporal variability of the some of the input parameters (e.g. H2O & temperature profiles)?

We mean that we did not use average retrieval parameters as done in AIRWAVEv1, instead we compute the retrieval parameters for 6 latitude bands and 4 months. Then during the retrieval these are used as look-up-tables. In the revised version of the paper we rephrased:
“Secondly, we computed the retrieval parameters taking into account both their seasonal and latitudinal dependence” —> “Secondly, we compute the retrieval parameters for different latitude bands and for four months that, in the retrieval, are used as look-up-tables”

12. Section 2 line 70 “We recall’: Was never said earlier in this paper.

We removed “ We recall here that”.

13. Section 2.1 line 83 “F includes the atmospheric and surface radiance contribution”. What is exactly F? This is not clear. Do you mean this is related to the temperature profile? Sea surface emissivity is already included later in the equation, so what is left? The temperature surface?

In the revised version of the paper we clarified this by explicitly indicating what is F. See also reply to reviewer #1.

14. Section 2.1 line 93 “relative effective absorption cross-section”: what do relative and effective mean here? Do you mean the absorption cross-section integrated along the average light path (by opposition to the vertical atmospheric layers)?

With effective here we mean that the cross section is multiplied for the lambda value. This is the same definition used in Casadio et al., 2016. In the revised version of the paper we replaced “effective absorption cross section (sigma)” with “effective absorption cross section (lambda*sigma)”

15. Section 2.1 line 104 “We verified...”: Where is it shown? Please support your claimed verifications with adequate figures to convince the reader. Quantify this linearity (e.g. high correlation coefficient value).

To clarify this we add a figure in the revised version of the paper and we modify the text as follows:

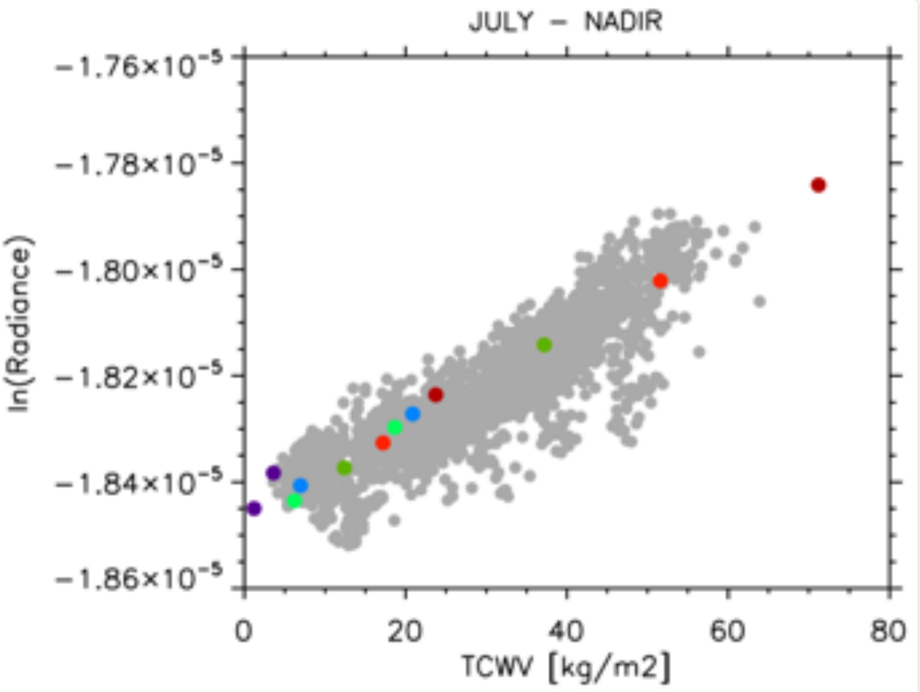

Figure 1: logarithm of radiance ratio at nadir as a function of TCWV in simulated atmospheric scenario. Grey dots represent the same quantity using real AATSR radiances and coincident SSMI TCWV for the along track measurements on the 5 and 6 August 2008.

In Fig. 1 the colored dots represent the values of the logarithm of radiance ratio in equation (1) as a function of the TCWV for the different atmospheric scenarios. We report only the values obtained for the sub satellite scans using the IG2 water profiles for the Summer season multiplied for 0.5 and 1.5. The different colors represent different latitude bands (going from red for tropical to blue for polar). The grey dots represent the radiance ratio calculated from along track AATSR measurements on the 5 and 6 of August 2008 aggregated at SSMI resolution (0.25° 0.25°). The value of TCWV associated to each AATSR sub-satellite measurement was obtained from coincident SSMI measurements. In order to minimise the impact of random error, only measurements with SSMI pixel coverage (calculated as the ratio between the actual and the maximum number of ATSR measurements that can be present into a SSMI pixel) greater than 10% were used for this exercise. Figure 1 shows that: a) the simulated radiances correctly reproduce the real measurement behavior; b) the relation between the radiances and the TCWV can be considered as linear.

Actually, we find in this case a correlation of 0.904 for real data and 0.92 for the simulated ones (p-value of 7.2630294e-05).

16. Section 2.1 line 110 “average of all the G values obtained with different water vapour content”: Please clarify the series of values for H2O content that you used or the list of atmospheric conditions. Where do appear the zenith angles? They should already be, in theory, in G. J, emissivities, and F no?

We added: “(to vary the water vapour content we multiplied the water vapor profile for 0.5, 0.75, 1., 1.25, 1.5)”
after
” For this reason, for each atmospheric scenario the average of all the G values obtained with different water vapour content is used”.
For the zenith angles the reviewer is right, we added additional information on this, see reply to comments 8, 18 and 23.

17. Section 2.1 line 117 “sort of effective water vapour cross section”: Please reformulate more properly. Such a description is rather vague and ambiguous. What do you mean by effective here?

We remove the sentence.

18. Section 2.1 Eq.s 10 et al: Please be more specific by adding clearly all the angles in each equation: each view has a specific viewing angle. Furthermore, do you consider exactly the right zenith angle per pixel sensor? Or do you have a kind of average zenith angle for nadir and forward views? The Nadir view (cf. “NAD”) cannot have only 1 zenith angle, or I miss something...

From equation 12 onward we explicit the angular dependence. We calculate all the parameters at the 11 tie point positions. It means that we calculate the equations for 11 nadir angles (from 0 to 21 degrees) and 11 Forward angles (from 53 to 55.3 °). Then we interpolate using each single pixel across track position.
To clarify this, in the paper we added: “Equations (11), (12), (13) were solved for the 11 couples of viewing angles corresponding to the tie points. The angles cover a range from 0 to 21 degrees in the NAD case and from 53 to 55 degrees in the FWD case.” after “Equations (10), (12) and (13) are the solving equations used in AIRWAVEv2, while AIRWAVEv1 makes use of equations (11), (12) and (13). “

19. Section 2.1 line 136 “direct effect on the retrieval precision”: And accuracy as well?

A preliminary assessment of the accuracy of the new method can be found in Appendix A, Section 5.1 using simulated radiances.

20. Section 2.2 line 173 “fixed wind speed”: Why is it fixed? Why this value?

Due to wind speed variability, in both algorithm version, we prefer to fix the value of the wind speed and then treat this as an error source (see section 5.3). However, as can be noticed, this impact is negligible in equatorial regions, very low (0.7%) in midlatitude regions and is about 2.7 % in polar regions when the wind speed reaches the high value of 25 m/s. We choose this value (3 m/s) as a reference because is a reasonable trade-off between 1 m/s and 25 m/s that are extreme values available in the University of Edinburgh emissivity database. The 3 m/s is quite close to the average wind speed over the sea that is about 6 m/s (e.g. Monhan: “The Probability Distribution of Sea Surface Wind Speeds. Part I: Theory and SeaWinds Observations”, Journal of Climate, 19, 2006. or data from Copernicus Marine environment monitoring centre data on 100km monthly L$ 2007-2012 Climatology Global Wind).

In the revised paper in section 2.2 we add: “Due to wind speed variability, in both algorithm version, we prefer to fix the value of the wind speed and then treat wind variations as an error source (see Sect 5.3)”, before the end of the section.

21. Section 2.2 line 235 and further: “a good correlation is obtained against both datasets, as highlighted by the correlations and bias values reported in the same figure”. Please don’t let the reader thinking and looking by himself for these numbers. Report them adequately in the relevant paragraphs.

Following the reviewer’s suggestion in this section we changed:
“Globally, a good correlation is obtained against both datasets, as highlighted by the correlations and bias values reported in the same figure.”
with
“Globally, a good correlation is obtained against both datasets, as highlighted by the correlations (0.948 with SSM/I and 0.918 with ARSA) and bias values (0.02 +/- 4.79 kg/m2 with respect to SSM/I and 0.19 +/- 6.12 kg/m2 with respect to ARSA).”

and
“The improvement in the performances of the new dataset is clearly visible at all latitudes.”
with
“The improvement in the performances of the new dataset is clearly visible at all latitudes, and in particular for regions with latitude higher than 45-50° where the negative values obtained with AIRWAVEv1 disappear. In addition, a significant reduction of the spread is highlighted.”

Then we add in Table 2 the results of the validation of AIRWAVEv1 as extracted from Papandrea et al., 2018.

22. Section 2.2 line 260: How the new algorithm reduces the impact of the sensor noise? This is not explained before. Any evidence?

It is at the end of Section 2.1 we evaluate the impact of the sensor noise using the new equations.

23. Section 2.3 lines 184-185: I don’t fully understand here. What do you interpolate exactly? I guess that now for each individual sensor pixel, you use the adequate zenith angle right?

As stated before, we calculate the retrieval parameters for the 11 tie points. Then using the across track position of each sensor pixel we interpolate the retrieval parameters calculated for the 11 tie points angles at the exact pixel position (and zenith angles).
To clarify we replaced:” In V2 we replaced the a-posteriori correction by directly calculating the retrieval parameters for each of the above described tie points of the nadir and forward swaths and interpolating the results at each position of the ground pixels.”
with:
“In AIRWAVEv2 we replaced the a-posteriori correction: We calculated the retrieval parameters for each of the above described tie points of the nadir and forward swaths, then we obtained the parameters at the exact ground pixel position interpolating these values and using the ground pixel across track position.”

24. Section 4 and appendix: Section 4 deserves more quantitative results with rigorous evaluation and validation of the AIRWAVE v2 to be in line with the title. More dataset, and more quantitative analyses per scan angle (since this is one of the claimed improvement). Also, how well does this approach achieve w.r.t to more classical approaches considered on thermal infrared sensors (e.g. Landsat, METEOSAT, etc...)? Moreover, I don’t understand why Section 5 is here reported as an appendix. Some claims are written in the conclusion section, but were never reported before. I had to find out that some additional works were done in this appendix which is not obvious. Also what about the impact of the sea temperature surface? And H2o profile? Does it play a rule somewhere?

In Section 4 we added the results of direct comparison of AIRWAVEv1 and AIRWAVEv2 adding in table 2 the results of AIRWAVEv1 validation.
About the analysis per scan angles: as shown in Fig.0 above, the variations with scan angles depend also on season. AIRWAVEv2 approach is to select the parameters from look up tables through a multivariate interpolation on a 3-dimensional grid (trilinear). Decouple the effects of latitude and scan angle variation is thus not straightforward.
Regarding the validation with additional datasets, this is behind the scope of this paper. Actually, we present here the validation with both satellite data and radiosondes. The intrinsic nature of these two datasets and the AIRWAVE one are very different and independent to guarantee a good benchmark for validation. Furthermore, the scopes of this paper are to present the AIRWAVEv2 dataset, compare its performances with respect to AIRWAVEv1 and describe the new algorithm, as described in the title.
We prefer to keep Section 5 in the Appendix to ease the readability of the paper. Following the reviewer's suggestions, we add in the revised version of the paper an estimate of the impact of additional components such as surface temperature and H2O profile.
In particular, we change the H2O profile varying randomly of 5% H2O at each level and we changed the SST randomly of 3K. When performing this test, we keep the value of the temperature of the last layer equal to the SST (no contrast). We report the results for water vapor in a new column in Table 3, while we prefer to substitute the results of the impact of varying temperature profile alone with the ones obtained when varying both SST and T profile (with no contrast between SST and temperature in the last layer). Consequently, we change the title of section 5.2 "Atmospheric temperature profile" in "Atmospheric temperature and water vapor profiles and SSTs"
In this section we rewrite the section in this way:
"One of the main error sources that can affect the AIRWAVE TCWV retrieval is the assumption of a fixed temperature profile. Actually, the atmospheric opacity is closely linked to the atmospheric density and thus to the atmospheric temperature. To estimate the impact of temperature on the retrieved TCWV, twenty different temperature profiles were randomly perturbed by ±3 K on a 1 km equi-spaced altitude grid. In order to account also for possible changes related to SST variation we change the SST accordingly to the value of the temperature in the lowest layer. Then, simulated BTs were produced with the RTM and were used to perform the TCWV retrievals for the three instruments in equatorial, mid-latitude and polar July conditions for the north hemisphere and the results were compared with respect to the unperturbed case. In the third column of Table 3 we summarise the findings of this analysis for each of the three instruments, reporting the STD of the difference both in absolute and in percentage values. The impact of these perturbations is of the order of 6% and is higher in the equatorial and mid- latitude regions and lower at the poles. Indeed, in the equatorial region, due to the higher water vapour content, the atmosphere is more opaque than at the poles so that temperature variations have a larger impact on the retrieved TCWV. These tests were also performed varying the atmospheric profile alone. Very similar but slightly higher errors are found in these cases.
Another relevant error sources can be due to differences in water vapor profile shape. To evaluate this error, we varied the water vapor profile randomly up to 5% at each atmospheric level. At maximum the impact is of 1% in equatorial case (atmospheric opacity, see the fourth column in Table 3)."

25. Table 1: What are the considered zenith angles considered here for the nadir and forward views?

They are the sub-satellite ones (0 and 55 degrees). We added this information in the Table 1 caption.

26. Table 3: Please check and correct the units. Wind speed and temperature profile cannot be in kg/m2.

In Table 3 we did not report the values of temperature and wind but their impact on the TCWV, for this reason it is in kg/m2.

27. Apart of illustrations, what are the purposes of Figs1-4? I don't see any additional validations with them? Seem they take space with a lot of redundant information. I would advise to group them in 1 single plot with 4 panels. So then you can add more validations that would be kore relevant for this paper.

These figures have no validation purpose. They show the climatology of the TCWV obtained from the AIRWAVEv2 dataset. Following the reviewer's suggestion, we grouped figures 1-4 in two figures, one with TCWV and STD maps for the four months and one for zonal and meridional means.

28. Fig5: What are the differences between "mean" (left panel) and "bias" (right panel)?

None, in the revised version of the paper we used "BIAS" in both.

29. Figs5-6-7: Please precise the time period associated with all these figures. And the considered areas for Fig.5.

These figures cover the entire (A)ATSR period from 1991 to 2012. We added this information in the revised version of the paper in figures caption.

Proposed additional bibliography

Zhao-Liang Li, Li Jia, Zhongbo Su, Zhengming Wan & Renhua Zhang (2003) A new approach for retrieving precipitable water from ATSR2 split-window channel data over land area, International Journal of Remote Sensing, 24:24, 5095-5117, DOI: 10.1080/0143116031000096014

J. A. Sobrino & M. Romaguera (2008) Water-vapour retrieval from Meteosat 8/SEVIRI observations, International Journal of Remote Sensing, 29:3, 741-754, DOI: 10.1080/01431160701311267

Lindstrot, R., Preusker, R., Diedrich, H., Doppler, L., Bennartz, R., and Fischer, J.: 1D-Var retrieval of daytime total columnar water vapour from MERIS measurements, Atmos. Meas. Tech., 5, 631-646, https://doi.org/10.5194/amt-5-631-2012, 2012.

We added Lindstrot and Li.

The Advanced Infra-Red WAter Vapour Estimator (AIRWAVE) version 2: algorithm evolution, dataset description and performance improvements

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Abstract. ~~The~~ Total Column Water Vapour (TCWV) is a key atmospheric variable ~~and its evaluation is generally performed, at global scale,~~ which is generally evaluated at global scales through the use of satellite data. Recently a new algorithm, called AIRWAVE (Advanced Infra-Red Water Vapour Estimator), has been developed for the retrieval of the TCWV from the Along-Track Scanning Radiometer (ATSR) instrument series. The AIRWAVE algorithm ~~performs the TCWV retrieval~~ retrieves TCWV exploiting the dual view of the ATSR instruments using the infra-red channels at 10.8 and 12 μm and ~~combining~~ nadir and forward observation geometries. The algorithm was used to produce a TCWV database over sea from the whole ATSR mission. When compared to independent TCWV products, AIRWAVE Version 1 (~~V1~~AIRWAVEv1) database shows very good agreement with ~~almost no bias~~ an overall bias of 3% all over the ATSR missions~~, with the exception of the~~ . A large contribution to this bias comes from the polar and the ~~costal~~ coastal region where AIRWAVE underestimate the TCWV amount. In this paper we describe an updated version of the algorithm, specifically developed to ~~overcome these problems~~reduce the bias in these regions. The AIRWAVE Version 2 (~~V2~~AIRWAVEv2) accounts for the atmospheric variability at different latitudes and the associated seasonality. In addition, the dependency of the retrieval parameters on satellite across-track viewing angles is now explicitly handled. With the new algorithm we produced a second version of the AIRWAVE dataset. As for ~~V1~~AIRWAVEv1, the quality of ~~V2~~ AIRWAVEv2 dataset is assessed through the comparison with the Special Sensor Microwave/Imager (SSM/I) and with the Analyzed Radiosounding Archive (ARSA) TCWV data. Results show significant improvements in both biases ~~and RMSE~~(from 0.72 to 0.02 kg/m^2) and standard deviations (from 5.75 to 4.69 kg/m^2, especially in polar and costal regions. A qualitative and quantitative estimate of the main error sources affecting the ~~V2~~ AIRWAVEv2 TCWV dataset is also given. The new dataset has also been used to estimate the water vapour climatology from the 1991-2012 time series.

1 Introduction

A key issue in assessing the climate change is the precise knowledge of the distribution and variability of the Total Column of Water Vapour (TCWV), i.e. the vertically integrated atmospheric water vapour content. Actually, ~~the~~ TCWV is closely linked to clouds, precipitation and thus to the hydrological cycle (Allan et al., 2014)~~and for~~. For this reason it is one of the GCOS (Global Climate Observing System) Essential Climate Variables (ECVs). Since water vapour plays such a crucial role in meteorological as well as in climatological aspects, it is important to gather spatial and temporal thorough information about its distribution. At global scale, this can be achieved through the use of satellite missions. In the last decades measurements from several sensors were used for this purpose. Among them, sensors operating in the microwave regions as the Special Sensor Microwave Imager (~~SSMI~~ SSM/I onboard Defense Meteorological Satellite Program (DMSP) satellites) are used to infer accurate TCWV amount over ocean surfaces (Wentz, 1997), while sensors operating in the visible and near-infrared spectral range provide precise TCWV retrieval on land surfaces (e.g. Medium Resolution Imaging Spectrometer (MERIS)/ENVISAT (Lindstrot et al., 2012), or Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites (Diedrich et al., 2015)).

TCWV retrievals from infrared spectral regions were performed from Advanced Very High Resolution Radiometer (AVHRR; Emery, 1992) measurements, using the split window technique, (Sobrino et al., 1991; Li et al., 2003) and from MODIS (Seemann et al., 20
TCWV retrievals from infrared channels over land suffer of the limited knowledge of the temperature and the emissivity of land surfaces (Lindstrot et al., 2014).The Along-Track Scanning Radiometer (ATSR, Delderfield et al. (1986)) instrument series had as main objective the accurate retrieval of sea surface temperature for climate studies. However, Casadio et al. (2016) demonstrated that it is possible to retrieve accurate and precise TCWV from its day and night time measurements, ~~combining~~ using the ATSR Brightness Temperature (BT) collected from nadir and forward views in the channels at 10.8 and 12 μm in clear sky day and night sea scenes. The algorithm (named AIRWAVE, Advanced Infra-Red Water Vapour Estimator) exploits a sea emissivity dataset and calculations performed with a dedicated Radiative Transfer Model (RTM). A detailed description of the AIRWAVE algorithm is given in (Casadio et al., 2016). The first version of AIRWAVE TCWV dataset (hereafter ~~V1~~AIRWAVEv1), spanning from 1991 to 2012, is freely available from the GEWEX G-VAP website (G-VAP website) in form of monthly fields at 2°×2° regular grid resolution ~~(Schroder et al., 2018).~~ from 2003 to 2008 (Schroder et al., 2018). Due to the legacy of the ATSR series, and the fact that the radiances are a fundamental climate dataset record, the AIRWAVE dataset is an important resource for water vapor studies. It's worth underlying here that ~~V1~~ AIRWAVEv1 was developed to demonstrate the possibility of retrieving TCWV values from the ATSR measurements. The main goal pursued in its development was to have a simple software that could produce good results when compared to independent datasets. For this reason, in the ~~V1~~ AIRWAVEv1 algorithm several approximations were made. AIRWAVEv1 use fixed retrieval parameters along the globe and TCWV are corrected for viewing angles variability in nadir and slant by using an empirical correction factor.

Papandrea et al. (2018), aiming at the validation of the ~~AIRWAVE-v1~~ AIRWAVEv1 dataset, compared the data with the TCWV from ~~SSMI~~ SSM/I and Analyzed Radiosounding Archive, (ARSA website)) for the whole mission. This exercise demonstrated a general good quality of ~~AIRWAVE-v1 dataset~~ AIRWAVEv1 dataset (average correlative bias of 0.72 kg/m^2 vs SSM/I and 0.80 kg/m^2 vs ARSA, below the 1 kg/m^2 indicated in the GlobVapour project (Lindstrot et al., 2010)) apart for the polar regions and some coastal regions where an underestimation of the TCWV was found. In this paper we describe the new version of the AIRWAVE algorithm (hereafter ~~V2~~AIRWAVEv2) developed to overcome ~~theese~~ these weaknesses by accounting for latitudinal and angular variations of the retrieval parameters. The new algorithm has been applied to all the available ATSR Level 1B Top of Atmosphere radiance products acquired over water surfaces in clear sky and in day/night conditions (same as for ~~V1~~AIRWAVEv1) to produce the ~~V2~~ AIRWAVEv2 dataset. We show here the new TCWV climatologies derived from the 20 years of ATSR data together with the results of an extensive validation exercise performed repeating the same comparisons reported in (Papandrea et al., 2018). The new dataset shows improvements in terms of both bias and spread of the differences with respect to another dataset with respect to what achieved with ~~V1~~AIRWAVEv1.

This article is structured as follows: In section 2 we describe the new algorithm developed to produce ~~V2~~AIRWAVEv2, the improvements in retrieval scenarios and the strategy used for the selection of latitude and seasonal dependent retrieval parameters. In section 3 we describe the ~~V2~~ AIRWAVEv2 dataset, the TCWV climatology and its validation agains ~~SSMI~~ SSM/I and ARSA data and compare the performances of ~~V2 against V1~~AIRWAVEv2 against AIRWAVEv1, finally, conclusions are given in section 4.

2 The AIRWAVE version 2

Papandrea et al. (2018) demonstrated the ~~general~~ high quality of ~~AIRWAVE-v1~~ AIRWAVEv1 by comparing the retrieved TCWV with corresponding ~~SSMI~~ SSM/I and ARSA TCWV. However, in the same paper, the authors highlighted that at latitudes higher than 50° the agreement was not as good as for the rest of the globe. They speculated that this was due to the fact that AIRWAVEv1 makes use of ~~average retrieval parameters , calculated under~~ retrieval parameters calculated though RTM simulations of tropical and mid-latitude atmospheric scenarios then averaged and used for the whole globe. This choice was driven by the consideration that, being ~~V1~~ AIRWAVEv1 applicable to water and cloud-free scenes only, the number of cloud-free measurements over the sea at high latitudes is significantly smaller than at mid-latitudes and tropical regions. Thus, a trade-off between generality (i.e. good precision at all latitudes), actual latitudinal coverage of cloud-free measurements and software complexity was the main driver for this choice. Moreover, ~~V1~~ AIRWAVEv1 makes use of retrieval parameters computed for the along track viewing geometries only and uses an a-posteriori correction for the scenes pointing outside the orbit track.

The need to have a TCWV dataset of homogeneous quality at all latitudes and viewing geometries has driven the development of an improved version of the AIRWAVE algorithm, ~~V2~~AIRWAVEv2. The improvements were achieved through three main steps. Firstly, we modified the way in which some of the approximations of the solving equations were handled, leading to an improved retrieval precision. Secondly, we ~~computed~~ compute the retrieval parameters ~~taking into account both their seasonal and latitudinal dependence~~for different latitude bands and for four months that, in the retrieval, are used as look-up-tables. Finally, we calculated the retrieval parameters for different viewing angles to directly account for across track variations. We discuss these modifications in the following subsections. All the computations described in the paper have been made using the HITRAN2008 database (Rothman et al., 2009) for the spectroscopic data and the IG2 database (Remedios et al., 2007) version

4.1 for the atmospheric scenarios. ~~We recall here that the~~ The IG2 database was developed to be used as model atmosphere in the analysis of the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)/ENVISAT measurements (that cover the same spectral region of the IR channels of ATSR). The IG2 database contains atmospheric vertical profiles of pressure, temperature and abundances of the molecules active in the the MIPAS spectral region, different for each year of the mission and divided into six latitudinal bands (polar, mid-latitude and equatorial for both ~~north and south~~ North and South hemispheres) and four seasons.

2.1 Improvements in the solving equations

The starting point for the calculations of ~~V2~~ AIRWAVEv2 retrieval parameters is the master equation of AIRWAVE Version 1. Since the expressions are the same for both nadir and forward geometry, we report here the equations for the general case, omitting the subscripts NAD (for NADIR) of FWD (for FORWARD) geometries. We reproduce here some of the equations reported in (Casadio et al., 2016) to help the reader in the comprehension of this article. The master equation of AIRWAVE algorithm is eq. (12) of the above mentioned work (now eq. 1):

$$\ln\frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} = \ln\frac{F_1^{\lambda_1}}{F_2^{\lambda_2}} + \ln\frac{\epsilon_1^{\lambda_1}}{\epsilon_2^{\lambda_2}} + \ln\frac{\gamma_1^{\lambda_1}}{\gamma_2^{\lambda_2}} + \lambda_2\tau_2 - \lambda_1\tau_1 \tag{1}$$

The subscripts 1 and 2 represents the terms calculated in the 10.8 and 12 μm channels respectively. λ_1 is the value of the frequency in the 10.8 μm channel and λ_2 in the 12 μm channel. J_1 is the radiance that reaches the TOA for the 10.8 μm channel, J_2 is the radiance that reaches the TOA for the 12 μm channel, F includes the atmospheric (J_a) and surface radiance ~~contribution~~ (J_s) contribution and is F=1+$\frac{J_a}{\epsilon-\tau J_s}$, ϵ is the sea emissivity, γ is a constant arising from the Planck law, τ are the optical depths at the two wavelength. Since only H_2O and CO_2 significantly affect the optical depth into ATSR Thermal Infrared (TIR) channels we can write:

$$\ln\frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} = \ln\frac{F_1^{\lambda_1}}{F_2^{\lambda_2}} + \ln\frac{\epsilon_1^{\lambda_1}}{\epsilon_2^{\lambda_2}} + \ln\frac{\gamma_1^{\lambda_1}}{\gamma_2^{\lambda_2}} + \lambda_2\tau_2^{H_2O} - \lambda_1\tau_1^{H_2O} + \lambda_2\tau_2^{CO_2} - \lambda_1\tau_1^{CO_2} \tag{2}$$

then re-naming

$$G = \ln\frac{F_1^{\lambda_1}}{F_2^{\lambda_2}}, E = \ln\frac{\epsilon_1^{\lambda_1}}{\epsilon_2^{\lambda_2}}, \chi = \ln\frac{\gamma_1^{\lambda_1}}{\gamma_2^{\lambda_2}} \tag{3}$$

we get:

$$\ln\frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} = G + E + \chi + \lambda_2\tau_2^{H_2O} - \lambda_1\tau_1^{H_2O} + \lambda_2\tau_2^{CO_2} - \lambda_1\tau_1^{CO_2} \tag{4}$$

In ~~V1~~ AIRWAVEv1 we assume that the optical depth (τ) is the product of the vertical column of H_2O by the relative effective absorption cross section ($\lambda\ \sigma$), normalised to the air mass factor (AMF) for the given line of sight angle:

$$\lambda_2\tau_2^{H_2O} - \lambda_1\tau_1^{H_2O} = \frac{\lambda_2\sigma_2 - \lambda_1\sigma_1}{AMF}TCWV \tag{5}$$

~~This implies that a linear behaviour exists between the water vapour optical depth and the TCWV is envisaged.~~This equation shows that a linear behaviour exists between the water vapour optical depth and the TCWV. The linear dependence ~~allows~~ is exploited to solve the AIRWAVE equation and to retrieve TCWV ~~with good accuracy~~ .

In the development of AIRWAVEv2 we investigated the possibility to find a more accurate solution of the AIRWAVE equation still preserving the linear dependence between water vapour optical depth and TCWV. We recall here that in AIRWAVEv1 the water absorption cross sections were obtained using MODTRAN (Berk et al., 2008) while all the other values were obtained with the dedicated RTM, developed for ATSR measurements simulations and described in (Casadio et al., 2016). For ~~V2~~ AIRWAVEv2 , a different approach was adopted for the calculation of effective absorption cross section. We have simulated ATSR synthetic radiances for the different atmospheric scenarios of the IG2 database and thus with different water vapor content. A detailed descriptions of these simulations is given in Sect. 2.2.

Using these simulations and ATSR-SSM/I collocated TCWV, we verified that $ln\frac{J_1^{\lambda_1}}{J_2^{\lambda_2}}$ correctly reproduces the real measurement behaviour as function of TCWV and that this relation is in first approximation linear. In Fig. 1 the colored dots represent the values of the logarithm of radiance ratio in equation 1 as a function of the TCWV for the different atmospheric scenarios. We report only the values obtained for the sub satellite scans using the IG2 water profiles for the Summer season multiplied for 0.5 and 1.5. The different colors represent different latitude bands (going from red for tropical to blue for polar). The grey dots represent the radiance ratio calculated from along track AATSR measurements on the 5 and 6 of August 2008 aggregated at SSMI resolution (0.25° × 0.25°). The value of TCWV associated to each AATSR sub-satellite measurement was obtained from coincident SSMI measurements. In order to minimise the impact of random error, only measurements with SSMI pixel coverage (calculated as the ratio between the actual and the maximum number of ATSR measurements that can be present into a SSMI pixel) greater than 10% were used for this exercise. Figure 1 shows that: a) the simulated radiances correctly reproduce the real measurement behavior; b) the relation between the radiances and the TCWV can be considered as linear. Actually, we find in this case a correlation of 0.904 for real data and 0.92 for the simulated ones (p-value of 7.3×10^{-05}). Therefore we can now re-write equation (4), isolating the terms that account for the water content ($\tau_1^{H_2O}$and $\tau_2^{H_2O}$):

$$\ln\frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} - G - \chi - E - \lambda_2\tau_2^{CO_2} + \lambda_1\tau_1^{CO_2} = \lambda_2\tau_2^{H_2O} - \lambda_1\tau_1^{H_2O} = \Delta\tau \tag{6}$$

The G term of equations (3) and (4) is not as constant as supposed and partially verified in (Casadio et al., 2016), and may depend on the different water vapor content. For this reason, for each atmospheric scenario the average of all the G values obtained with different water vapour content is used (to vary the water vapour content we multiplied the water vapor profile for 0.5, 0.75, 1., 1.25, 1.5) . Equation (6) can thus be written as:

$$\ln \frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} - G_{AVG} - \chi - E - \lambda_2 \tau_2^{CO_2} + \lambda_1 \tau_1^{CO_2} = \Delta\tau \tag{7}$$

Therefore for each scenario and geometry we can write:

$$\ln \frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} - G_{AVG} - \chi - E - \lambda_2 \tau_2^{CO_2} + \lambda_1 \tau_1^{CO_2} = \Delta\tau = \Delta\sigma \cdot TCWV + \Delta\rho \tag{8}$$

In this equation, $\Delta\sigma$ and $\Delta\rho$ represent the slope and intercept of the straight line representing the behaviour of the term containing the radiances as a function of the TCWV. In the testing version of the AIRWAVEv2 code, we estimated these parameters using the values of the radiances and the TCWV obtained perturbing the IG2 water vapor amount by a factor 0.5 and 1.5. ~~With respect to V1, in V2 the $\Delta\sigma$ is a sort of "effective" water vapour cross section.~~ Grouping the terms in equation (8) as in (Casadio et al., 2016) we get:

$$TCWV = \Phi - \frac{G}{\Delta\sigma} \tag{9}$$

where Φ is the "water vapor pseudo-column" that in AIRWAVEv2 is defined as :

$$\Phi = \frac{\ln \frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} - \chi - E - \lambda_2 \tau_2^{CO_2} + \lambda_1 \tau_1^{CO_2} - \Delta\rho}{\Delta\sigma} \tag{10}$$

This formula is sightly different from the one used in (Casadio et al., 2016) due to the presence of the $\Delta\rho$ term:

$$\Phi = \frac{\ln \frac{J_1^{\lambda_1}}{J_2^{\lambda_2}} - \chi - E - \lambda_2 \tau_2^{CO_2} + \lambda_1 \tau_1^{CO_2}}{\Delta\sigma} \tag{11}$$

If in eq. 9 now we explicit the dependence on the viewing angles we get:

$$TCWV_{NAD} = \Phi_{NAD} - \frac{G_{NAD}}{\Delta\sigma_{NAD}} \quad and \quad TCWV_{FWD} = \Phi_{FWD} - \frac{G_{FWD}}{\Delta\sigma_{FWD}}$$

$$\Phi_{NAD} = \frac{\ln \frac{J_1{}_{NAD}^{\lambda_1}}{J_2{}_{NAD}^{\lambda_2}} - \chi - E_{NAD} - \lambda_2 \tau_2{}_{NAD}^{CO_2} + \lambda_1 \tau_1{}_{NAD}^{CO_2} - \Delta\rho_{NAD}}{\Delta\sigma_{NAD}} \quad with \quad \Phi_{FWD} = \frac{\ln \frac{J_1{}_{FWD}^{\lambda_1}}{J_2{}_{FWD}^{\lambda_2}} - \chi - E_{FWD} - \lambda_2 \tau_2{}_{FWD}^{CO_2} + \lambda_1 \tau_1{}_{FWD}^{CO_2} - \Delta\rho_{FWD}}{\Delta\sigma_{FWD}} \tag{12}$$

while the TCWV given by the combined use of nadir and forward pseudo column is:

$$TCWV = \alpha \cdot \Phi_{NAD} + \beta \cdot \Phi_{FWD} \tag{13}$$

where

$$\alpha = \frac{1}{1-\frac{\Delta\sigma_{FWD}}{\delta\cdot\Delta\sigma_{NAD}}} \quad and \quad \beta = \frac{1}{1-\frac{\delta\cdot\Delta\sigma_{NAD}}{\Delta\sigma_{FWD}}} \qquad with \quad \delta \approx \frac{G_{FWD}}{G_{NAD}} \tag{14}$$

Equations (10), (12) and (13) are the solving equations used in ~~V2, while V1~~ AIRWAVEv2, while AIRWAVEv1 makes use of equations (11), (12) and (13). ~~The~~ Equations (10), (12) and (13) were solved for the 11 couples of viewing angles corresponding to the tie points. The angles cover a range from 0° to 21° in the NAD case and from 53° to 55° in the FWD case. The new equations were used to compute a new set of retrieval parameters. For consistency purposes, in ~~V2~~ AIRWAVEv2 the computations were performed with the dedicated RTM as for ~~V1~~AIRWAVEv1. An example of the difference between the parameters used for ~~V1 and V2~~ AIRWAVEv1 and AIRWAVEv2 is given in Table 1 for tropical scenario and sub-satellite view configuration. As can be noticed, the larger differences are for α, β and $\Delta\sigma$ parameters: there is a reduction of the α and β parameters of a factor of about 50 from ~~v1 to v2~~AIRWAVEv1 to AIRWAVEv2, while $\Delta\sigma$ is reduced by a factor of 30.

These changes have a direct effect on the retrieval precision. We can have an estimate of the improvements of the precision of ~~V2 retrievals against V1~~ AIRWAVEv2 retrievals against AIRWAVEv1 using the following consideration: in AIRWAVE we can estimate the expected precision by multiplying the measurement random error by a factor of $\alpha/\Delta\sigma$. Therefore in ~~V1~~ AIRWAVEv1 we multiply the random error by a factor of 53/1.9 (= 28) while in ~~V2~~ AIRWAVEv2 the multiplicative factor is 1.7/0.08 (= 21). In case of polar atmosphere this ratio is further reduced reaching a value of 13. Since the overall random error is about 0.25% for AATSR and ATSR-2 and 0.6% for ATSR-1, we have that the precision for AATSR and ATSR-2 improves from 7% to 5% and for ATRS-1 goes from 17% to 12% for tropical atmosphere and in ~~V2~~ AIRWAVEv2 reaches 3% for AATSR ad ATSR-2 and 8 % for ATSR-1 in polar atmosphere. In worse cases, the precision has at maximum 1% higher value in the extreme across track of the swath with respect to the sub satellite points. From these considerations it follows that ~~V2~~ AIRWAVEv2 parameters should improve the retrieval performances.

2.2 Improvements in the retrieval scenario

n ~~V1~~ AIRWAVEv1 we make use of the same set of retrieval parameters for all measurements of a single ATSR instrument. Independent sets of parameters are calculated for the three missions, while within each mission no dependencies on different atmospheric/surface conditions or seasons was considered. In ~~V2~~ AIRWAVEv2 the retrieval parameters are estimated not only according to the instrument type but also accounting for possible latitudinal and seasonal variations. To this aim, we have used the aforementioned RTM to compute all the required quantities exploiting the model atmospheres of the IG2 database. Since the IG2 database was specifically developed for the MIPAS/ENVISAT mission, it covers only the time range from 2002 to 2012, while the ATSR series operated from 1991 to 2012. However, the inter-annual variations of most of the species active in the ATSR thermal infrared spectral range are generally much smaller than the corresponding seasonal ones. Therefore we used the data for one year only (2010), and we considered the inter-annual variations as systematic error sources (see Appendix A for an estimate of these errors).

To better reproduce the variability of the atmospheric scenarios that were observed by the ATSR instruments, we therefore calculated the retrieval parameters exploiting the profiles for all the six latitude bands and the four seasons included in the IG2 datasets for one year only.

The AIRWAVE solving equations do not explicitly make use of the Sea Surface Temperature (SST). However, it is used in the Radiative Transfer (RT) computations to estimate the retrieval parameters. The sea surface emissivity values are instead used both in the parameters estimation and in the AIRWAVE retrieval. While over land the emissivity is characterised by a large spatial difference (it indeed varies as a function of soil type, vegetation cover, etc.), over sea its variation is in general relatively small. For this reason in ~~V1~~ AIRWAVEv1 we used constant emissivity values calculated for the nadir and forward viewing angles with fixed SST (285K) and wind speed (3 m/s). In the new version of the algorithm, coherently with the approach used for the atmospheric scenarios, the retrieval parameters have been computed using dedicated SST values for each season and latitude band. The SST monthly means were produced for the corresponding six latitude bands and for the four seasons using ECMWF ERA-Interim daily fields data with a regular latitude/longitude grid of 0.75° × 0.75° (241 × 480 grid points).

The emissivity of each scenario has been computed using the data extracted from the University of Edinburgh database (Embury et al., 2008). This dataset contains emissivities tabulated as a function of wave number (600-3350 cm^{-1} or 3-16.7 μm), viewing angle (0-85°), temperature (270-310 K), and wind speed (0-25 m/s at 12.5 m). For the RTM computations we used the full spectral dependency of the emissivity. Since in equation 3 of AIRWAVE we use a single emissivity value for each channel, we estimated it by convolving the spectral emissivity with the ATSR filter functions. The nadir and forward viewing angles of the instruments have been defined at eleven tie points of the ATSR swath (pixels associated with specific points equally spaced across a single image or instrument scan). For each tie point we then used the corresponding viewing angles to extract the correct emissivity values, with a fixed wind speed (3 m/s), as for ~~V1.~~ AIRWAVEv1. Due to wind speed variability, in both algorithm version, we prefer to fix the value of the wind speed and then treat wind variations as an error source (see Sect. 5.3).

2.3 Across track variations of the retrieval parameters

A simplification present in ~~V1~~ AIRWAVEv1 is that the retrieval parameters are calculated only for the sub-satellite viewing angles (55° for forward view and 0° as nadir viewing angle). However, due to the ATSR configuration, the nadir viewing angles varies from 0° (sub-satellite) to approximately 21° (across track edge of the ATSR swath, ~~±~~ ± 250 km from nadir), while the forward viewing angles range from 53° to 55°. Significant TCWV differences between centre and edge swath are, thus, expected.

In ~~V1~~ AIRWAVEv1 the across-track dependence of TCWV is corrected a-posteriori. The correction was calculated on the basis of TCWV retrievals performed over simulated brightness temperatures (BTs).

However, this approximation might not be sufficiently adequate depending on the used atmospheric scenario. Furthermore, a slight asymmetry with respect to the sub-satellite track position is expected as the ATSR instruments are tilted of about 4° respect to the flying direction of the satellite. Therefore the a-posteriori correction of ~~V1~~ AIRWAVEv1 cannot fully reproduce all these features. In ~~V2~~ AIRWAVEv2 we replaced the a-posteriori correction~~by directly calculating~~: We calculated the retrieval parameters for each of the above described tie points of the nadir and forward swaths~~and interpolating the results at each position of the ground pixels~~, then we obtained the parameters at the exact ground pixel position interpolating these values and using the ground pixel across track position.

2.4 Selection of the retrieval parameters

The computation of the retrieval parameters, described in the previous sections, produced a set of 1584 retrieval parameters for each ATSR mission (6 coefficients × 6 latitude bands × 4 seasons × 11 tie points) store in dedicated look-up tables (LUTs). In order to select the most suitable set of parameters for each ATSR measurement, a multivariate interpolation on a 3-dimensional grid (trilinear) has been applied to the six retrieval coefficients ($\Delta\sigma$, G, $\Delta\rho$) and the emissivity for both the FWD and the NAD geometries.

3 ~~AIRWAVE V2~~ AIRWAVEv2 dataset: description, climatology and validation

The ~~AIRWAVE V2~~ AIRWAVEv2 TCWV data are produced, as for the ~~V1~~ AIRWAVEv1 dataset, processing Level 1B measurements acquired over water ~~and~~ surfaces (sea and lakes) and in clear sky conditions in both nadir and forward views (according to the Level 1B cloud mask). The output files are saved in Interactive Data Language (IDL) binary files (.sav extension), however they can be easily converted in other formats (e.g. netcdf) upon request. The parameters contained into the files are structured in two groups, in the first one (named HIRES) the parameters are given at native resolution (1 ×1 km^2) while in the second one (named ~~SSMI~~SSM/I) the parameters have been aggregated to ~~SSMI~~ SSM/I resolution (0.25° × 0.25° grid). Both groups contain: the TCWV, the latitude, the longitude, the across track index value (0-512) and a day/night flag. The ~~SSMI~~ SSM/I group, in addition, contains the value of the ~~standard deviation and the~~ number of elements aggregated within the ~~SSMI grid cell~~ SSM/I grid cell and the standard deviation of the TCWV value associated to each cell.

The climatologies have been derived using all the available years and sensors of the ATSR family. Using the AIRWAVEv2 products aggregated at the 0.25° × 0.25° grid, we obtained for each month day/night TCWV averages and standard deviations. The final monthly files are also saved as IDL binary files but can be converted in other formats and are available upon request.

Figures ~~from 1 to 4~~ 2 and 3 show sketches of the climatology for January, April, July and October obtained from 20 years of ATSR daytime measurements. Similar results are obtained for nigh-time retrievals (not shown here). In ~~each figure we report on the left the~~ Fig.2 we report in panels a), c), e), g) the TCWV global distribution at 0.25° grid resolution and its standard deviation ~~on the left panel, in the central panel on top row~~ in panels b), d), f) and h). In Fig.3 panels a), c), e), g) we show the TCWV meridional mean together with its standard deviation, while on ~~the bottom row~~ panels b), d), f) and h) we report the TCWV zonal mean.

The geographical distribution of the median values of the TCWV reflects the behaviour of general atmospheric circulation. Higher TCWV values, associated to strong convection in the Inter Tropical Convergence Zone (ITCZ), are located around the equator while lower values are found in the polar regions. Also the zonal means as a function of latitudes reflect this behaviour, while the zonal meridional means show a more homogeneous behaviour. Here lower TCWV values are found in coincidence of longitudes where we have extended land presence in the equatorial region. The mean and the absolute standard deviation show similar features, with higher values in the ITCZ region. As can be noticed, the seasonal movements of the ITCZ from North (in Northern ~~hemisphere~~ Hemisphere summer) to South (in Northern ~~hemisphere~~ Hemisphere winter) can be clearly detected (Castelli et al., 2018). In general, the standard deviations in the region where the TCWV maximum is located are of the order of 15% and up to 20% in polar regions. The zonal means reflect the shift of the ITCZ during the year with maximum values of TCWV in ~~northern hemisphere~~ Northern Hemisphere reached in July.

The quality of the ~~V2~~ AIRWAVEv2 dataset is evaluated through the same method adopted for ~~V1~~ AIRWAVEv1 and reported in (Papandrea et al., 2018). The ~~V2~~ AIRWAVEv2 dataset is compared to the TCWV obtained from the ~~SSMI~~ SSM/I satellite and to data available from the ARSA.

In this contest, these two datasets are complementary, as the ~~SSMI~~ SSM/I TCWV are not retrieved for measurements in proximity of coasts (minimum distance about 60 km), while the selected ARSA stations are located in coastal areas.

The ~~SSMI~~ SSM/I dataset is produced from the ~~SSMI~~ SSM/I instrument series onboard the ~~Defense Meteorological Satellite Program (DMSP)~~ DMSP polar orbit satellites since 1987. For this comparison, we used the 0.25° v7 daily product obtained from the F13 satellite produced by Remote Sensing Systems. In fact, differently from the other DMSP satellites, the local time of the ascending node of F13 (18:00 UTC) is more stable than the one of the other satellites with only a variation of 1 hour during the whole mission. For the comparison with ~~SSMI~~ SSM/I we used the ~~AIRWAVE V2~~ AIRWAVEv2 data aggregated at 0.25° resolution covering the time period from 1995 to 2009. The ARSA dataset spans from January 1979 to present and contains water vapour concentration profiles at specific pressure levels. To obtain the TCWV we vertically integrate these values. For the comparison with the ATSR data, only stations surrounded, even partially, by water are used. More details about the selection of ATSR and ARSA coincident data are reported in (Papandrea et al., 2018).

The zonal means (calculated in bins of 2 degrees for all the datasets, and reported in Fig. 4) show the good quality of AIRWAVEv2 data with respect to both radiosondes and satellite data at all latitudes. In Fig. 4, the AIRWAVEv1 data are overplotted for comparison. The improvement in the performances of the new dataset is clearly visible at all latitudes, and in particular for regions with latitude higher than 45-50° where the negative values obtained with AIRWAVEv1 disappear. In addition, a significant reduction of the spread is highlighted.

In Fig. 5.5 we show the Bi-dimensional histograms of the comparisons between ~~V2 and SSMI (left panel~~ AIRWAVEv2 and SSM/I (panel a) and ARSA (~~right panel~~ panel b). The ~~SSMI~~ SSM/I measurements are homogeneously distributed over the globe, while ARSA radiosounding stations are mainly located at mid-latitudes (see Fig.5.5) and this is reflected in the bulk of the ARSA TCWV values ranging between 0-30 kg/m^2.

Globally, a good correlation is obtained against both datasets, as highlighted by the correlations ~~and bias values reported in the same figure.~~ (0.948 with SSM/I and 0.918 with ARSA) and bias values (0.02 ± 4.79 kg/m^2 with respect to SSM/I and 0.19 ± 6.12 kg/m^2 with respect to ARSA). We highlight that, in the validation exercise, we compare SSM/I data in coincidence with AIRWAVEv2 ones. Since AIRWAVE is applicable only to clear sky measurements this is a method to filter out SSM/I cloudy TCWV and thus to avoid biases due to different sensitivity related to the used spectral range. When comparing to radiosondes, the small bias we found demonstrate that AIRWAVE TCWV are sensitive also to low atmospheric levels. In particular the comparison with the same histograms of ~~V1~~ AIRWAVEv1 (see Fig. 1 of Papandrea et al. (2018)) highlights the correction of negative values in polar and costal regions in the new version of the dataset.

~~The zonal means (calculated in bins of 2 degrees for all the datasets, and reported in Fig. 4) also show the good quality of V2 data with respect to both radiosoundes and satellite data at all latitudes. In Fig. 4, the V1 data are overplotted for comparison. The improvement in the performances of the new dataset is clearly visible at all latitudes.~~ Figure 5.5 reports the geographical distribution of the mean TCWV differences with respect to ~~SSMI~~ SSM/I and ARSA in absolute and percentage values. In comparison to ~~AIRWAVE-v1~~AIRWAVEv1, see Fig. 3 of Papandrea et al. (2018), the differences with ~~SSMI~~ SSM/I are reduced at all latitudes. The longitudinal patterns of the differences are similar to the ones of ~~V1~~ AIRWAVEv1 except for the equatorial pacific region where ~~V2~~ AIRWAVEv2 shows a slightly higher positive bias. The reasons for this behaviour are under investigation. In the majority of costal regions, where ~~V1~~ AIRWAVEv1 underestimated the TCWV, ~~V2~~ AIRWAVEv2 is now in agreement with ARSA results (no ~~SSMI~~ SSM/I data close to coast).

In Table 2 we summarise the results of this comparison for both ARSA and ~~SSMI~~ SSM/I and for different scenarios and missions. The average bias is about 0.0 $\pm$ 4.7 kg/m^2 with respect to ~~SSMI~~ SSM/I and 0.2 $\pm$ 6.1 kg/m^2 with respect to ARSA. If we compare these results with the ones for ~~V1~~ AIRWAVEv1 (reported in Table 2 to ease the comparison) we can clearly see the improvement in both the biases and the standard deviations(0.7 $\pm$ 5.7 kg/m^2 with respect to ~~SSMI~~ SSM/I and 0.8 $\pm$ 7.7 kg/m^2 with respect to ARSA). As can be seen from Fig.s 4 and 7 and from results in Table 2 ~~(to be compared with those in Table 2 of Papandrea et al. (2018))~~ the improvement in the bias is obtained at all latitudes; it is however more evident in polar regions (from 5.5 $\pm$ 5.1 kg/m^2 in ~~V1~~ AIRWAVEv1 to 1.3 $\pm$ 3.5 kg/m^2 in ~~V2 versus SSMI~~ AIRWAVEv2 versus SSM/I and from 4.1 $\pm$ 6.5 kg/m^2 in ~~V1~~ AIRWAVEv1 to 0.9 $\pm$ 4.6 kg/m^2 in ~~V2~~ AIRWAVEv2 when using ARSA). Slight difference between the three ATSR missions are consistent with the related uncertainties.

In Fig. 7 we show monthly mean evolution of the differences (and their standard deviation), between the TCWV obtained from correlative measurements and ~~V2~~AIRWAVEv2. As for ~~V1~~AIRWAVEv1, these differences are quite stable over time, with the exception of the beginning of the ATSR-1 mission (1991-1994). As explained in Papandrea et al. (2018), this can be due to the failure of 3.7 μm channel that impacted the ATSR cloud screening. In general, the differences with respect to the radiosonde exhibit a higher seasonality due to pronounced variability of atmospheric and surface conditions in costal areas.

It is worth noticing that the spread of the ~~AIRWAVE-v2~~ AIRWAVEv2 is always smaller than the one of ~~AIRWAVE-v1~~AIRWAVEv1. This is partially due to the new algorithm that reduces the random error component due to noise on the retrieved TCWV.

The above described results indicate that the ~~V2~~ AIRWAVEv2 algorithm reduces the global bias with respect to ~~SSMI~~SSM/I, from about 0.7 kg/m^2 of ~~AIRWAVE-v1~~ AIRWAVEv1 to 0.0 kg/m^2 and improves the standard deviations (STD) of up to 20% with respect to ~~V1. In V2~~AIRWAVEv1. In AIRWAVEv2, the STD values are essentially constant for all the scenarios and missions, highlighting the un-biased nature of the dataset with respect to ~~SSMI~~ SSM/I (cloud-free). When using ARSA data the bias reduces from 0.8 kg/m^2 to 0.2 kg/m^2 and the standard deviations of 21%.

4 Discussion and Conclusions

The second version of the AIRWAVE TCWV dataset described in this work, has been validated against ARSA and ~~SSMI~~ SSM/I equivalent products.

As expected also from the analysis of synthetic retrievals, the most significant ~~AIRWAVE Version 2~~ AIRWAVEv2 improvement is achieved at polar latitudes. In polar regions the bias versus SSM/I improves of 4.2 kg/m^2 and of 3.2 kg/m^2 versus ARSA. In both cases the standard deviations are reduced of about 1.6-1.9 kg/m^2. However, improvements at mid-latitudes are also found. The average bias with respect to SSM/I improves of about 0.7 kg/m^2 and the standard deviation is reduced of about 1 kg/m^2. In case of validation against radiosondes the bias in AIRWAVEv2 is reduced of about 0.6 kg/m^2 with respect to AIRWAVEv1 and the standard deviation is reduced of 1.6 kg/m^2.

These improvements are due to the fact that the ~~V2~~ AIRWAVEv2 retrieval parameters account for atmospheric variability. No statistically significant trend can be found in the comparison with ~~SSMI~~ SSM/I and ARSA in both versions of the database, while a seasonal dependence of the differences is observed, with larger bias in July and August, mainly due to the differences in mid-latitude north TCWV retrievals. In general, we find slightly drier results with respect to ARSA and ~~SSMI~~ SSM/I with both versions. This is possibly due to the fact that the temporal mismatch between the ATSR and the correlative measurements does not allow to exclude all ~~SSMI~~ SSM/I TCWV retrieval obtained under cloudy conditions, or to wrong cloud mask assignation. As discussed, the use of retrieval parameters that are calculated in conditions different from the ones present in the observed scenario can cause biases on the obtained TCWV. We point out that the major source of errors on the retrieved TCWV comes from the temperature profile assumptions, while erroneous assumptions of other gases (e.g. HNO$_3$, CFC-11, CFC-12, CO$_2$) have an almost negligible impact. The obtained RMSE value of about 7% is of the same order of this error.

Beside the improvements on ATSR TCWV retrievals given by the AIRWAVE Version 2 dataset, the method described in this work can be the basis for a similar approach for SLSTR (Sea and Land Surface Temperature Radiometer, on board COPERNICUS SENTINEL-3, (Donlon et al., 2012)).

Acknowledgements

This work has been performed under the ESA-ESRIN Contract No. 4000108531/13/I-NB. The authors gratefully acknowledge ECMWF for SST data, the GlobVapour project for providing the combined MERIS+SSM/I water vapour product. SSM/I and ~~SSMIS~~ SSM/IS data are produced by Remote Sensing Systems. Data are available at www.remss.com/missions/ssmi.

5 Appendix A: Evaluation of AIRWAVE Version 2 main systematic and random errors

This appendix provides an estimate of the main error sources (random and systematic) that affect the ~~V2~~ AIRWAVEv2 dataset. To facilitate the use of the errors together with the TCWV contained into the dataset, we summarize the results of this appendix in Table 3. ~~V2~~ AIRWAVEv2 retrieval parameters accounts for atmospheric and surface variability of the observed scenes. However, real observed scenes can obviously deviate from the simulated ones. An evaluation of the errors induced by these deviations is then required. For this reason we analyse, through the use of synthetic radiances, the major sources of errors that can affect AIRWAVEv2 retrieval i.e. (in order of importance): the influence of the atmospheric temperature profile variations, the impact of sea emissivity changes due to the wind and the impact of interfering atmospheric species. Furthermore, an estimate of the random error component due to the noise is also reported.

5.1 Retrieval approximations

In order to evaluate the impact of systematic errors due to the retrieval approximations, we performed some tests of TCWV retrievals from simulated radiances. We used Top Of the Atmosphere (TOA) sub-satellite track Brightness Temperatures (BTs) simulated with the RTM at 10.8 and 12 μm in nadir and forward geometries as input to the retrieval chain (no random noise was added). The BTs were produced using different TCWV amounts for each given scenario (e.g. water vapour profiles were multiplied by 0.5, 0.75, 1.25, 1.5), while all the other atmospheric profiles were kept constant. Results of this exercise show that TCWV is correctly retrieved with an error of ± 3%. For comparison purposes, we performed a similar test using the ~~V1~~ AIRWAVEv1 approach. For ~~V2~~ AIRWAVEv2 tests, the same atmospheric conditions used to compute the retrieval parameters have been adopted, while for ~~V1~~ AIRWAVEv1 larger errors are expected due to the fact that the atmospheric variability is not taken into account. Despite this, this analysis shows that ~~V1~~ AIRWAVEv1 performs well for medium-high TCWV (>30 kg/m^2), where the differences are below 10%. For TCWV values between 10-20 kg/m^2, the differences range between -10 and -30%. ~~V1~~ AIRWAVEv1 underestimates the low TCWV values (below 10 kg/m^2) with differences going from -50% to -150/-200%. This was also reported in (Casadio et al., 2016), where the authors compared AIRWAVE TCWV with collocated ECMWF counterparts showing a dry bias at high latitudes (where the TCWV values are small). The tests on synthetic radiances indicate that the ~~V2~~ AIRWAVEv2 parametrisation solves this issue.

5.2 Atmospheric temperature and water vapor profiles and SSTs

One of the main error sources that can affect the AIRWAVE TCWV retrieval is the assumption of a fixed temperature profile. Actually, the atmospheric opacity is closely linked to the atmospheric density and thus to the atmospheric temperature. To estimate the impact of temperature on the retrieved TCWV, twenty different temperature profiles were randomly perturbed by ±3 K on a 1 km equi-spaced altitude grid. In order to account also for possible changes related to SST variation we change the SST accordingly to the value of the temperature in the lowest layer. Then, simulated BTs were produced with the RTM and were used to perform the TCWV retrievals for the three instruments in equatorial, mid-latitude and polar July conditions for the ~~north hemisphere~~ North Hemisphere and the results were compared with respect to the unperturbed case. In the third column of Table 3 we summarise the findings of this analysis for each of the three instruments, reporting the STD of the difference both in absolute and in percentage values. The impact of ~~the perturbations on the temperature profile~~ these perturbations is of the order of 6~~%~~ % and is higher in the equatorial and ~~mid-latitude~~ mid- latitude regions and lower at the poles. Indeed, in the equatorial region, due to the higher water vapour content, the atmosphere is more opaque than at the poles so that temperature variations have a larger impact on the retrieved TCWV. These tests were also performed varying the atmospheric profile alone. Very similar but slightly higher errors are found in these cases. Another relevant error sources can be due to differences in water vapor profile shape. To evaluate this error, we varied the water vapor profile randomly up to 5% at each atmospheric level. At maximum the impact is of 1% in equatorial case (atmospheric opacity, see the fourth column in Table 3).

5.3 Wind Speed

A further source of error that can affect the TCWV retrievals is the value used for the sea emissivity, which enter directly into equations (10) and (11). Sea emissivity depends upon wavelenght, sea surface temperature, viewing angles and wind speed. As stated in Sect. 2.2, in ~~V2~~ AIRWAVEv2 we accounted for emissivity variations due to the viewing angles and sea surface temperatures. All the calculations were performed at a fixed wind value of 3 m/s. In order to assess the possible systematic effects due to wind variations on the retrieved values, we varied the emissivity according to the wind speed at three values as tabulated in the University of Edinburgh emissivity database: 1 m/s, 10 m/s and 25 m/s.

The emissivity has a different value and spectral behaviour with different wind speeds. The fourth column of Table 3 report the difference of the TCWV retrieved for simulated measurements with the 25 m/s wind speed with respect to the reference case. As expected, the impact is almost negligible in the equatorial band, where the higher opacity of the atmosphere reduces the sensitivity of ATSR measurements to the surface conditions, while increases toward the poles where, due to the low atmospheric opacity, the surface effects become relevant with respect to the atmospheric component. Furthermore, in case of polar conditions, the effects of the wind on the retrieved TCWV is not linear, with enhanced variations for wind speed of 25 m/s, as not only the intensity but also the spectral shape of the surface emissivity varies in function of the wind speed. The possible presence of white caps, generated by high speed winds, has not been considered in this study

5.4 Interfering atmospheric constituents

The AIRWAVE algorithm, in both versions, accounts for the contribution to the radiance of the two main gases active into the ATSR channels (H_2O and CO_2). However some other species have spectroscopic features in the ATSR channels. In Fig. 8, the CO_2, HNO_3 and CFCs spectra in the 10-13 μm wavelength range are shown, along with the ATSR filter functions (all in arbitrary units). In order to have a complete view of the possible error components, we assessed the interfering species impact in case their abundance differs from the one used in the reference scenarios to compute the retrieval parameters.

Among the considered species, HNO_3 shows significant latitudinal and seasonal variability while CO_2 and CFCs exhibit inter-annual trends (Remedios et al., 2007). For this reason we separately accounted for the effects due to latitudinal and inter-annual variability. We used the IG2 database version 4.1 and our RTM to produce synthetic BTs. For each season/latitude band we generated synthetic BTs using the proper IG2 atmospheric status but the profile of the investigated species, for which we used all the different available profiles. The generated BTs were then used to retrieve the TCWV to assess the systematic error induced by the expected variability of the interfering species.

Latitudinal and seasonal variations of HNO_3 impact ATSR-1 and ATSR-2 BTs more than AATSR, because of the different shapes of the TIR filter functions, and can produce differences up to 0.3 K in the 11 μm band (mid-latitude vs tropical north in January). For CFC-11 seasonal differences in the tropics are of the order of 0.001 K in the 12 μm band and for CFC-12 we get 0.03 K in the 11 μm band, while latitudinal variations reach 0.04 K from tropical to mid-latitude atmospheres for both channels. CO_2 latitudinal variations can produce a maximum difference of 0.003 K on nadir BT. The impact of maximum latitudinal variations of HNO_3, CFCs and CO_2 on the retrieved TCWV is reported in Table 3. The largest contribution is due to HNO_3 latitudinal variation and is of the order of 0.6%, while the CFCs latitudinal variations produce differences of 0.15% and CO2 of 0.01% only. Furthermore, the impact of using mid latitude profiles instead of tropical profiles for all species but H_2O has a maximum impact of 0.22%. Seasonal variations are almost negligible for CO_2 and CFCs, while they are only 0.6% for HNO_3. Thus we can safely assume that the latitudinal and seasonal variations of the interfering species represent a minor error source for the AIRWAVE TCWV for both ~~V1 and V2~~AIRWAVEv1 and AIRWAVEv2.

To evaluate the impact of inter-annual variations also for all the ATSR series, we would need the CO_2 and CFCs profiles from 1991 to 2012. However, as mentioned in the previous sections, the IG2 database contains data from the 2002 onwards. In this work, the CFCs and CO_2 profiles from 1991 to 2001 were inferred scaling the 2002 profiles using the trend given in the last IPCC report for CO_2 and in the Mauna Loa observatory website ((Global Monitoring Division website) website, see also Aoki et al. (2003) and Minschwaner et al. (2013)) for CFC-11 and CFC-12. The impact on the ATSR BTs due to the inter annual variations of CO_2 and CFCs has been evaluated for each mission. We calculated the synthetic spectra using the CFC-11, CFC-12 or CO_2 profile for the initial and final year of each mission. Then we calculated, for each instrument, the differences of retrieved TCWV at the beginning and at the end of each mission. Results for CO_2 and CFCs are shown in Table 3. The influence of CO_2 annual variations on the retrieved TCWV is of the order of 0.004 kg/m^2 (<0.01 %). For CFCs we obtain 0.002 kg/m^2. We can then conclude that the impact of VMR latitudinal and seasonal variations on retrieved TCWV is negligible (maximum value 0.6%), and that the systematic effect of CO_2 and CFCs long term variations over the missions are even smaller (0.07%).

5.5 Noise

Finally we analyse the impact of the measurement noise on the retrieved TCWV (see last column of Table 3). The measurement noise was simulated applying a random perturbation of ±0.037 K on the BTs of the two channels of ATSR-2 and AATSR and a perturbation of ±0.1 K on the ATSR-1 channels (Smith et al., 2012). For each instrument, we have generated one thousand values and we have evaluated the standard deviation of the obtained TCWV that we report in absolute and percentage values in Table 3. The standard deviation is maximum at the poles, as expected since there the TCWV and S/N ratio are lower. For ~~V2~~ AIRWAVEv2 we get 18% for ATSR-1 and 6% for ATSR-2 and AATSR in the worst case. To be noticed that ~~V2~~ AIRWAVEv2 approach has, for all the scenarios, better performances with respect of ~~V1~~ AIRWAVEv1 (see Casadio et al. (2016)).

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Table 1. AIRWAVE v1 and ~~v2~~ AIRWAVEv2 retrieval parameters for tropical summer atmosphere and along track configuration (sub-satellite view at 0° and 55°).

		α	β	δ	$\Delta\sigma_{NAD}$	$\Delta\sigma_{FWD}$	G_{NAD}	G_{FWD}	$\Delta\rho_{NAD}$	$\Delta\rho_{FWD}$
					10^{-06}	10^{-06}	10^{-06}	10^{-06}	10^{-06}	10^{-06}
ATSR-1	~~V1~~ AIRWAVEv1	50.7	-49.7	1.65	1.49	2.41	-5.30	-8.82	—	—
	~~V2~~ AIRWAVEv2	1.72	-0.72	1.69	0.06	0.05	-6.59	-11.1	6.59	11. 2
ATSR-2	~~V1~~ AIRWAVEv1	50.5	-49.5	1.63	1.74	2.78	-6.36	-10.4	—	—
	~~V2~~ AIRWAVEv2	1.65	-0.65	1.67	0.07	0.04	-7.88	-13.1	7.89	13.2
AATSR	~~V1~~ AIRWAVEv1	53.1	-52.1	1.62	1.90	3.02	-7.06	-11.5	—	—
	~~V2~~ AIRWAVEv2	1.67	-0.67	1.66	0.08	0.05	-8.74	-14.5	8.77	14.6

Table 2. AIRWAVE TCWVs compared with SSM/I and ARSA stations. Results are given also for AIRWAVEv1. Absolute differences along with the standard deviations are reported for the global (all latitudes), equatorial (~~25S-25N~~25° S-25° N), mid-latitude (~~25S-60~~25-60° S and ~~25N-60~~25-60° N) and polar (>60° N or >60° S) scenarios. Average values for the ATSR-1, ATSR-2 and AATSR are also provided.

		SSM/I-AIRWAVE					ARSA-AIRWAVE				
Instrument	Scenario	N $\times 10^5$	BIAS-v2	STD-v2	BIAS-v1	STD-v1	N $\times 10^5$	BIAS-v2	STD-v2	BIAS-v1	STD-v1
				kg/m^2					kg/m^2		
All	Global	3110	0.02	4.69	0.72	5.75	3.01	0.19	6.12	0.80	7.73
All	Equator	1560	-0.17	4.79	-0.17	5.57	0.87	-0.70	6.60	-2.40	7.74
All	Midlat	1380	0.07	4.84	1.12	5.89	1.80	0.49	6.10	1.69	7.44
All	Polar	170	1.32	3.51	5.55	5.14	0.35	0.86	4.59	4.12	6.47
ATSR-1	Global	190	-0.20	5.17	1.15	6.17	0.48	-0.71	6.24	0.23	7.62
ATSR-2	Global	1390	0.24	4.77	0.80	5.87	1.00	0.70	6.04	1.13	7.65
AATSR	Global	1520	-0.16	4.70	0.58	5.77	1.53	0.13	6.11	0.75	7.81

Table 3. Impact of different error sources on AIRWAVEv2 dataset.

Instrument	Scenario	Temp profile+SST kg/m^2	H_2O profile kg/m^2	wind (25 m/s) kg/m^2	HNO_3 kg/m^2	CFC-11 kg/m^2	CFC-12 kg/m^2	CO_2 kg/m^2	CFC-11 trends kg/m^2	CFC-12 trends kg/m^2	CO_2 trends kg/m^2	Noise kg/m^2
ATSR-1	Equatorial	~~3.6~~ 3.2	0.5	-0.003	0.2	0.07	-0.07	0.003	-0.006	0.014	0.01	4.8
		~~(6.9%)~~ (6.1%)	(1.0%)	(-0.01%)	(0.4%)	(0.14%)	(-0.16%)	(0.006%)	(-0.01%)	(0.03%)	(0.03%)	(9%)
	Midlat	~~1.9~~ 1.2	0.1	0.214								4.8
		~~(6.1%)~~ (4.2%)	(0.5%)	(0.69%)								(16%)
	Polar	~~0.6~~ 0.3	0.1	0.448								3.0
		~~(3.9%)~~ (1.6%)	(0.5%)	(2.70%)								(18%)
ATSR-2	Equatorial	~~3.7~~ 3.5	0.5	-0.008	0.15	0.05	-0.05	-0.003	0.015	0.009	-0.02	1.6
		~~(7.0%)~~ (6.6%)	(1.0%)	(-0.01%)	(0.3%)	(0.1%)	(-0.1%)	(-0.006%)	(0.03%)	(0.02%)	(-0.05%)	(3.1%)
	Midlat	~~2.0~~ 1.4	0.2	0.230								1.6
		~~(6.6%)~~ (5.1%)	(0.6%)	(0.74%)								(5.2%)
	Polar	~~0.7~~ 0.4	0.1	0.467								1.0
		~~(4.2%)~~ (2.0%)	(0.5%)	(2.8%)								(6.1%)
AATSR	Equatorial	~~3.7~~3.5	0.5	-0.012	0.28	0.08	-0.07	0.006	0.01	0.01	-0.03	1.4
		~~(7.1%)~~ (6.7%)	(1.0%)	(-0.02%)	(0.56%)	(0.17%)	(-0.15%)	(0.01%)	(0.02%)	(0.02%)	(-0.07%)	(2.8%)
	Midlat	~~2.1~~1.5	0.2	0.204								1.5
		~~(6.8%)~~ (5.4%)	(0.6%)	(0.66%)								(4.8%)
	Polar	~~0.7~~ 0.4	0.1	0.447								0.9
		~~(4.3%)~~ (2.2%)	(0.5%)	(2.7%)								(5.6%)

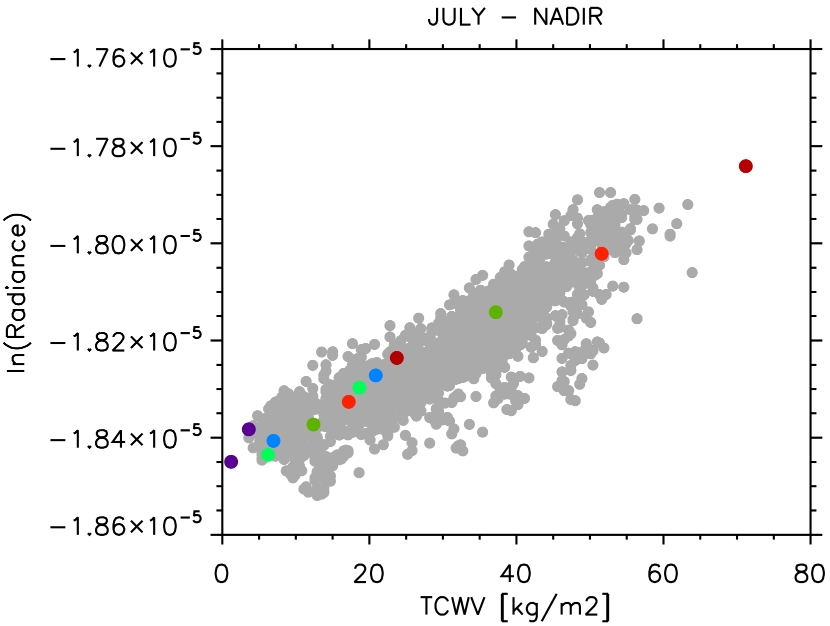

Figure 1. Logarithm of radiance ratio at nadir as a function of TCWV in simulated atmospheric scenario. Grey dots represent the same quantity using realAATSR radiances and coincident SSMI TCWV for the along track measurements on the 5 and 6 August 2008.

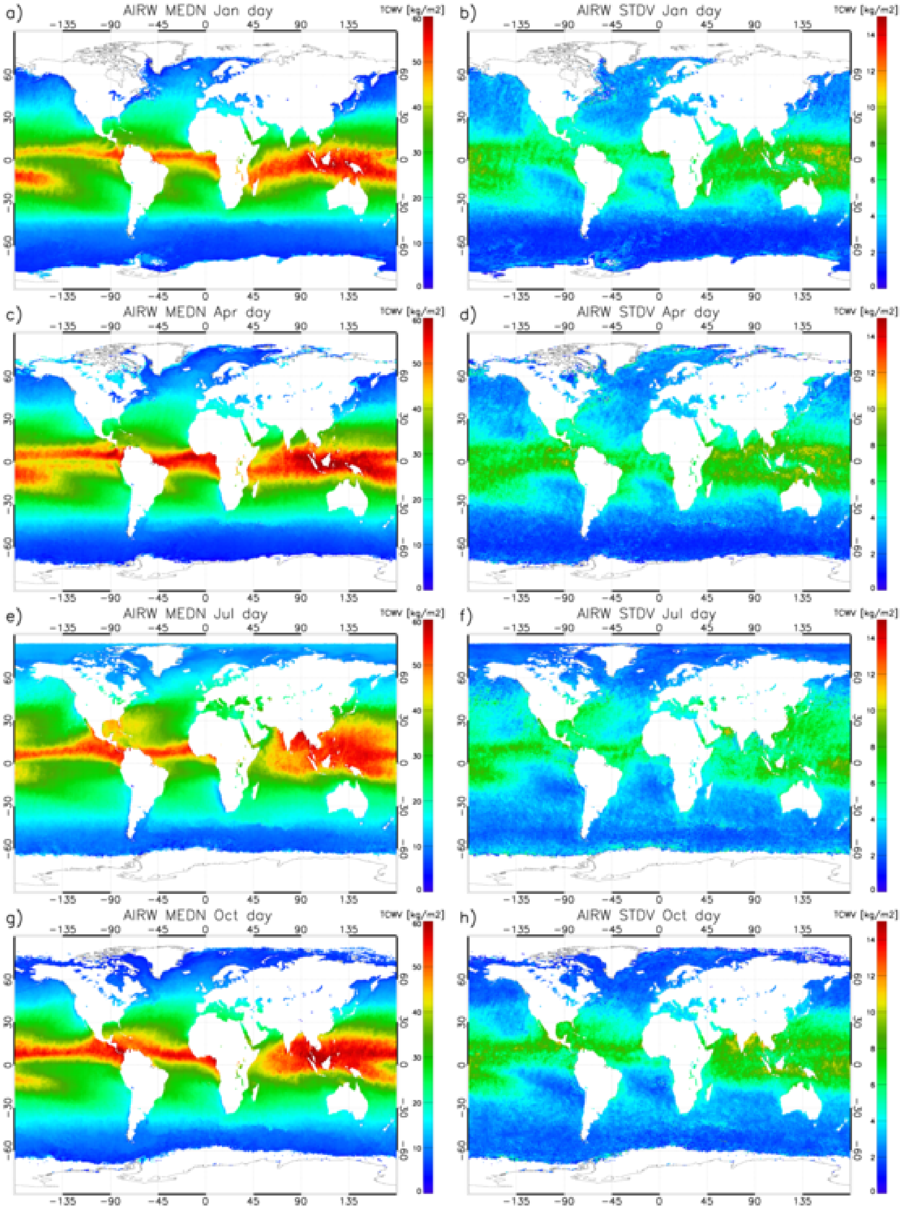

Figure 2. Climatology of daytime TCWV from AIRWAVEv2 dataset for January (a), April (c), July (e) and October (g) from 1991-2012, and standard deviations for same moths (respectively b, d, f, h).

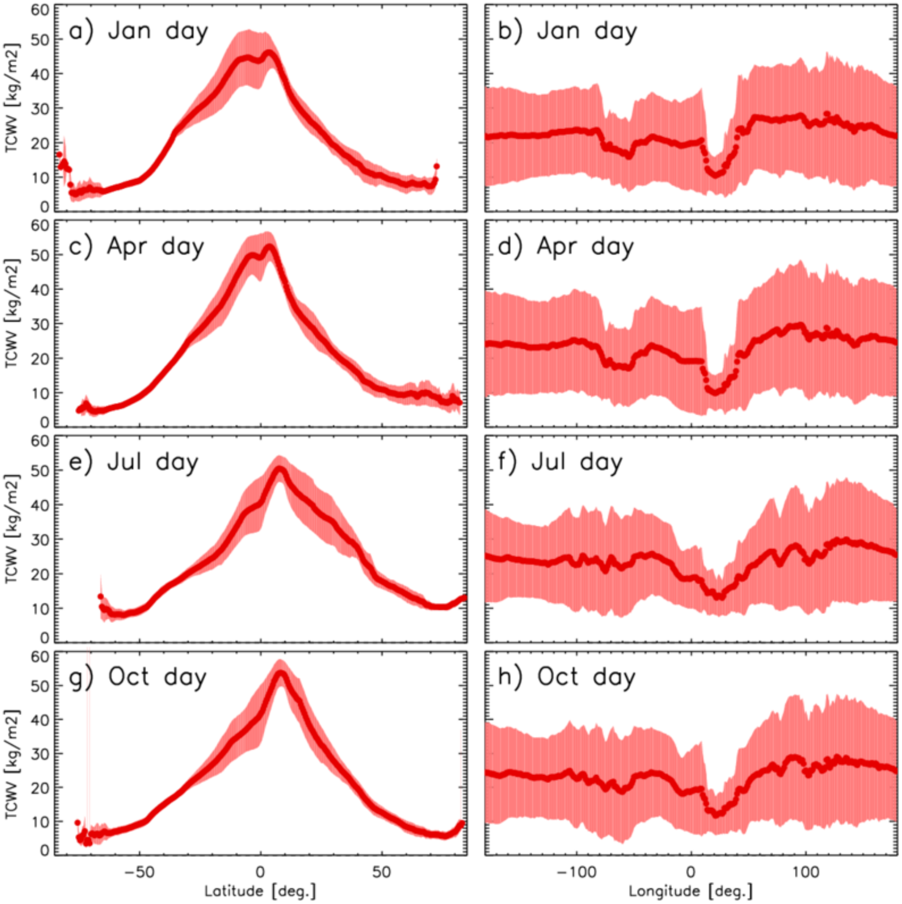

Figure 3. TCWV distribution as function of latitude (median and standard deviation) (a, c, e, g) and as function of longitude (b, d, f, h).

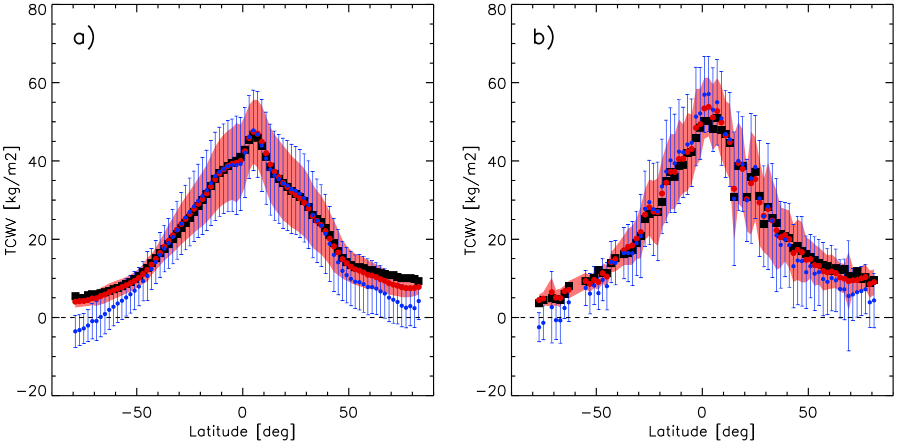

Figure 4. Zonal means of TCWV for AIRWAVEv1 (blue), AIRWAVEv2 (red) and correlative measurements (black): SSM/I (a) or ARSA (b). The data have been averaged in 2 degrees latitude bins. ARWAVE TCWVs standard deviations are also reported.

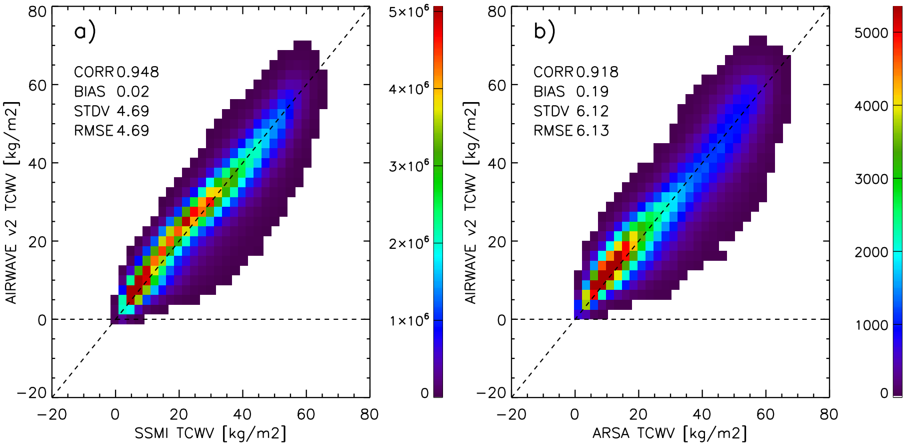

Figure 5. AIRWAVE TCWV vs SSM/I TCWV (a) or ARSA TCWV (b). The bin size is 2.5 kg/m^2. The colour scale indicates the number of elements of the histogram. The data cover the period from 1991 to 2012.

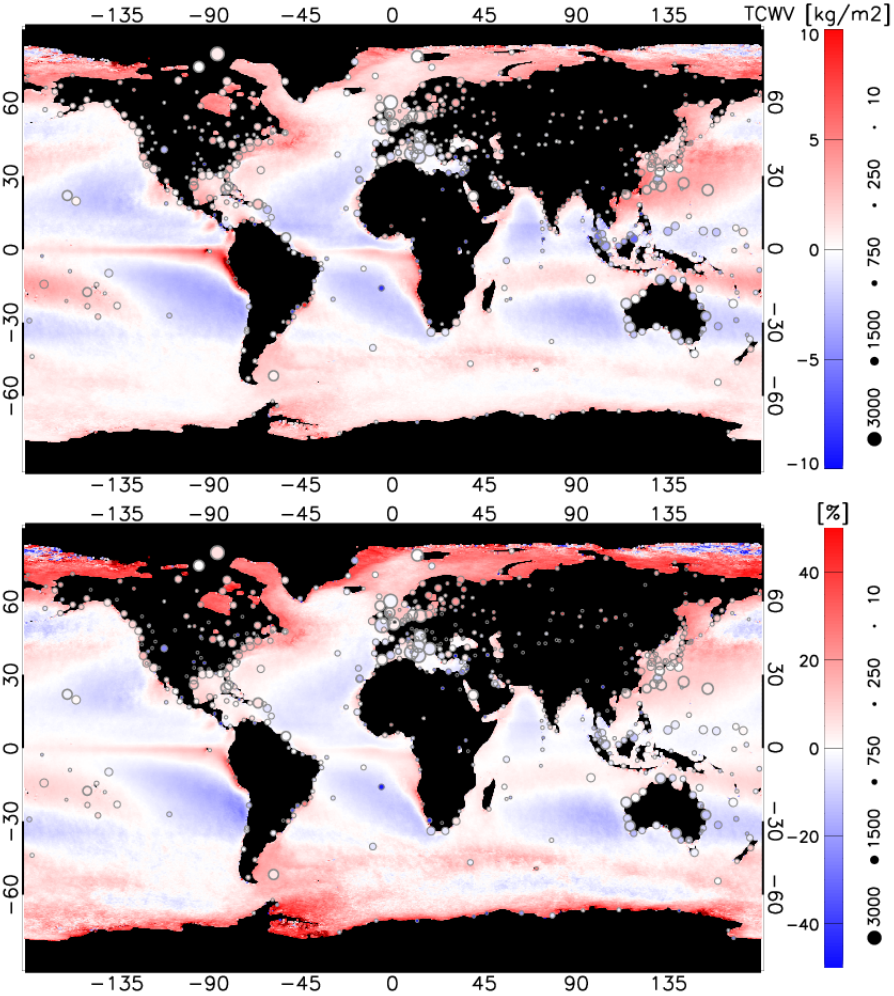

Figure 6. Average absolute (top) and relative (bottom) TCWV difference (SSM/I-AIRWAVE) at 0.25° × 0.25° spatial resolution. Average ARSA-AIRWAVE TCWV differences are overplotted with circles; the size of the symbols is proportional to the number of matches (see legend). The data cover the period from 1991 to 2012.

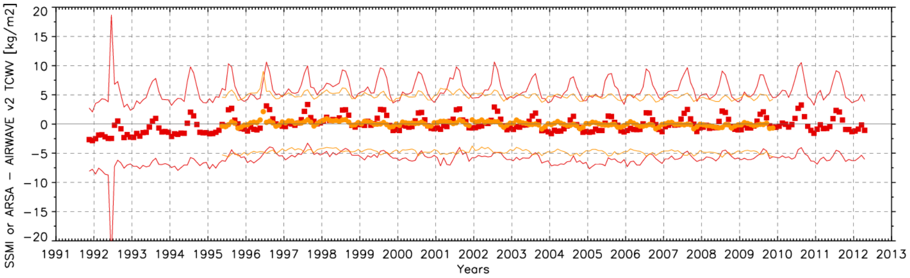

Figure 7. SSM/I-AIRWAVE TCWV (orange) and ARSA-AIRWAVE TCWV (red) monthly mean trends. The difference between the correlative measurements and AIRWAVE TCWV STDV is also reported.

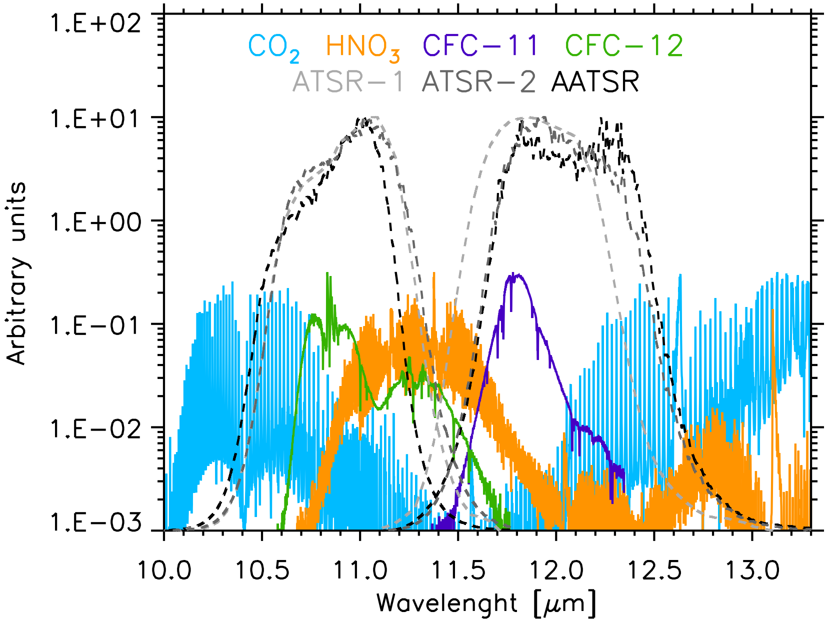

Figure 8. CO_2, HNO_3, CFCs spectral lines and ATSR filter functions (arbitrary units).