Assimilation of Doppler Radar Radial Winds data in the HARMONIE-AROME model configuration run at AEMET

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1 Introduction

The current HARMONIE-AROME (Bengtsson et al., 2017) operational suite in AEMET that runs on the Nimbus supercomputer is based on a 3DVar data assimilation with a 3h cycle and the large scale mixing for humidity activated. It assimilates conventional observations from SYNOP, SHIP, DRIBU, AMDAR, and TEMP reports, GNSS ZTD data, ATOVS satellite radiances from AMSUA and AMSUB/MHS instruments, ASCAT, 2 meter temperature and relative humidity assimilated in upper air and radar reflectivity from 40 radars from three countries: Portugal, Spain and France.

As a mesoscale convection-permitting model, it is important to assimilate observations containing detailed information on appropriate scales (Ballard et al. 2016; Gustafsson et al. 2018,). Both the reflectivity and the Doppler radial winds (DRWs) from radars are high resolution observations and as have been demonstrated for different mesoscales systems like MM5, WRF, HIRLAM or HARMONIE, (Xiao et al. 2007, Wang et al. 2013, Lindskog et al. 2004; Salonen et al. 2011, Wattrelot et al. 2014 they have proven to be beneficial to numerical weather prediction systems.

The introduction of the radar reflectivity in AEMET operational HARMONIE-AROME system in 2019 has demonstrated to be beneficial, and to complement other humidity data assimilated from GNSS ZTD, ATOVS and Radiosonde observations. It produced a positive impact on HARMONIE forecasts, especially on precipitation. This improvement was mainly associated to a decrease of the False Alarms ratio. The assimilation procedure for radar reflectivity and some results can be found in Sánchez-Arriola et al. (2019).

DRWs are currently assimilated operationally at several centres (Xiao et al. 2008; Simonin et al. 2014) and a significant positive impact on the forecast (Montmerle and Faccani 2009; Xue et al. 2013, 2014) has been demonstrated. Once reflectivity data started to be assimilated operationally, efforts in AEMET have been devoted to also assimilate DRWs data from Spanish, French and Portuguese radar networks.

This document describes the process followed to assimilate these data processed and disseminated by OPERA, and the results obtained with respect to the current AEMET operational NWP run configuration.

2 Radar observations assimilated

Currently, the AEMET HARMONIE-AROME operational run assimilates reflectivity data from Portuguese (2), Spanish (15) and French (23) weather radars (Sánchez-Arriola et al., 2019). In this study, the additional DRWs observations that have been assimilated come only from the Spanish and French networks.

Data from Portuguese, Spanish and French radars are routinely exchanged by EUMETNET OPERA program (Saltikoff et al., 2019). These data are processed and pass a quality filter common to all the other radars of the European National Meteorological Services, so to be harmonized. As a result, homogeneous files are produced and disseminated at European level in conditions to be assimilated by NWP models.

The Spanish network is composed of C-band Doppler radars covering the Spanish peninsular territory (13), and the Balearic and Canary Islands respectively. They operate at 5620MHz except that at the Basque Country that does it at 5600MHz. Each radar makes a complete volume scan every 10 min, performing 19 different elevations (PPIs), from 0.5º to 25º. PPI sweeps are performed with two maximum ranges: 240km (long range products) and 120km (short range products). Short-range products use a dual PRF (900/1200Hz) which allows the Nyquist velocity of these short-range products to be 48.1 m/s. Radial wind is one of them. It is obtained at 0.5km resolution.

AEMET is sending to OPERA corrected (Z) and uncorrected (T) reflectivities at 1km resolution (240km range) coming from 0.5º, 1.4º and 2.3º elevations, and Doppler radar radial winds at 0.5km resolution (120km range) coming from 0.5º and 1.4º elevation angles.

Both reflectivities and radial winds at a larger number of elevation angles coming from the French radars network are exchanged by OPERA. They have been also used in this study.

The OPERA data received in AEMET has been preprocessed and quality controlled by BALTRAD software (Michelson et al., 2018). Some minor changes have been needed to adapt the reference cycle 40h.1.1 HARMONIE-AROME code to the operational context in AEMET to be able to assimilate these observations.

When using volume data of both reflectivity and radial velocity from OPERA there are a few challenges that needs to be taken into account. One of them is that the data is of a very high spatial resolution and need to be reduced to avoid representativeness errors and correlated observations. To face this and a few other caveats, a preprocessing tool for the OPERA data is included within HARMONIE system. This tool harmonizes the input data and creates super observations (SO) in order to reduce the density (Ridal et al., 2017). It has been seen that quality control of the radar observations is really important and it has also been shown that using super observations gives better scores than a simple thinning (Martin Ridal, personal communication). Radar reflectivities are used in operational or pre-operational production in most HIRLAM/HARMONIE countries following this approach.

The radial velocity observations present also other things that complicates the usage. One of these is the Nyquist velocity of the observations; if it is too low aliasing effects can occur and they will destroy the wind fields. There are de-aliasing methods available but the results from these are still not stable and therefore HARMONIE only use radial wind observations with a Nyquist velocity higher than 30 m/s. This is the case of DRWs from the Spanish and French radars.

Another issue to take into account is to quality control the radial velocities. So, HARMONIE only use wind information that are accompanied by a co-located reflectivity observation. Then the quality information from the reflectivities can be applied to the wind observations. Only the observations with an elevation angle higher than 1 degree have been selected. SO are generated with the ones whose quality "flag" assigned in the OPERA pre-processing exceeded a fixed threshold.

3 Data assimilation experiments

Several parallel experiments have been designed and carried out in AEMET to test the assimilation of DRWs with respect to the present configuration of the operational run. They have been run over one month long period: from 1st to 31 March 2020. This period was very rainy over the Iberian Peninsula. It should be noticed that during the last week of this period the number of available aircraft observations dropped drastically due to the reduction in flights caused by the COVID pandemic.

The CONTROL (AIBe) experiment run for this study is the operational suite based on HARMONIE-AROME cycle40h1.1. 3DVar data assimilation is used as upper analysis, with a 3h cycle and a large scale mixing of short range HARMONIE forecasts with ECMWF fields to create the first guess for the analysis. This procedure is also activated for humidity. The analysis assimilates conventional observations from SYNOP (including 2 meter temperature and relative humidity), SHIP, DRIBU, AMDAR, and TEMP reports, GNSS ZTD data, ATOVS satellite radiances from AMSUA and AMSUB/MHS instruments, ASCAT, and all the available radar reflectivity observations from the 40 radars from three countries: Portugal, Spain and France that cover the model area. The model runs at 2.5 horizontal resolution and 65 vertical model levels extending up to 10 hPa, over a geographical domain centered on the Iberian Peninsula that includes the Balearic Islands.

A preliminary experiment has been conducted introducing additionally DWRs from the French and Spanish radars. It was not necessary to run a spin up period, because it started from the same variational bias correction coefficients (to correct the bias from ATOVS and GB GNSS ZTD observations) and first guess from the operational suite. DWRs had already been assimilated passively over a different period, but the experiment was not parallel to the operational run. During this previous period, quality control of these data was an issue.

In this preliminary experiment over March 2020, default values in the HARMONIE-AROME code for relevant parameters for the assimilation of DRWs were kept. Most of them are documented in Montmerle y Faccani (2009). In particular, a value of 20m/s is used as rejection limit for DRWs innovations in the first guess check. DRWs are also thinned to avoid correlated observation errors by retaining the best data within 15 × 15 km^2 boxes. Observation error standard deviation is formulated following a linear increase with distance to radar. With the default formulation, it oscillates between 1m/s and 2m/s at 120km. Notice that this increase rate is half than the proposed in Montmerle and Faccani (2009).

Diagnostic of the preliminary assimilation of Doppler radar radial winds

The main goal of this preliminary experiment was to investigate the quality of the data itself, both for each radar separately and for all the data together. Plots of histograms of innovations for the different radars showed that the quality of the DRWs data could differ between radars (not shown here), and that not all of them seem to have the required Gaussian distributions. Also the number of data was highly variable among them. We observed these features both at Spanish and French radars.

Figure 1 (left) shows the total number of DRWs SO per analysis time that entered the data assimilation (and were not rejected by quality control checks) at different heights for the whole period. The highest number of them is found at around 3000m, whereas the lowest one corresponds to the uppermost levels (7000-1000m). AEMET is only exchanging radial winds obtained at two low elevation angles, and SO from Spanish radars are created from only one of them (1.4º). These figures may be compared to the number of assimilated wind observations from aircraft and from radiosondes to see the differences between them. On one hand, DRW SO are available at all analysis times (whenever there is reflectivity data) although this is not the case for aircraft observations at night, and of course for radiosondes, which are only launched at 00 and 12UTC. On the other hand, before the coronavirus pandemic produced a drastic decrease in aircraft data, the number of radal wind SO was 2 to 4 times greater than that of aircraft wind observations, depending on the level (not shown).

Figure 1 (right), displays the RMS of innovations per analysis time at different height levels. It can be observed that the size of innovations is higher at 7000-10000m height layers, where the number of DRW observations is also smaller. Nevertheless, too high innovations are found at the rest of levels in the atmosphere, but in a lesser percentage. We have not investigated the origin of this big innovation size, so we cannot discard, e.g. the data preprocessing, the SO creation and the observation operator apart from data quality.

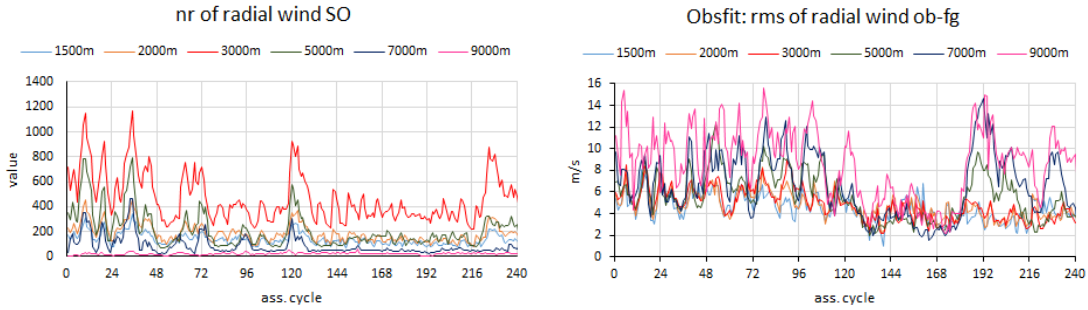

Figure 1: Time series of the number of radial wind observations (left), and of RMS of the innovations of DRWs at different vertical levels for the preliminary experiment carried out to assimilate DRWs.

In order to improve the first guess check decisions in the screening part of assimilation, histograms and transformed histograms of all innovations for DRWs observations assimilated have been obtained to identify the first guess departures of observations having gross errors according to Andersson and Järvinen (1999). They are shown in **Figure 2.** Extended tails at both sides of the innovations distribution (left) show clear non-Gaussian innovations corresponding to data with gross errors. The transformed histogram of innovations (right) reveals that the rejection limit value used for DRW observations in these experiments (the threshold where innovations apart from Gaussian) should be more restrictive (around 5m/s) than the one used by default (20m/s).

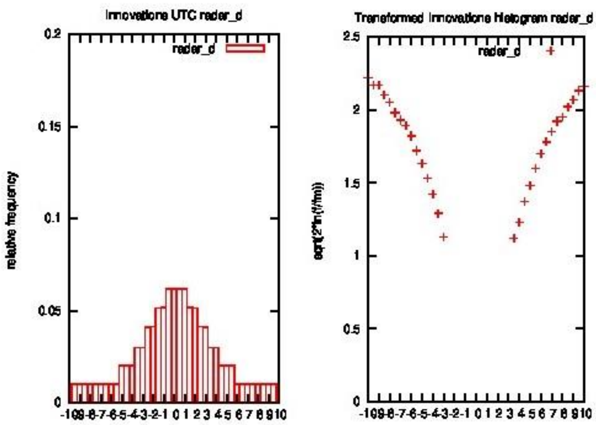

Figure 2: Histogram (left) and transformed histogram (right) of all innovations of Doppler Radar Radial Winds for March 2020

A new experiment was then conducted using this adjusted first guess check limit (5m/s) and assimilating these observations actively. It led to some decrease of the number of assimilated observations and innovation size was controlled, but it resulted in a forecasts deterioration with respect to the CONTROL AIBe forecasts skill (not shown).

More diagnostics were obtained to understand the assimilation performance of these observations. Although SO had been created trying to avoid it, and these SO data were also thinned in the screening step, we investigated if horizontal error correlation still existed in these data. The idea was to better tune the thinning of data in the screening, if these diagnostics indicated that this was needed. Then the Desroziers technique (Desroziers et al., 2005) was applied to obtain the horizontal error correlation of DWRs. The results obtained are displayed in **Figure 3.** It shows that observation error correlation drops to 0.2 around 20km distance. This horizontal distance is close but slightly larger than the thinning distance value applied in the screening to radar data (15km).

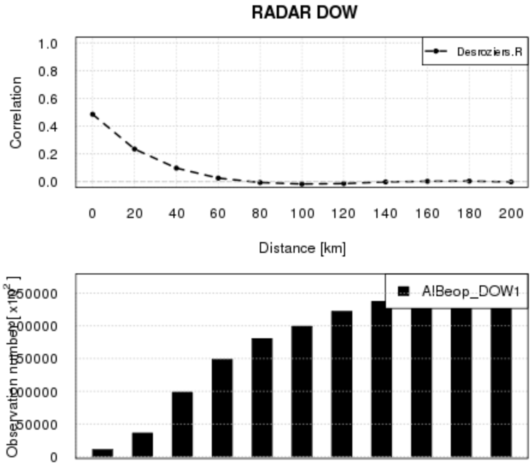

Figure 3: Estimation of horizontal error correlations based on Desroziers et al.(2005) (top) and the number of collocations (bottom) as a function of separation distance for DRWs observations

We additionally looked at the values of observation errors for DWRs and compared them to those of radiosonde and aircraft wind. **Figure 4** (left) shows that the observation error assigned to Doppler winds, although its increase with distance to radar, is much lower than the one assigned to the other two observation types, and therefore the model trusted wind data from DRWs more than from radiosonde and aircrafts whose innovations size was smaller/similar to that of DWRs. Taking also into account the huge DWRs spatial density, and that perhaps these scales are not being represented enough in the background error covariance matrix used, the DWRs weight in the analysis could be overestimated.

Design of a refined data assimilation of Doppler radar radial winds

Taking into account the conclusions achieved with the diagnostics obtained, a new experiment called AIBeop_DOW16 was designed and run.

This experiment modifies the default setup in respect to:

- The first guess check limit has been increased to 5m/s (instead the former 20m/s).
- The thinning distance has been increased to 25km (instead the former 15km).
- The formula for observation error standard deviation has been modified. The rate of error increase with distance to radar has been kept, but the independent term has been inflated after some empirical tuning. In this way, DRWs error ranges between 3-4m/s (instead the former 1-2m/s). It should be noticed that, although their data assimilation systems are different, other NWP centers (DWD, UKMO) give DRWs an observation error value larger than the one used by default in the HARMONIE-AROME code (Waller et al., 2019).

Figure 4 (right) displays values of sigmao for DRWs observations in this new experiment as compared to those assigned to radiosonde and aircraft wind.

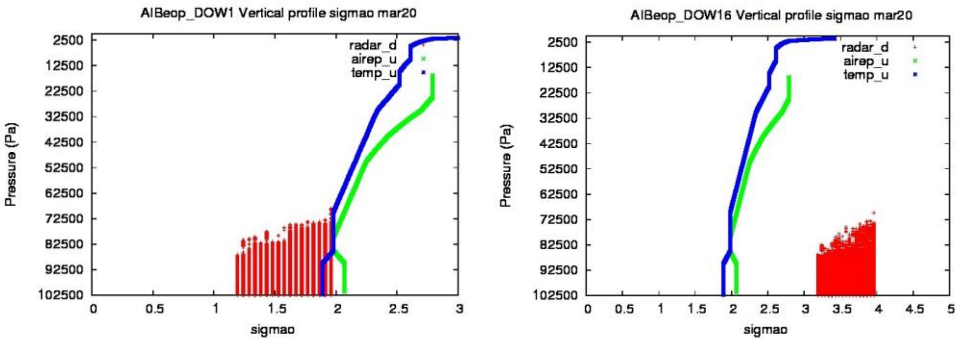

Figure 4: Vertical profile of observation error standard deviation (sigmao) values for wind observations from Doppler Radar radial Wind (only up to 700hPa), AIREP and radiosondes. Default values (left), and modified values used in AIBeop_DOW16 experiment (right).

The new experiment called AIBeop_DOW16 with these updates has been run over the same period of study.

Data assimilation performance in AIBeop_DOW16 experiment

Some additional diagnostics have been obtained to check the functionality of the changes introduced in the experiment AIBeop_DOW16.

Figure 5 shows the observation fit of DRWs to the first guess and to the analysis for the different height levels in the atmosphere corresponding to AIBeop_DOW16 experiment with tuned parameters of the DRWs data assimilation. It can be observed that innovations size has substantially decreased with the new first guess check limit applied (in comparison to **Figure 1**, right). The analysis increments are also smaller due mainly to the inflated sigmao for DRWs in AIBeop_DOW16 (not shown). It also allows to see that many DRWs with high innovations at the uppermost levels have been filtered out by the usage of the new rejection limit value. At any case, inspection of the analysis residual and innovation of individual data shows that some DRWs that were actively assimilated were not supported by the rest of observations, indicating that their quality might not be good or there are deficiencies with data processing (not shown).

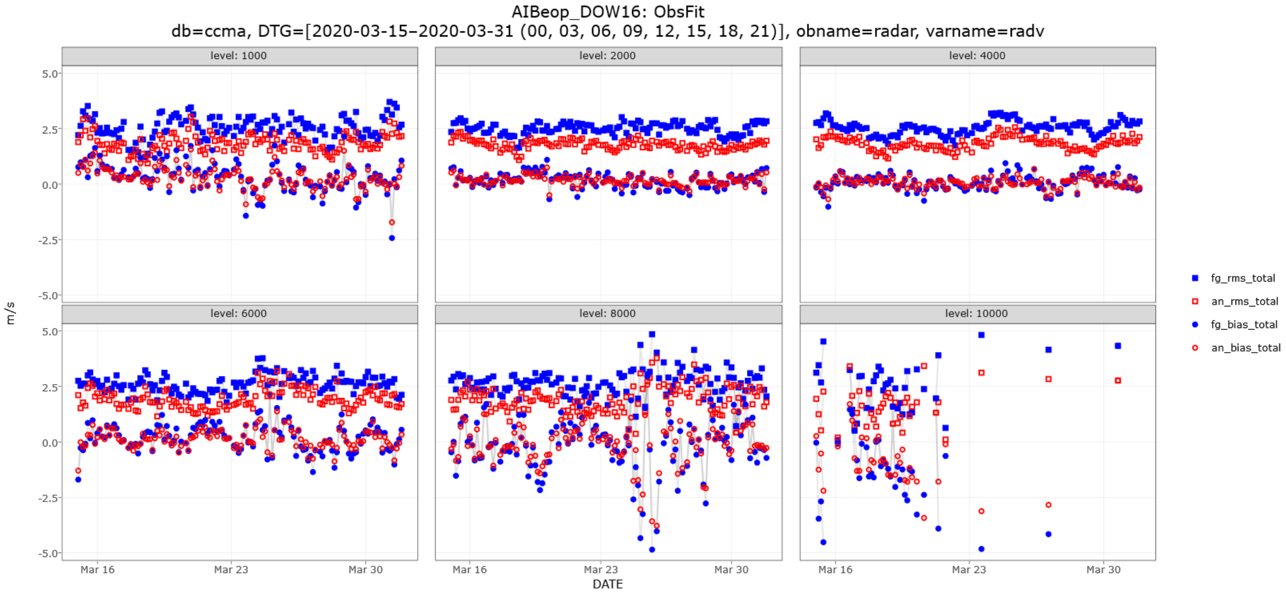

Figure 5 Observation fit to the first guess (blue) and to the analysis (red) for AIBeop_DOW16 experiment at different height levels

The Absolute Degree of Freedom for Signal (DFS) diagnostic is shown for AIBeop_DOW16 experiment (**Figure 6**). It allows to see the information content of all observation types assimilated. The impact of both Radar-Z and Radar-DOW has decreased in AIBeop_DOW16 experiment with respect to previous ones due to the larger data thinning of radar observations (the same thinning is applied to reflectivity derived relative humidity profiles and to radial winds). In case of RADAR-DOW it is also due to the higher observation error assigned to these data in this experiment. The total weight of Doppler radar radial winds in this experiment is comparable to that of aircraft wind observations (slightly smaller), although the larger number of DRWs observations compared to that of aircraft data.

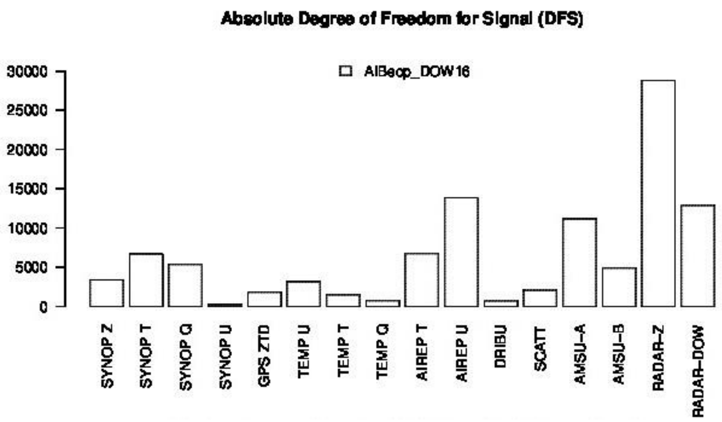

Figure 6: DFS plot showing the Absolute Degree of Freedom for Signal of AIBeop_DOW16 experiment

4 Results: impact on forecasts

The impact of the assimilation of Doppler radar radial winds has been assessed by means of the objective verification of model forecasts against SYNOP and TEMP observations over the four weeks period of study. The following figures show the most relevant features found. They display verification scores reached by the two experiments described in the text: CONTROL (AIBe, in red) and the revised assimilation of DRWs (AIBeop_DOW16, in green).

The revised assimilation of DRWs seems to be positive for precipitation and surface wind forecasts of high impact events. At **Figure 7,** the Kuiper Skill Score for 10meter winds, and 12h accumulated precipitation is shown. It can be seen how the skill of 10meter wind forecasts clearly improves for AIBop_DOW16 experiment for the stronger wind speed intervals. This is due to a better Probability of Detection since the False alarm rate is the same for both experiments. In case of precipitation, a positive impact is found for the largest precipitation amounts at the different accumulation intervals and the reason is the improvement of both the Probability of Detection and False Alarm rate. An improvement of 2 meter temperature forecast has also been found (not shown).

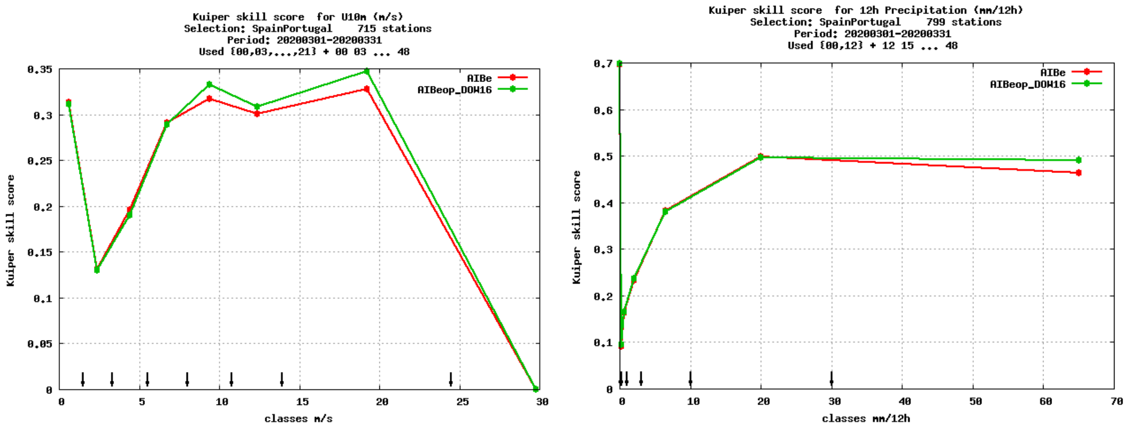

Figure 7: Verification of CTRL (red) vs AIBeop_DOW16 (green) forecasts. (a) Kuiper Skill Score of 10m wind, (b) Kuiper Skill Score of 12h accumulated precipitation,

The overall influence of this revised assimilation of DRWs has shown to be neutral for most of the variables. **Figure 8** displays the vertical profiles of forecast bias and error standard deviation for (a) wind speed and (b) relative humidity, obtained by comparison against observations from the 16 existing radiosonde stations in the domain. However, wind speed bias is slightly larger at 700 and 500 hPa. The wind speed weakening at these levels will be further investigated in a future work. On the other hand, a small positive impact is found for relative humidity at 850-700hPa, not statistically significant, at all forecast lengths. This improvement in humidity is more noticeable the last week of the period, when the number of aircraft data decreased drastically (not shown).

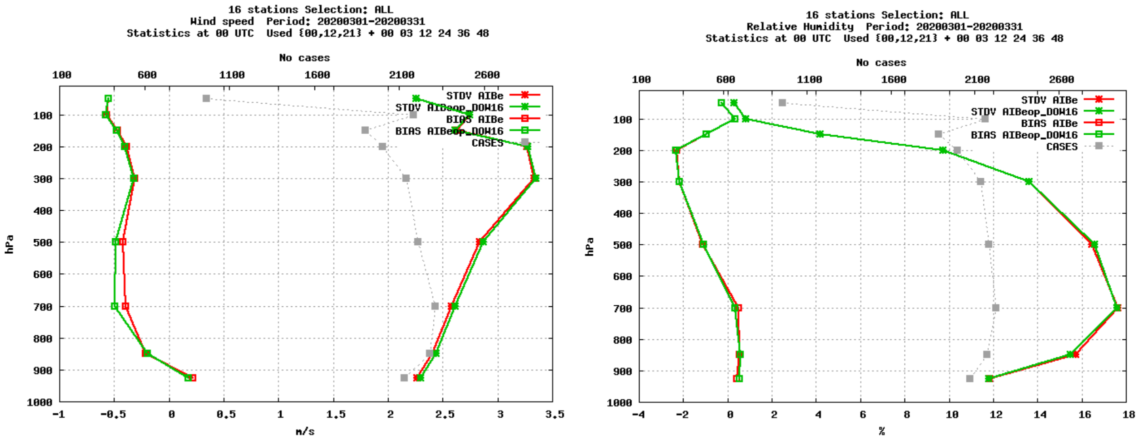

Figure 8: Vertical profile of verification scores (bias and standard deviation) obtained by CTRL (red) and AIBeop_DOW16 (green) forecasts using radiosonde observations: wind speed (left), relative humidity (right).

7 Conclusions and further work

Doppler radar radial winds (together with reflectivities) from the Spanish and French weather radars have been assimilated by two experiments parallel to the HARMONIE-AROME run operational in AEMET over one month long period (March 2020).

The preliminary experiment conducted to assimilate these new radial winds data with the default settings in cycle40h1.1 of HARMONIE presented very high radial wind innovations. Some tuning of first guess check limits has allowed to filter them, but active assimilation of the rest of DRWs data produced a negative impact on some forecasted parameters.

Additional diagnostics of the data assimilation performance have been obtained and have led to a larger revision of quality control and data thinning parameters. Observation error standard deviation for these data has been also empirically inflated, after comparing it against that of other observation types. The revised configuration of DRWs assimilation has been tested in a new experiment over the same period. A rather neutral impact is then found in forecasts of upper air parameters. However, the revised DRWs assimilation shows to improve surface wind speed and precipitation forecasts in high impact weather conditions.

Although the results finally found are rather promising, additional work is required to better understand the source of high innovations of DRWs, to tune the quality control of these data, to advance in characterizing its errors (the role of not only distance to the radar but also elevation angle similarly to Waller et al., 2019), to improve the construction of the SO (with regards to the size, quality index limit of the observations to include...), in connection with the data thinning strategy.

The background error covariances B matrix used by the assimilation algorithm when assimilating these observations having a high spatial density is also of paramount importance (Bojarova and Gustafsson, 2019), and must be taken into account. These experiments have used a B matrix calculated with downscaled ECMWF Ensemble Data Assimilation (EDA) members. Work is ongoing at AEMET to calculate it using BRAND (B-randomization) and HARMONIE EDA methods that might better represent small scale background errors, being more apropriate for radar data assimilation.

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