SCIENTIFIC REPORT

ACTION: ES1303 TOPROF

MEETING: SWG 3.7

TITLE: Status and next steps towards the assimilation of ground-based MWR observations

VENUE: DWD, Offenbach, Germany

DATE: 12-14 December, 2016

Produced by: R. Potthast (DWD, DE)

Submission date: 10.02.2017

Contributions by: D. Cimini (CNR-IMAA, IT), F. De Angelis (U. L'Aquila, IT), L. L. Kliesch (U. Köln, DE), U. Löhnert (U. Köln, DE), P. Martinet (Meteo France, FR)

Introduction

The Special Working Group (SWG) meeting 3.7 was co-organized by TOPROF WG3 (Microwave radiometers, MWR) and WG4 (Data Assimilation, DA). The aims of SWG3.7 are the following:

- Review the results of the Observations minus Background (O–B) analysis carried out within the collaboration between WG 3 and 4;
- Review updates on instrument and data processing development;
- Advertise the potential of MWR observations for data assimilation, numerical weather prediction (NWP), and operational meteorology to a broader community, especially coming from National Weather Service (NWS);
- Review bias correction techniques currently adopted at various NWS;
- Update on current plans for DA of ground-based observation networks at various NWS;
- Agree on next steps towards the achievements of TOPROF objectives;
- Discuss follow-up initiatives involving a coordinated MWR network

Thus, the following participants gathered in Offenbach at the premise of the German Weather Service (Deutscher Wetterdienst, DWD): O. Caumont (Meteo France, FR), D. Cimini (CNR-IMAA, IT), F. De Angelis (U. L'Aquila, IT), M. Ernst (U. Frankfurt), A. Haefele (MeteoSwiss, CH), S. Hafner (DWD, DE), H. Klein-Baltink (KNMI, NL), L.-L. Kliesch (U. Köln, DE), U. Löhnert (U. Köln, DE), P. Martinet (Meteo France, FR), B. Pospichal (U. Köln, DE), A. Schomburg (DWD, DE), C. Schraff (DWD, DE), R. Potthast (DWD, DE), M. Toporov (U. Köln, DE). D. Leuenberger (MeteoSwiss, CH) joined the meeting remotely.

The SWG3.7 meeting lasted from 13:00 Monday 12 to 13:00 Wednesday 14 December, 2017. The first half-day was dedicated to discussion of technical and instrumental aspects. The second full day was dedicated to a joint meeting of observers and modelers. The last half-day was dedicated to a summary and follow-up initiatives.

Achievements Through summarizing the latest activities towards assimilating MWR observations into NWP models, SWG3.7 paves the way to future coordinated activities in assimilating MWR data streams at national weather services (NWS).

I) 3DVAR assimilation of MWR retrievals

Results from a recently published DA experiment (Caumont et al., 2016) were reviewed. This study shows DA of atmospheric temperature and humidity profiles retrieved from a European-scale network of 13 MWR into the Meteo France convective-scale model AROME. The study considers a period of 41 days and an MWR O-B bias computed over the whole experiment period was removed prior to the assimilation. Typically, the bias was rather constant for all radiometer systems operating during the experiment. The study demonstrates that a MWR network can have a positive impact on the quantitative precipitation forecast (QPF) at lead times up to 18 h for larger rainfall accumulations (Figure 1 For all other considered variables, the impact is mostly neutral and no degradation due to the DA could be analyzed. Note, that the MWR observations were assimilated next to a large number of standard observations corresponding to the current observation network technology. The standard assimilated observations include those from ground-based networks and satellite sensors, and also from nearby or collocated radiosonde launch sites. Thus, Figure 1 shows that more positive impact is obtained when radiosondes are not assimilated.

In general, we conclude that a higher impact of MWR observations on QPF is to be expected if the following points are addressed.

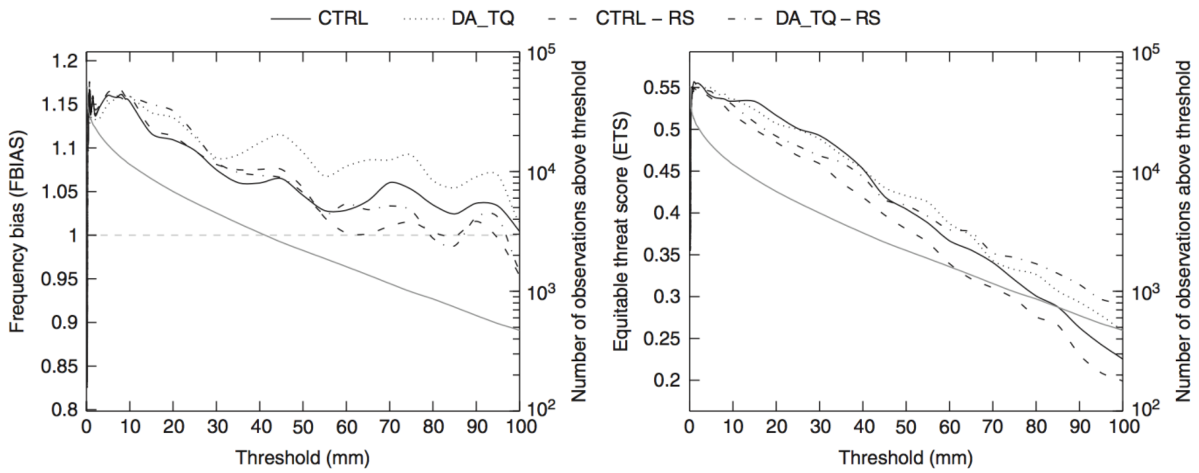

Figure 1: (From Caumont et al., 2016) Frequency bias (left) and equitable threat score (right) for 0–18 h accumulated precipitation forecasts against rain gauges. Grey solid lines indicate the number of observations. Lines correspond to control run (CTRL), MWR temperature and humidity assimilation (DA_TQ), control run with no radiosonde assimilation (CTRL−RS), and DA_TQ with no radiosonde assimilation (DA_TQ−RS).

- The instrument distribution in the network of this study was sparse and inhomogeneous. The future design of a MWR network should aim at complementing the existing operational radiosounding network to maximize its impact for data assimilation purposes.
- Increasing the density of the MWR network would likely increase the impact.
- The data were provided as observed, without dedicated monitoring of their quality. Improving the monitoring of data quality should generally help obtaining higher impact;
- Use of a fast radiative transfer operator, with its tangent linear and adjoint, for simulating ground-based MWR observations allowing the direct assimilation of observed brightness temperature instead of retrieved profiles.

In addition, this study focused on deep-convection events, while the assimilation of MWR data could also useful in other situations such as low-level fog.

Figure 2: Map of the six sites contributing to the O-B analysis: CESAR, Cabaw, The Netherlands (red), JOYCE, Jülich, Germany (black), LACROS, Leipzig, Germany (purple), Payerne, Switzerland (blue), RAO, Lindenberg, Germany (yellow), and SIRTA, Paris, France (brown).

II) O-B analysis on level1 data

Here, typical level1 O-B departures are analyzed to evaluate the potential of direct TB observations for DA. The data termed as "level1" describes the direct observables of MWR, namely brightness temperature (TB in K), which is a measure of the radiance received from the atmospheric emission.

An O–B analysis in radiance space contains a combination of errors originating from the observations themselves, the NWP model forecast, and the radiative transfer model apploed to the model output. Any constant bias arising from the O–B monitoring can be removed to guarantee the assumption of unbiased observations that is imperative to variational retrieval apporaches.

For this analysis, a dataset of O–B TB differences covering one year (2014) has been derived. TB observations have been collected at six sites across Europe (Figure 2), five of which deploy a RPG-HATPRO while the remaining one deploys a Radiometrics-MP3000A (Lindenberg, Germany). Clear-sky conditions have been selected to avoid cloud contamination using a three-fold screening: (i) 1-hour standard deviation of the MWR TB at 31 GHz (σ_C), (ii) sky infrared temperature from the 10.5 μm infrared radiometer mounted within the MWR housing (T_{IR}), and (iii) the quality/rain flag provided within the instrument data stream (flag). Periods with σ_C > 0.5 K, T_{IR} > -30°C, or flag > 0 were rejected. In addition, O–B TB differences larger than 3 standard deviations with respect to the mean difference were rejected in order to remove outliers.

Temperature, humidity and pressure profiles are extracted from the 3-hour AROME forecasts; the central model grid point profile (closest to the MWR observations) is used as background x_b. Clear-sky TB simulations are produced with RTTOV-gb, the ground-based version of RTTOV developed in the framework of TOPROF (De Angelis et al., 2016).

Figure 3 shows statistics of the O–B TB departures in clear sky conditions for a continental site in central Europe (JOYCE, Germany). MWR TB from HATPRO at 14 frequencies and on at 7 elevation angles (90-42-30-19.2-10.2-5.4-0°) are available. The computed statistics are bias, standard deviation, and RMS.

At 90° elevation angles, the K-band (20-30 GHz) channels show O-B departures decreasing from the line center (bias: 0.9 K, RMS: 1.8 K) towards the higher-frequency window channel (bias: 0.6 K, RMS: 1.0 K). These values are within the expected range of operational MWR observations that have **not** been optimized for network application. Clearly, there is a high potential for improving the bias through adequate calibration monitoring / performance control. Towards lower elevation angles, O-B departures are amplified in magnitude (i.e. at 10° elevation angle the RMS reaches 10 K), however keeping a similar shape with respect to frequency channel (panels B to F). One reason for this is the increasing air mass with decreasing elevation angle leading to an amplification of any humidity profile difference. Even larger differences are found at 5° elevation angle in the K-band (biases larger than 14 K). The large discrepancies at low elevation angles are attributed to deficiencies in the radiative transfer model. First, 5° and 10° are outside the elevation angle range used in RTTOV-gb development and second, MWR bandwidth, beamwidth as well as propagation effects are not considered. The latter all can cause large biases between simulations and observations, especially at lower elevation angles and will be addressed in future since. Observations are at low-elevation angles are expected to contain significant information on humidity variations on the order of 1km.

O-B departures in the V-band show different behavior at lower frequency (i.e. transparent) and higher frequency (i.e. opaque) channels. Opaque channels (54-58 GHz) show low bias, std, and RMS (all within 0.5 K), with little variation in elevation angle. Opaque channels are close to saturation and are not affected by water vapor or clouds. Transparent channels show large biases (up to 2 K) with relatively low std (1.0 K). The large bias at lower V-band channels (50-54 GHz) are likely due to a combination of calibration and absorption model uncertainties. In fact, these channels suffer from larger calibration uncertainty, due to the relative low opacity; consequently, also absorption models have larger uncertainty due to lack of well calibrated data usable for tuning spectroscopic parameters. However, this analysis demonstrates that little variability is associated to these bias values. Thus, biases can be safely corrected for so that the unbiased observation assumption, on which the variational assimilation scheme is based, is fulfilled.

O-B monitoring is also an extremely valid tool for detecting instrument malfunctions in near real time. For example, looking at the O-B time series for JOYCE (Figure 4), it is evident that the 31.4 GHz channel shows much larger differences until June the 3rd. On this day, a new absolute calibration was performed. These results suggest the implementation of a similar monitoring tool for all sites deploying MWR as part of the MWR data quality control procedure.

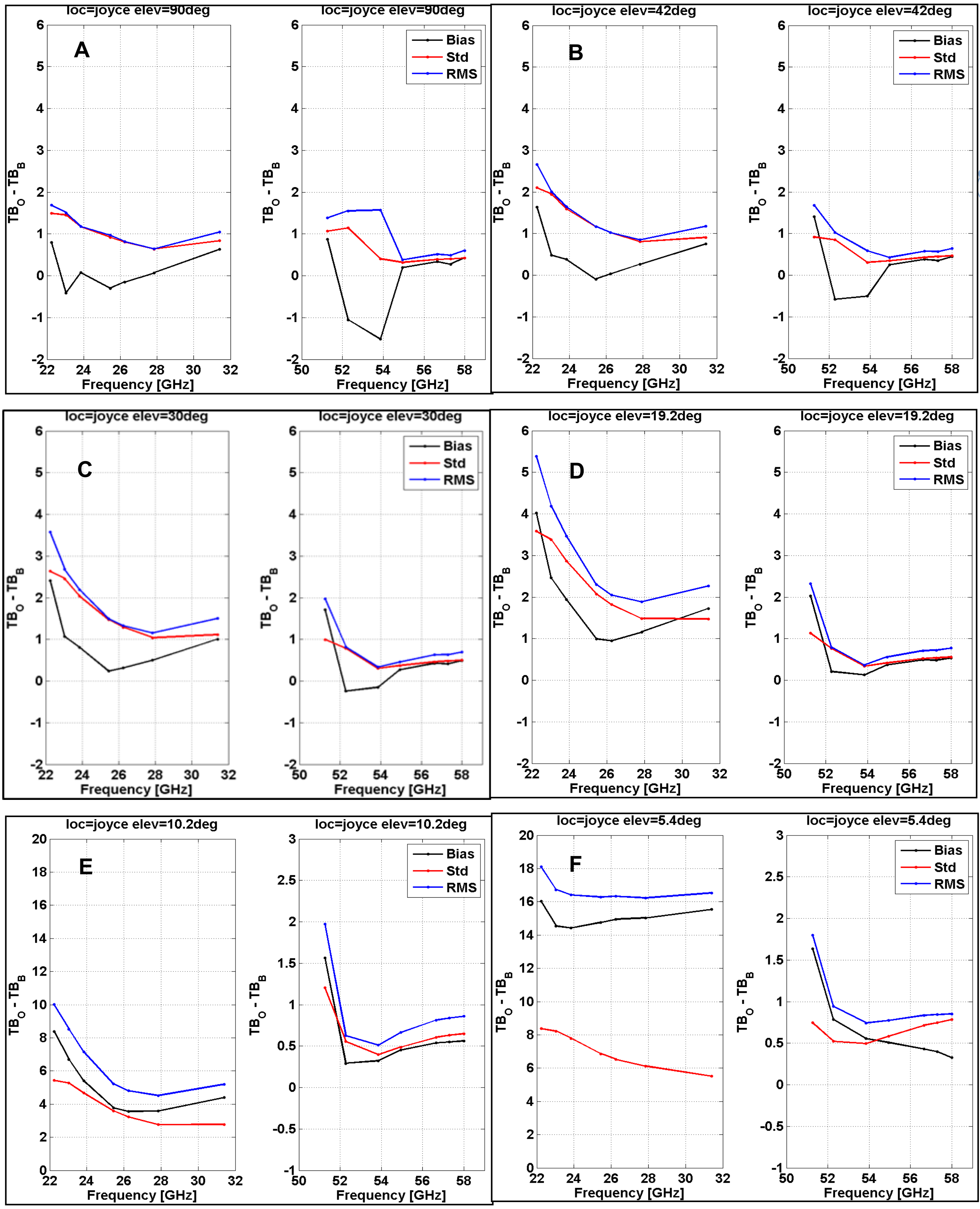

Figure 3: Statistics of the differences between measured TB and TB simulated with RTTOV-gb from AROME profiles for JOYCE in clear-sky conditions. Biases are shown with black lines, standard deviations with red lines and RMS with blue lines. Panels A, B, C, D, E, and F refer respectively to 90, 42, 30, 19.2, 10.2, and 5.4° elevation angle.

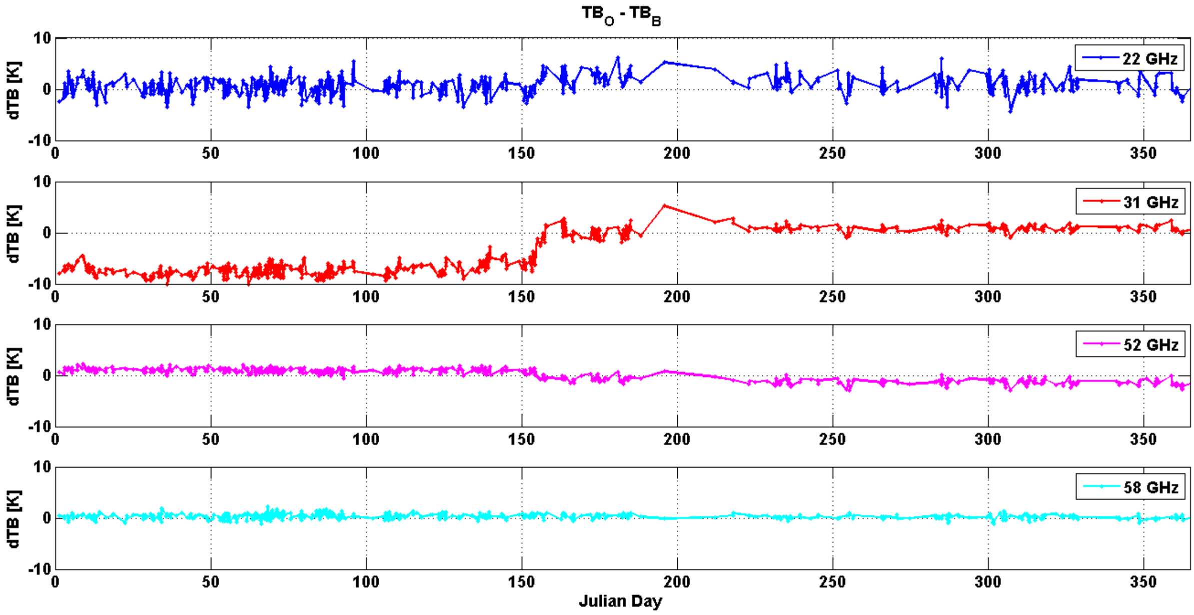

Figure 4: Time series of TB O-B at channel 22.24, 31.40, 52.28, and 58.0 GHz in JOYCE. The second panel from the top shows a mis-calibration of the 31 GHz channel up to Julian day 160 (3 Jun 2014).

III) O-B analysis on level2 data

In accordance to the level1 O-B statistics, O-B departures have also been derived for level2 data. Again, temperature, humidity and pressure profiles are extracted from the 3-hour AROME forecasts; the central model grid point profile (closest to the MWR observations) is used as background x_b. In this case, however, no restrictions to clear-sky have been made. The applied multi-variate regression schemes for temperature and humidity are applicable to all-sky cases. Typically, temperature profiles are most accurate in the lowest 500 m above ground with rapidly decreasing vertical resolution above. Note, that humidity profile information is typically confined to two independent layers, however with high accuracy concerning the vertically integrated value.

In order to compare with the AROME background, all-sky retrieved temperature and absolute humidity profiles have been interpolated to the AROME vertical grid and evaluated as a function of time and height. As an example, time series of 10-day-averaged O-B daily statistics for the temperature profile during a persistent high-pressure system over JOYCE are shown in Figure 5. The std plot show highest differences during the morning-time break-down of the stable nocturnal boundary layer and the following conversion to a well-mixed lower-layer. The departures are the smallest when the boundary layer is well mixed (12-17). It is also interesting to note, that obviously there is too much night-time cooling at the surface in the AROME model (close-to-surface bias during 1-7 UTC). The large bias from 12 UTC onward in 400 to 700 m height is due to the boundary layer height higher in the model than in the MWR observations. These comparisons show that MWR potentially deliver means to evaluate and initialize small-scale models in the boundary layer where often, small temperature offsets can have large impacts.

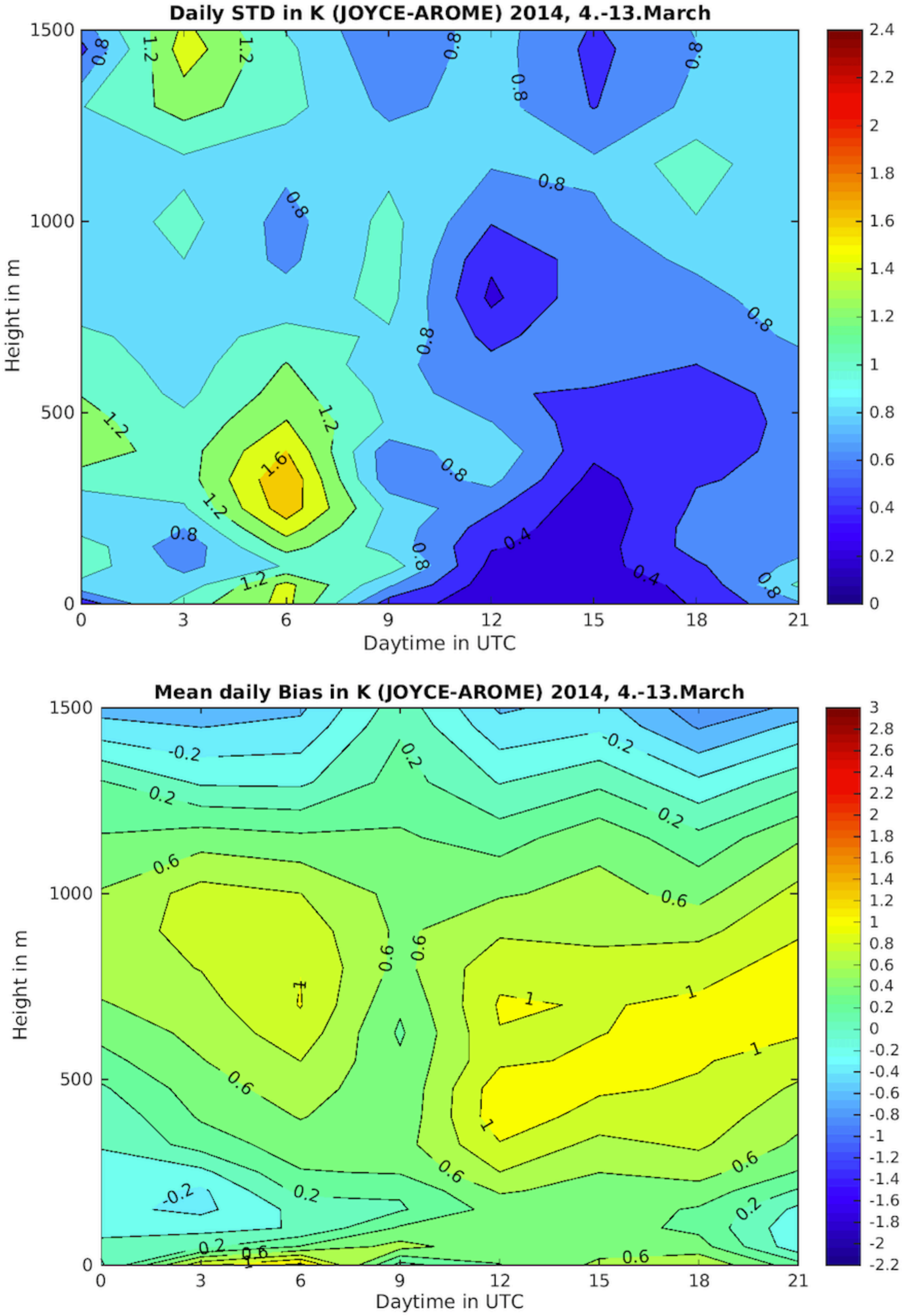

Figure 5: Time series temperature O-B statistics (Top: STD(MWR-AROME); Bottom BIAS(MWR-AROME) during a 10-day period of stable high-pressure weather at JOYCE.

IV) 1DVAR retrievals

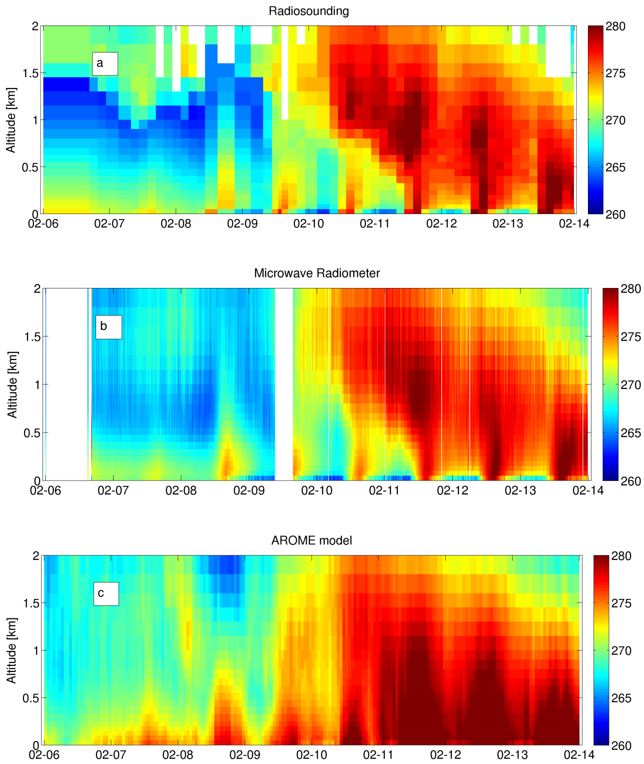

Figure 6: Time series of temperature profiles during IOP 1 from (a) radiosounding, (b) Microwave Radiometer, (c) AROME

One-dimensional (i.e. vertical profile) variational (1DVAR) retrievals of temperature have been performed within AROME to quantify the benefits of MWR data for updating the model background. Temperature retrievals performed with the line-by-line ARTS radiative transfer model and the Qpack 1D-Var package have been applied to MWR data obtained during two Météo France campaigns. The first one studied the feasibility of assimilating MWR observations in AROME by deploying the instrument five-months on a site equipped with automated radiosonde observations. The 1DVAR retrievals were found to outperform neural network retrievals above 500 m and to significantly improve the AROME background especially in cloudy-conditions during which forecasts are known to be less accurate. A retrieval accuracy of 1.2 K could be obtained throughout the entire atmospheric column, most of the information above 3 km coming from the background. Temperature retrievals during the Passy-2015 Alpine campaign have then been introduced. This campaign aimed at understanding how wintertime boundary layer conditions in an Alpine valley can lead to high pollutant events. MWR temperature profiles have been compared to radiosondes launched every 3 hours during the campaign. During these conditions, the operational AROME model was found to highly overestimate the surface cooling making difficult the stabilization of the air mass (Figure 6). Large forecast errors up to -10 K were observed during the maximum stability at the surface. The AROME forecast error was found to be decreased from 8 K to less than 1 K close to the surface through the 1D-Var analysis of MWR observations (Figure 7). The AROME background was improved up to 2.5 km altitude. Consistent results were found with the fast radiative transfer model RTTOV-gb which meets the NWP requirements for a direct assimilation of brightness temperatures.

Also, the validation of both temperature and humidity retrievals with the NWP SAF 1DVAR/RTTOV-gb tool has been investigated. This, operational NWP applications developed 1DVAR tool, is more portable and much faster than Qpack. It was applied at the main MWR stations to replace common statistical regressions. Results of a one-month retrieval application at the Payerne is shown in Figure 8. An accuracy of 1 K in temperature was found with a significant improvement of the AROME background below 1 km. Linear regressions show larger errors especially above 1 km altitude. For humidity, 1DVAR retrievals outperform linear regressions throughout the entire atmospheric column with a large decrease of the bias. The AROME background is also slightly improved during the analysis. In terms of integrated water vapour, the RMS is reduced from 1.21 to 0.89 kg/m².

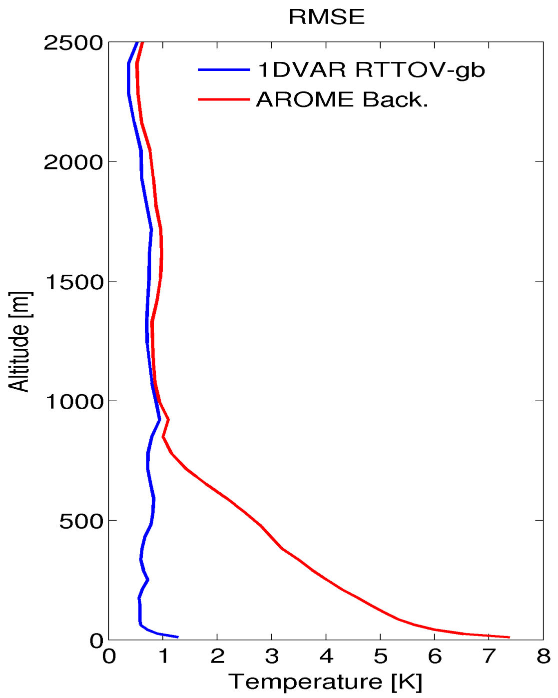

Figure 7: RMSE of temperature profiles with respect to radiosondes: MWR retrievals in blue, AROME 1-h forecast in red

These results show that MWR can bring a significant amount of information in the boundary layer where NWP forecasts suffer from large uncertainty and which is currently under-sampled by current observation networks.

V) Current situation at NWS

After the previous results were discussed, representatives of the NWS and MWR experts discussed on the necessary next steps for making MWR observations suitable for DA.

The analyses showed, that a bias correction scheme is typically needed for MWR observations. Roland Potthast (DWD) and Pauline Martinet (Météo France) presented the variational bias correction scheme currently used at Météo France and ECMWF and most probably in the future also at DWD. In this scheme the bias is expressed as a linear regression according to predictors depending on the instrument: air mass, scan position, integrated water vapor. A new control vector is then defined combining the usual atmospheric variables (temperature, humidity, wind) and the bias predictor coefficients. The observation operator is also extended to account for the observation bias. At each assimilation cycle, both the atmospheric variables and the bias coefficients are updated starting from the values computed at the previous cycle. Some examples in the case of satellite observations showed that most of the bias trend is corrected by an offset and the bias correction depends on the NWP model used for the assimilation concluding that each center should compute its own bias correction.

Pauline Martinet from Météo France highlighted that MWR are considered as very informative in the boundary layer where the atmosphere is highly under-sampled and should provide valuable information in the assimilation system. However, the lack of human resources makes difficult any concrete proposal of including MWR in the operational assimilated observations for the near future (1 to 2 years). However, Météo France agreed to carry out a near real time monitoring of core MWR stations computing O-B departures in level1 and possibly in level2 space. These O-B departures will feed a dedicated website to demonstrate the stability and availability of MWR observations. A PhD thesis should also start by the end of 2017 to evaluate the potential of MWR during fog conditions exploiting two field campaigns carried out in 2015 and 2016 in the North-East of France.

Maria Toporov from the University of Cologne presented her PhD thesis (started in 2016) project together with DWD as part of "Extramurale Forschung". It aims at combining existing satellite observations (AMSU, IASI, SEVIRI etc..) with ground-based observations of microwave radiometers, but also water vapor DIAL. The forecast of stability indices is improved by the inclusion of ground-based observations enabling a better forecast of convection. A virtual MWR network over Germany will be simulated using COSMO re-

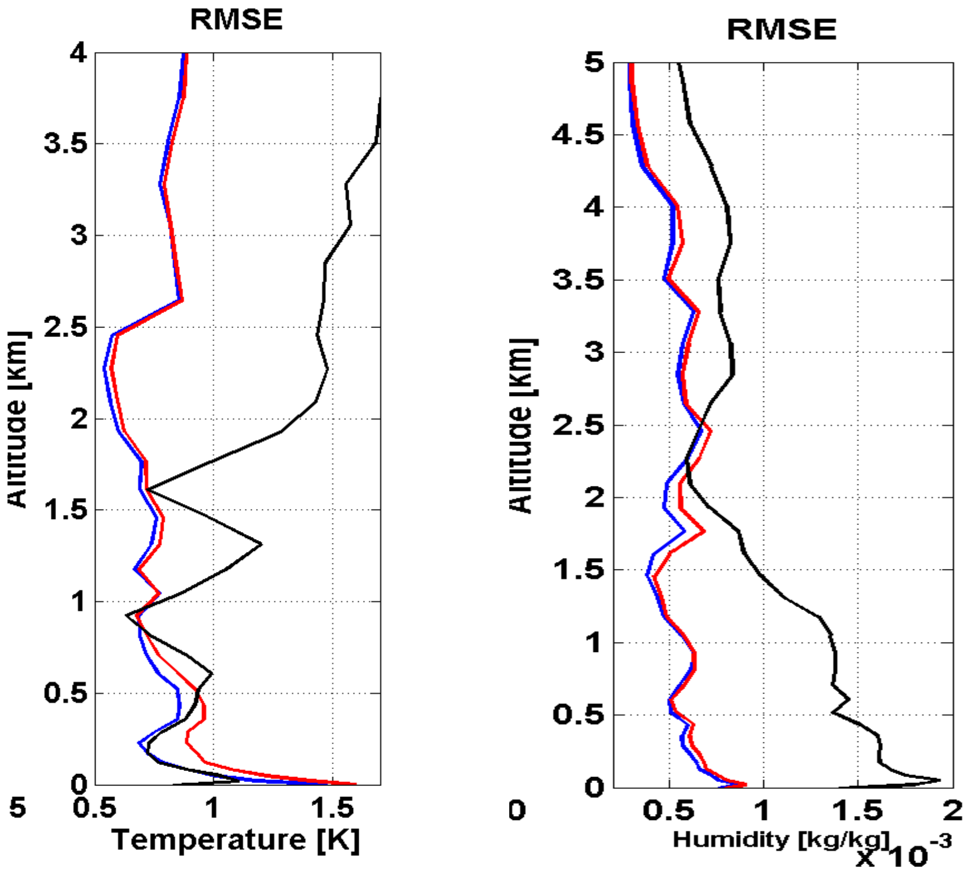

Figure 8: RMSE of 1D-Var retrievals against radiosondes using RTTOV-gb and Payerne MWR observations: temperature (left panel) and humidity (right panel).

analyses and RTTOV-gb model. In cooperation with DWD, OSSE experiments highlighting the impact of ground-based remote sensors for the improvement of the 3D atmospheric state will be carried out in the next years. A major tool will be RTTOV-gb, which shall be installed at DWD this year.

Alexander Haefele from MétéoSwiss presented a recent study of O-B departures with the COSMO model in level2 space (temperature and humidity profiles) for different forecast ranges (0h to 12h). This study showed a fast increase of the O-B departures with the forecast range for altitudes below 2 km. The departures are also much larger during cycles in which MWR are not assimilated. MWR are thus expected to bring valuable information in the altitude range where the forecast error increases the most and to be complementary to radiosonde networks. In the future, MétéoSwiss highlighted its interest in assimilating level2 retrieved profiles which requires less development in the model than directly assimilating brightness temperatures. However, no commitment can be taken at the moment due to a lack of human resources.

VI) Perspectives from NWS DA experts

MWR data has the potential to be an important observation type for short range atmospheric predictions in particular for rapid update cycles to improve forecast quality in the boundary layer. The *advantage* of MWR measurements is its high temporal resolution and the direct access to the lower part of the troposphere. Its *disadvantage* is the low vertical resolution which is inherent in underlying physics. Here, competing systems such as LIDAR based temperature and humidity measurements are being developed by scientists and engineers.

However, LIDAR is limited to clear sky measurements, whereas MWR is an *all-sky system*. Thus, from very basic meteorological and physical arguments MWR measurements enable us to gain unique and important insight into the boundary layer on a very high temporal resolution, which cannot be replaced by other systems. The initial assimilation tests are very encouraging, it is well-known that showing positive impact for a new observation system in an operational setup needs a lot of creativity to adapt tools, quality control, bias corrections and algorithms. Here, we see positive impact already on a local scale in the boundary layer. The integration of NWP and nowcasting will give further momentum to the development of these new observation systems in the coming years.

VII) Follow-up initiatives

Initiatives to raise the credibility of the MWR network to an operational level have been discussed. Updates from the EU Horizon 2020 GAIA-CLIM project (www.gaia-clim.eu) have been presented. The aim of GAIA-CLIM (Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring) is to improve the ability to use ground-based observations to characterize satellite observations for a number of atmospheric Essential Climate Variables (ECVs) (GCOS, 2010). One key outcome of GAIA-CLIM is the Virtual Observatory (VO) facility, a web-based tool for managing data co-locations and their uncertainties. The objectives of the VO are:

- Enhance exploitation of ground-based reference data for satellite product validation through organising access to data and comparison results;
- Integrate ground-based reference data with existing satellite-satellite comparisons and observation feedback from NWP models and reanalysis;
- Increase awareness among users on the concept of traceable uncertainty estimates;
- Provide a facility that can support Copernicus Services to analyse product quality in a sustainable routine mode.

The VO consists of an object-oriented modern data base that holds selected earth observations. It provides the functionality to select, explore, visualise, compare, analyse and export selected pairs of climate data sets. Data sets that have been identified by GAIA-CLIM as being already or potentially of "reference quality" may be ingested into the VO. As MWR are considered as potentially of "reference quality" (according to definition in Immler et al., 2010), MWR units have the possibility to contribute to the VO demonstrator. This participation would require the collection of an extended dataset for a period of about one year (2015, indicatively) from as many MWR as possible. The dataset must include level1 and level2 data in the agreed HD(CP)2 format. A dataset similar to the one collected for the O-B analysis would suffice.

The SWG3.7 participants agree in general on that the VO may be an opportunity for reinforcing the credibility of the MWR network, and thus are willing to consider the efforts associated with the dataset collection. This effort may be seen as a sort of place-holder for the MWR network, especially in the view that the VO has the potential to become part of Copernicus Services.

Actions

This SWG has made clear, that it is worth to continue towards the operational assimilation of MWR into NWP. For this, the workshop participants agreed on the following Action Items (AI).

1. The MWRnet stations JOYCE, Lindenberg, CESAR, LACROS, SIRTA and Payerne shall be asked to commit to a daily submission of MWR data.
   - For 2015 & 2016 as well as for on-going measurements
   - **Action on WG chairs Cimini & Löhnert**

2. Operator forum
    - for current and past issues of continuous MWR observations
    - possibly via a wiki realisation
    - **Action on Pospichal, Cimini, Czekala.**
3. New developments on real-time data streaming & monitoring
    - NWS optimally require data streams not older than 30min since recording.
    - RPG could test a newly developed software for an instrument operating at JOYCE controlled from University of Cologne and then make the data directly accessible to NWS.
    - **Action on Pospichal and Czekala.**
4. Long-term monitoring of MWR data on a daily basis
    - Meteo France volunteers to create quicklooks of O-B level1 data
    - Possible hosting of data and quicklooks hosted at University of Cologne.
    - Clear-sky screening necessary
    - **Action on Martinet, Caumont, Löhnert, Haefele**
5. EUMETNET - proposal for next phase starting 2019 & maintenance of RTTOV-gb
    - White paper to be prepared corresponding to advice from Haefele
    - Sabine Hafner and Alexander Haefele volunteered to investigate the requirements, with the advice of Stefan Klink
    - Paper to be prepared for the next STSC meeting in March, papers needed by mid-February, Sabine Hafner volunteered to circulate a template
    - **Action on Haefele, Hafner, Cimini, Löhnert**
6. Assimilation, definition of business case
    - TB assimilation, search for common funding
    - **Action on Martinet, Caumont, Cimini, Haefele, Löhnert, Schomburg, Czekala**

The scientific report will be posted on the TOPROF website: www.toprof.eu.

References

Caumont O., D. Cimini, U. Löhnert, L. Alados-Arboledas, R. Bleisch, F. Buffa, M. E. Ferrario, A. Haefele, T. Huet, F. Madonna, G. Pace, Assimilation of humidity and temperature observations retrieved from ground-based microwave radiometers into a convective-scale model, Quart. Jour. Roy. Met. Soc., doi:10.1002/qj.2860, 2016.

De Angelis, F., Cimini, D., Hocking, J., Martinet, P., and Kneifel, S.: RTTOV-gb – adapting the fast radiative transfer model RTTOV for the assimilation of ground-based microwave radiometer observations, Geosci. Model Dev., 9, 2721-2739, doi:10.5194/gmd-9-2721-2016, Online: http://www.geosci-model-dev.net/9/2721/2016/, 2016.

GCOS, GCOS Essential Climate Variables, 2010, Online: http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

Immler, F. J., Dykema, J., Gardiner, T., Whiteman, D. N., Thorne, P. W., and Vömel, H.: Reference Quality Upper-Air Measurements: guidance for developing GRUAN data products, Atmos. Meas. Tech., 3, 1217-1231, doi:10.5194/amt-3-1217-2010, 2010.