Assimilation of radial velocity from radars

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Contents

List of Figures

List of Tables

Introduction

The research on data assimilation of radar measurements to numerical weather prediction (NWP) models is getting attention recently within RC LACE. The reports from Bučánek (2020), Trojáková (2020) or Monteiro (2019) are the most recent examples. The majority of efforts is focused on radar reflectivity expliotation. This work is focused on radial wind assimilation.

The purpose of the stay was first to elaborate an overview analysis on the data available in OPERA OIFS. A bearing work was carried out by Kovačić (2018). Kovačić analysed the content of radar measurements in raw hdf5 files and prepared an overview of scanning strategies used in different RC LACE countries (Croatia, Czech Republic, Hungary, Slovenia, Slovakia, and Romania). In this study the scanning strategy overview was updated and extended by several non-LACE countries. Our main findings turned out to be consistent with the former results presented by Kovačić (2018).

Consequently the work continued with a statistical analysis of OMG (observation minus first guess) departures computed in a passive data assimilation experiment. This analysis revealed differences in quality of data from different countries which led to further research in frame of active data assimilation experiment where radial wind data were actively assimilated into ALARO model configuration operational at Czech Hydrometeorological Institute (CHMI). The averaged standard deviation index was computed according to the method presented by Montmerle and Faccani (2009).

Finally, the case study was designed as a proof of concept of noticeable impact of radial wind assimilation on several meteorological parameters forecast. The case study indicated potential improvement in weather forecast though a deeper systematic verification remains to be realized.

1 Data overview

The first tests were targeted to obtain a summary of radars with available radial wind and to understand the necessary parameters to calculate radial wind.

The overview analysis of available OPERA OIFS data was performed on a randomly selected 15' data sample from 2020-07-10 at 12 UTC.

A brief analysis on the number of available data depicted in Figure 1.1 indicates that the most numerous dataset is from Germany. The second most numerous dataset is from France where is the biggest amount of radars (in Figure 1.2) contributing to OPERA among radars belonging to RC LACE countries model domains (see Figure 3.2 in Section 3).

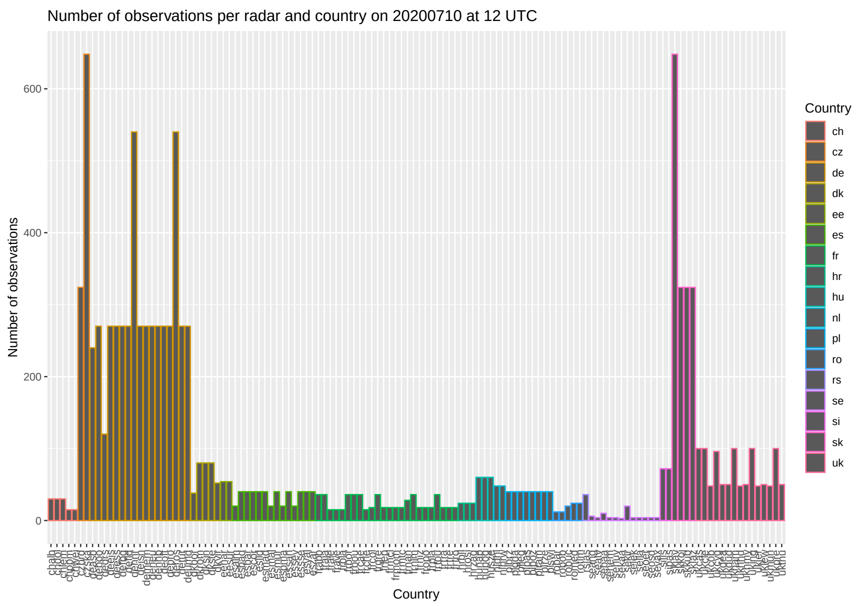


Figure 1.1: Number of observations per country at a randomly selected hour available in OPERA data.

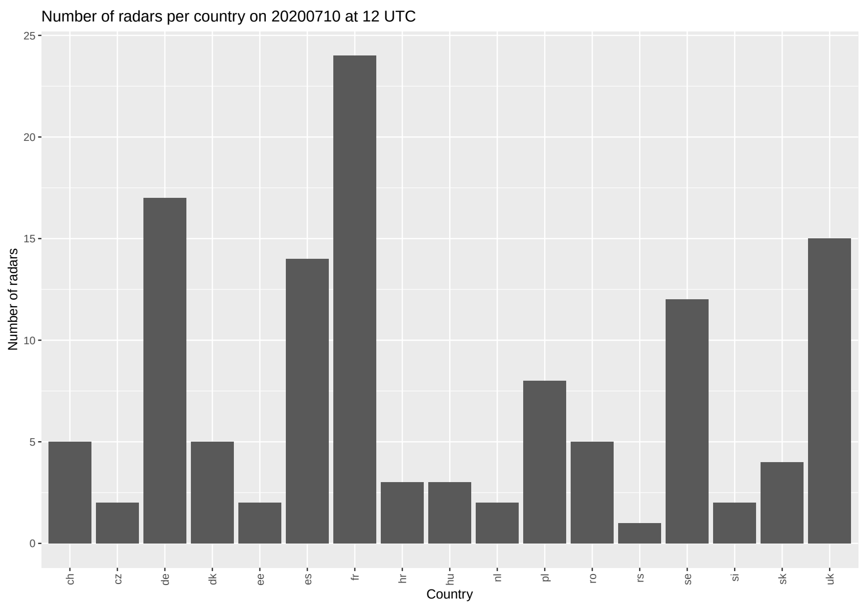


Figure 1.2: Number of radars per country at a randomly selected hour available in OPERA data.

The capability of measuring radial wind velocity is limited by Nyquist velocity which will be detailed in the next Section 1.1.

1.1 Nyquist velocity (NI)

Nyquist velocity (or $v_{\max}$) is the maximum velocity of the target that can be unambiguously measured by a radar. It depends on the radar settings, its pulse repetition frequency and wavelength as indicated in Eq. 1 retrieved from Şireci (2005).

$$v_{\max} = \frac{PRF\lambda}{4} \tag{1}$$

Another method to calculate Nyquist velocity is considering the Doppler dilemma (Eq. 2) explained in Şireci (2005) which describes that the product of maximum range (distance where radar can detect a target) and target velocity equals to a constant. Here c stands for the speed of light, in other words, the speed of the detecting signal and λ is the wavelength of radar signal.

$$v_{\max} r_{\max} = \frac{c\lambda}{8} \tag{2}$$

Further details on Nyquist velocity and related signal folding can be found in Şireci (2005) or Brown and Wood (2007).

The exact setting of Nyquist velocity varies with each radar and may change with the elevation angle too. The actual Nyquist velocity of each radar is limited by Doppler dilemma in Eq. 2.

A dual- or triple-PRF methods are applied to additionally increase the Nyquist velocity while maximum range is not influenced. The method is based on usage of combination of 2 (or 3) different PRFs typically in 3:2, 4:3, 5:4 ratios. Both (all) PRFs detect the same objects and considering the detection time difference, the velocity can be assesed.

Further details on calculation of Nyquist velocity from low, middle and high PRF can be found in Şireci (2005).

A basic pre-selection of radars from RC LACE domain with available radial wind data and based on Nyquist velocity limit >30 m/s was performed. The following Table 1 summarizes the Nyquist velocity values available for different countries in the randomly selected data sample from 2020-07-10 at 12 UTC.

Table 1: Overview of available radial velocity data and Nyquist velocity values at randomly selected data 2020-07-10 at 12 UTC.

Country	**radial winds**	**NI range [m/s]**
Czech Republic	available	missing
Croatia	available	17
Denmark	available	<8,47>
Estonia	available	<8,13>
Finland	available	8
France	available	<59,62>
Germany	available	<32>
Hungary	available	<8,47>
Iceland	—	—
Ireland	—	—
Malta	—	—
Netherlands	available	<6,80>
Norway	available	<48,111>
Poland	—	7
Portugal	available	<6,50>
Romania	—	8
Serbia	—	—
Slovakia	available	<40,64>
Slovenia	available	<8,41>
Spain	available	<3.48>
Sweden	available	<24,40>
Switzerland	available	<8,12>
UK	available	<4,48>

1.2 Scanning strategy

The overview analysis of the raw data from OPERA showed that different countries use different scanning strategies, even they modify them in time or per radar.

The following plot in Figure 1.3 depicts the usage of different Nyquist velocities depending on the elevation angle for countries which passed the basic pre-selection criterion (available radial wind and NI>30 m/s) mentioned in Section 1.1. Countries: Germany, France, Slovakia, Slovenia, United Kingdom, Sweden, Hungary and Denmark will be further analysed.

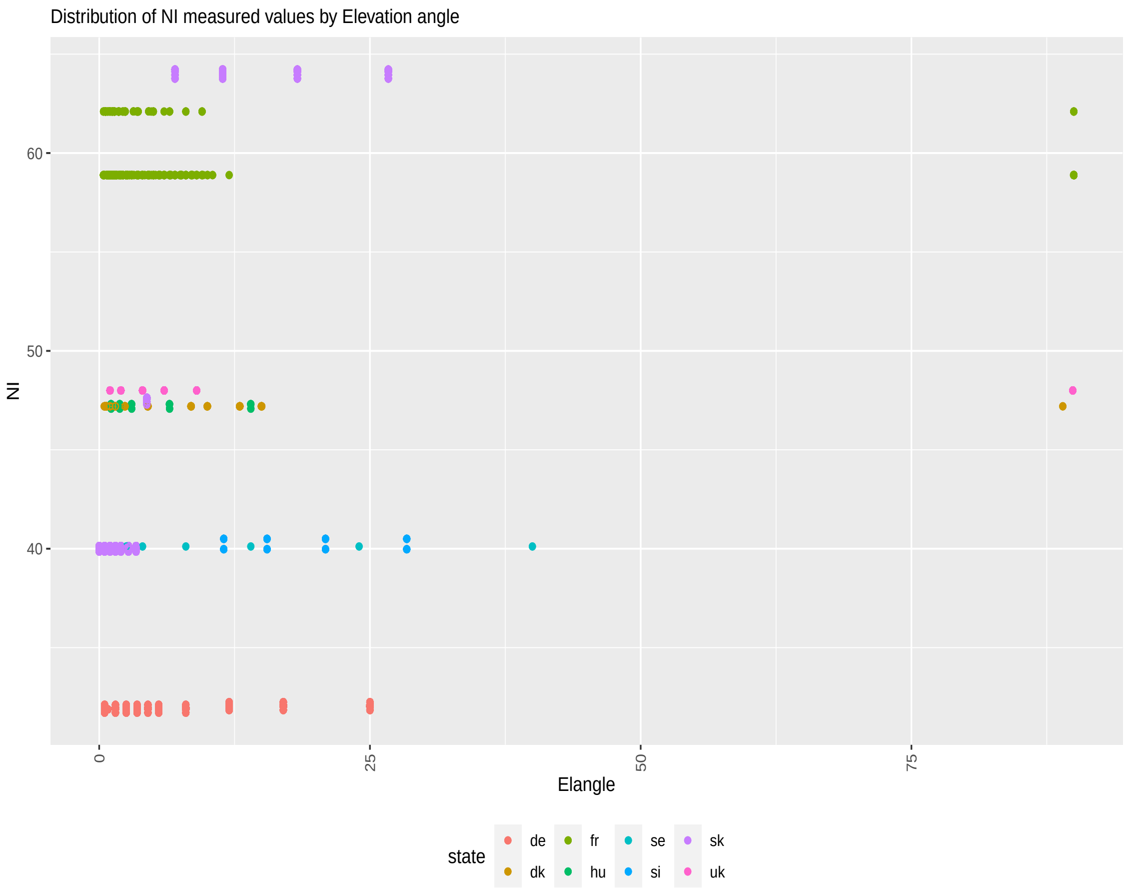


Figure 1.3: Usage of elevation angles and corresponding Nyquist velocities in RC LACE countries. The data is retrieved from OPERA.

Here come few examples of scanning strategy per country. The simplest scanning strategy is used in Slovakia (Figure 1.5), Slovenia and Denmark where the elevation angle in a single 360° scan is monotonously increasing and the full scan is repeated approximately every 5 minutes. Similar strategy is adopted by French radars though the elevation angles start from the greatest and decrease in time. A control 90° elevation angle is performed from time to time, it is usually used to check the radar calibration (*personal communication Hana Kyznarová, CHMI radar department*).

The German radars scanning strategy (Figure 1.4) is a combination of decreasing and later increasing elevation angles. This approach caused problems in HOOF regarding the separation of volume scans. This issue is not fixed yet in HOOF version 1.9.

Even more complicated scanning strategies are applied in case of UK and Swedish radars as plotted in Figures 1.6, 1.7.

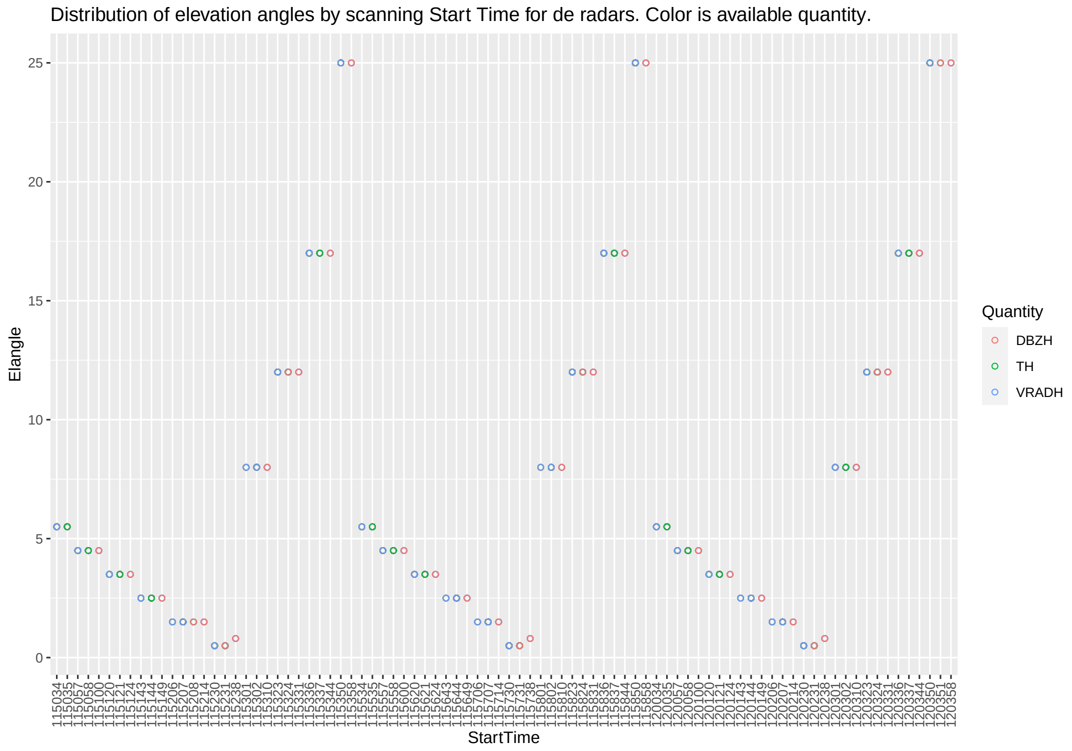


Figure 1.4: DE radars scanning strategy.

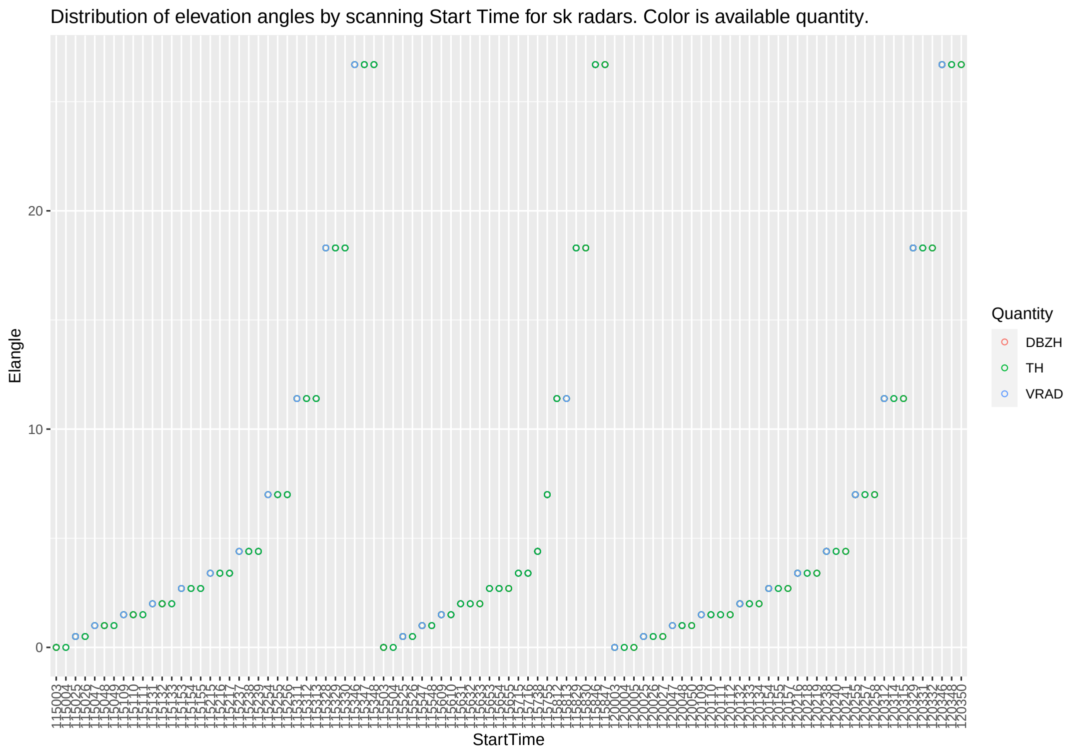


Figure 1.5: SK radars scanning strategy.

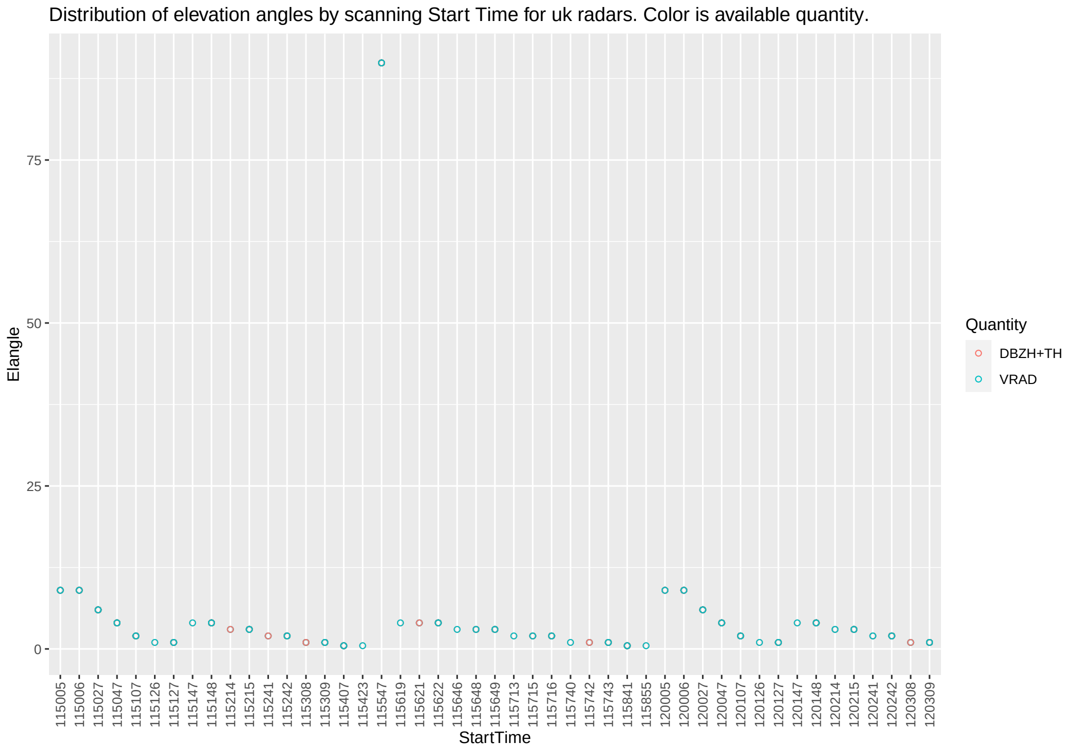


Figure 1.6: UK radars scanning strategy.

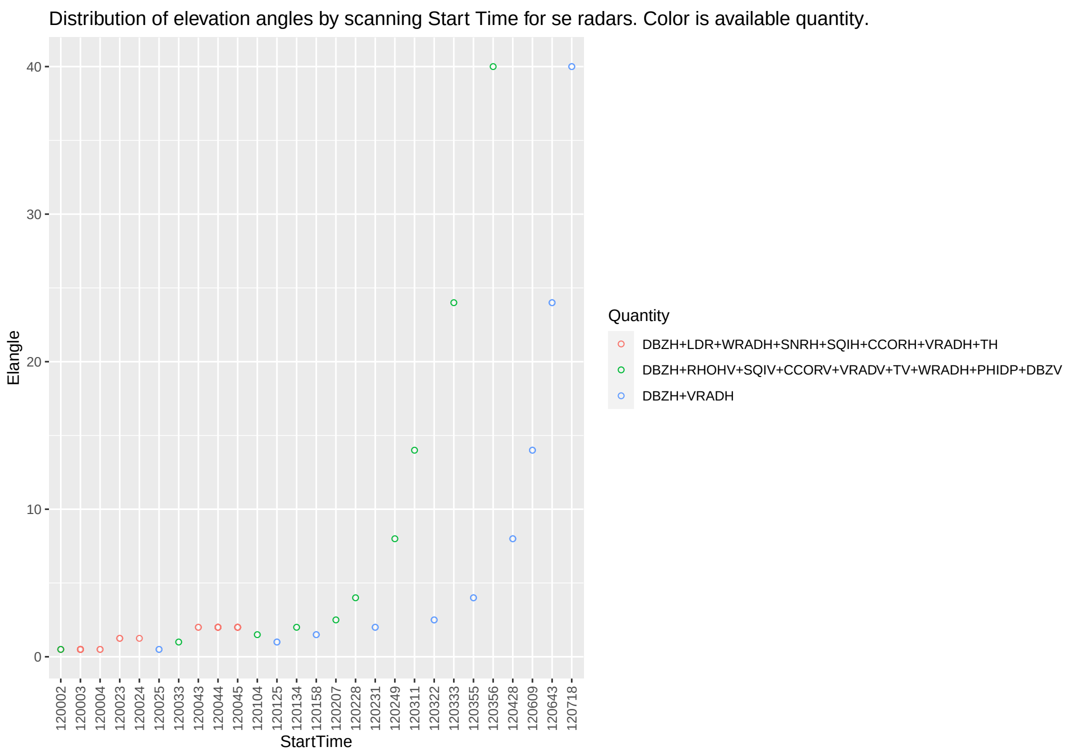


Figure 1.7: SE radars scanning strategy.

1.3 Radial velocity coding in hdf5 files

The measured values of radial wind velocity are coded as integers according to the formula in Eq. 3.

$$VRAD = gain * value + offset \tag{3}$$

The coding is different according to formula in Eq. 4 in Slovenia and Croatia as reported in Kovačić (2018). This was confirmed by brief analysis of data and also by Benedikt Strajnar (*personal communication*).

$$VRAD = NI * (gain * value + offset) \tag{4}$$

2 Data preprocesing

2.1 HOOF

A preprocessing of raw OPERA data is performed by HOOF application. HOOF is a tool designed to parse the raw datasets into separate volume scan of a unified format readable by BATOR. For more details see regularly updated documentation Smerkol (2020).

HOOF namelist was adapted to read radial wind velocity and radar attribute "/dataset/how/NI=0" was added to prevent crash when loading data where Nyquist velocity is not available as it is a necessary information for radial velocity processing by BATOR.

The requirements "/dataset/how/highprf = None" and "/dataset/how/lowprf = None" were deleted from HOOF namelist. HOOF crashed for UK radars (before deletion from namelist) because highprf attribute is not contained in the raw datasets.

2.2 BATOR

The code version exploited for the following assimilation experiments is based on cy43t2_bf10 with latest development from the Meteo France operational version (cy43t2_op4.03). The new developments contain: reading of new attributes from OPERA files NyquistVel, MinDetect, and TE (new Meteo France in-house quality product), the modification of calculations of the threshold of radar detection, bugfix in NraysPopulation select, and radial winds read only if OPERA attribute NyqistVel > HODIM%NIlimit defined in the namelist. The source code modset_Bator43t2_bf10+op4.03.tar can be provided upon request.

BATOR namelist settings were adapted to read all radars which passed through the general overview criterion related to Nyquist velocity.

The high 90° control elevation angles discovered in the general overview data analysis are disregarded in BATOR applying the condition copied from source code (subroutine bator_decodhdf5_mod.F90 in particular) and no error message is printed.

```
    if (.not.any(SelectedElangles%Elangle ==
FullDatasetList(i)%GData(j)%Attrib%Elangle) .and. &
        & FullDatasetList(i)%GData(j)%Attrib%Elangle < 80._jprb ) then
        NbSelectedElangles = NbSelectedElangles + 1
        SelectedElangles(NbSelectedElangles)%Elangle =
FullDatasetList(i)%GData(j)%Attrib%Elangle
    endif
```

2.2.1 Sampling

A simple comparison for two sampling settings via BATOR namelist (in section &HDF5, line HODIM%Sample=5000.0) was performed (not shown here). The default setting is 5 km sampling distance and the tested one was set to 1 km sampling distance.

The visualisation of raw data, once BATOR sampling was applied, showed much easier readability of Doppler velocity patterns although the increased density of data may increase the observation correlation error. Though the exact sampling method was not studied deeply and there are several questions on its usage.

It would be important to take into account the filter cleaner and median filter routines which are part of BATOR. For further experiments it is necessary to understand better whether sampling or smoothing by filters is applied first. It was also not studied whether any quality control is performed in BATOR and if how does it influence the filtering or sampling process or thinning realized further in screening.

3 Statistical analysis

3.1 Model setup

The assimilation experiments were computed on ALARO NH-v1B cy43t2pt_op1 model according to the operational setup at CHMI (Czech Hydrometeorological Institute) which details are listed in Figure 3.1 and model domain is displayed in Figure 3.2.

CMC	ALARO/CZ
status	operational
code version	cy43t2pt
physics	NH-v1B
resolution	2.3km
gridpoints	1069x853
vertical levels	87
time step	90s
assimilation cycle	6h
assimilation	DF Blending (filtering at truncation E102x81)
method	followed by 3D-Var
used observations	SYNOP, TEMP, AMDAR, SEVIRI, Mode-S
	MRAR CZ, Mode-S EHS (KNMI), AMV

Figure 3.1: Model setup exploited for experiments during the stay.

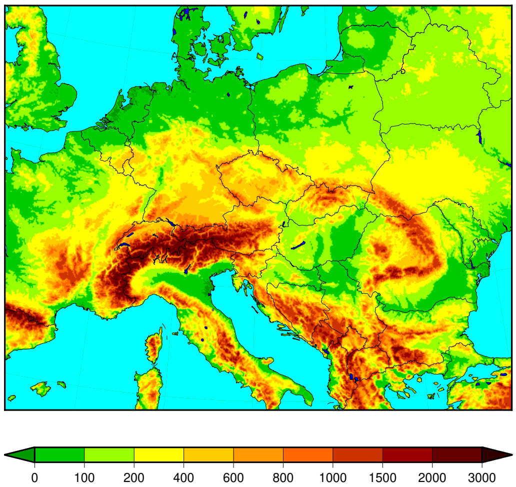


Figure 3.2: ALARO/CZ model domain

3.2 OMG departures

The passive assimilation experiment over the period from 2020-05-22 at 00 UTC to 2020-06-13 at 18 UTC was exploited for the statistical analysis of radial wind velocity data. The OMG departures were computed in screening configuration and a level by level analysis was performed.

First, a histogram of the overall dataset was plotted in Figure 3.3. It contains almost 9 M of measurements from 56 radars, the mean value equals 0.17 m/s and standard deviation is 5.87 m/s.

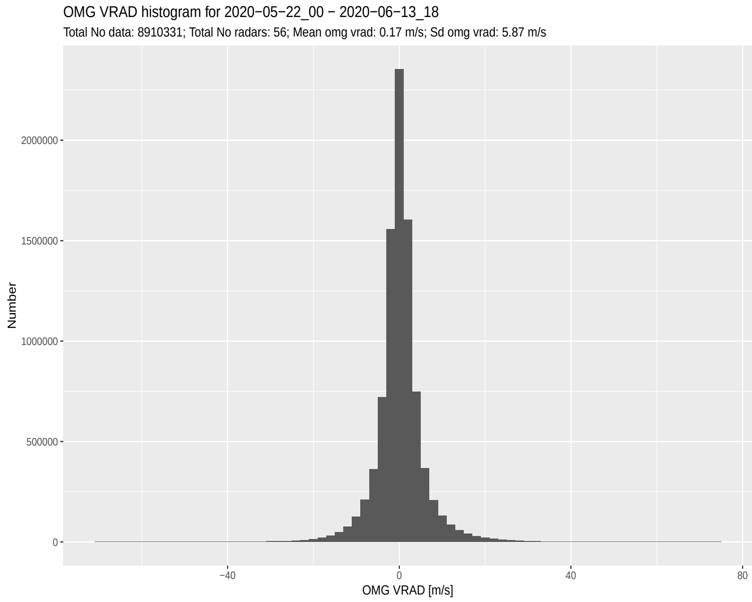


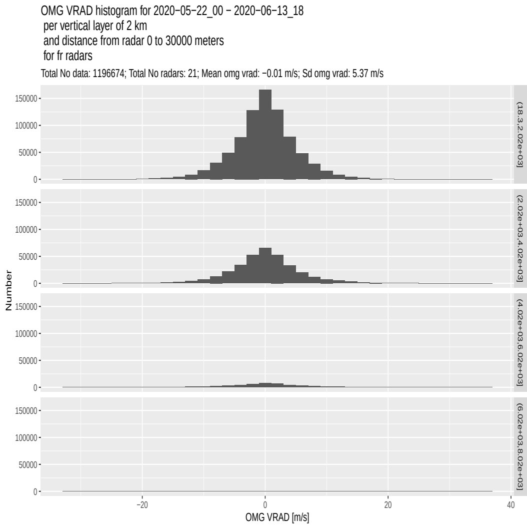
Figure 3.3: Overall OMG departures histogram.

The analysis continued by separation of different levels of the data considering the vertical layers, horizontal distance from the radar and selection by countries.

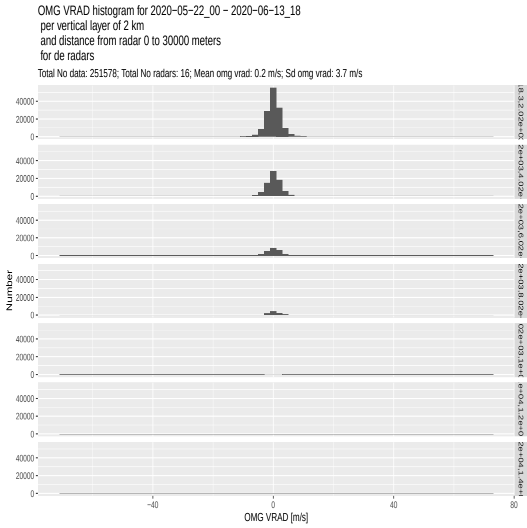
The histogram pattern changes to wider with increasing altitude above the ground. It is explained by the decreasing number of data in the selected cylinder up to 30 km from radar. The number of vertical layers available for the distance interval 0-30 km from the radar is related to the elevation angles and is different for each country. This behavior is similar for other 30 km distance intervals (e.g. 30-60 km, 60-90 km, 90-120 km and 120-150 km). Some countries (e.g Slovenia, several UK radars) do not reach the most distant intervals.

The main differences are noticeable between countries. Generally, the OMG departures histograms show satisfying results for France (Fig. 3.4a), Germany (Fig. 3.4b) or Slovakia (Fig. 3.4c) where the histograms are close to normal and not significantly biased. This is not the case for Danish data (Fig:3.4d). The statistical characteristics for Denmark may be influenced by lower number of available data or another reason which still has to be understood.

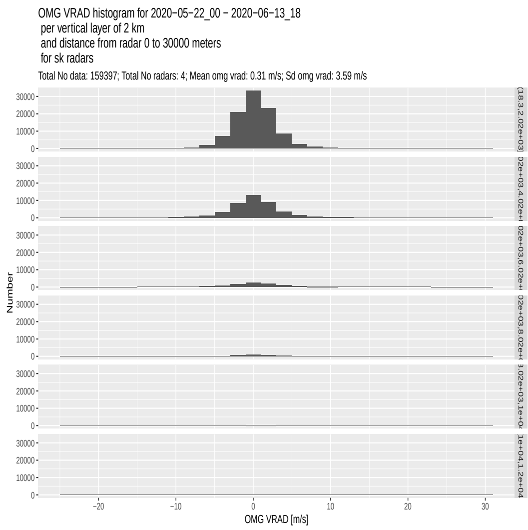
For completeness we checked the OMG departures histogram for wrongly coded radial velocity from Slovenia. The result is depicted in Fig. 3.4e). The coding method for Slovenia is described in Section 1.3.



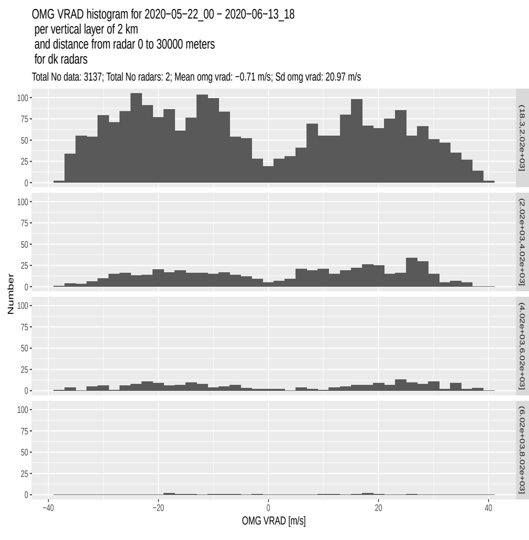
(a) FR



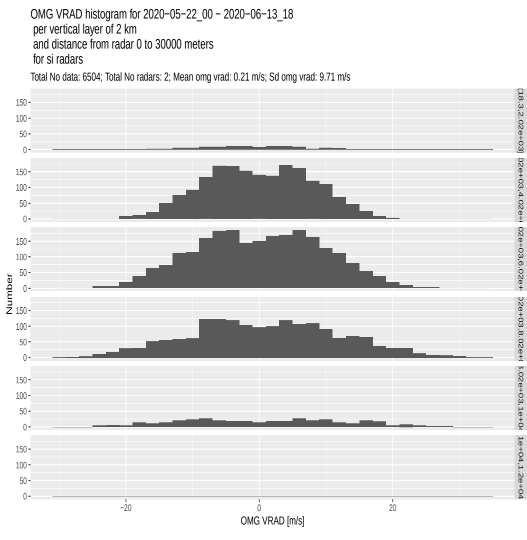
(b) DE



(c) SK



(d) DK



(e) SI

Figure 3.4: Histograms of OMG departures by country.

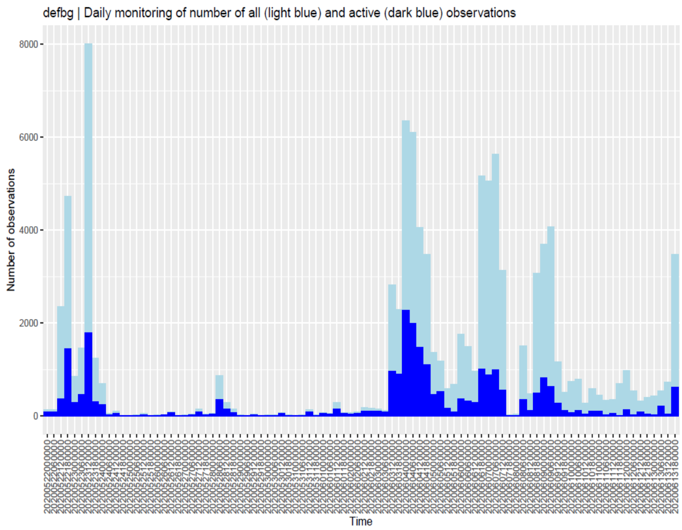
3.3 Standard deviation index

The reference paper by Montmerle and Faccani (2009) illustrated a diagnostics method for radar measurements monitoring. The approach is based on calculation of averaged standard deviation index according to the formula in Eq. 5. The studied data is divided into n_{az} slices of azimuth (10° wide) and n_{elev} elevations, PPIs (plan position indicator) in other words. Then $\sigma^2_{n_{\mathrm{az}}}$ is the radial variance for the selected azimuth slice and σ_{v_r} stands for the total averaged standard deviaton index.

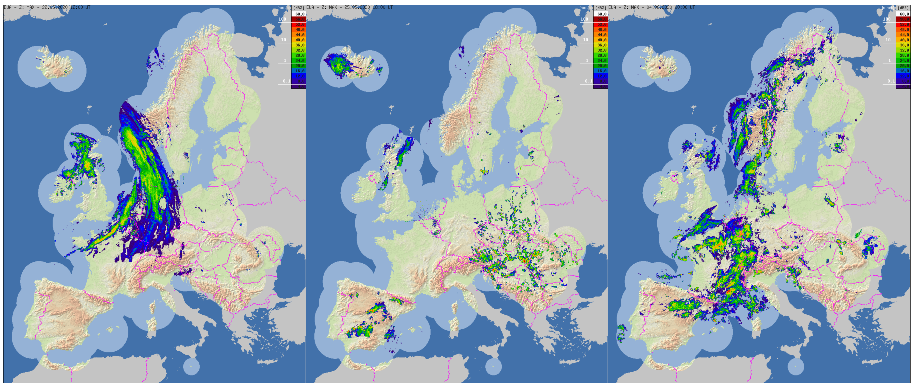
$$\sigma_{v_r} = \sqrt{\frac{1}{n_{\mathrm{elev}}} \sum_{i=1}^{n_{\mathrm{elev}}} \left(\frac{1}{n_{\mathrm{az}}} \sum_{j=1}^{360/n_{\mathrm{az}}} \sigma^2_{n_{\mathrm{az}}} \right)} \tag{5}$$

The statistics of the standard deviation index and corresponding number of observations were computed from data stored in ODB database after screening and contain OPERA OIFS data over 24 days assimilated for the purpose of the active data assimilation experiment which will be detailed in Section 4. This method was developed to systematically monitor the quality of measurements from each radar. Low values of standard deviation index (up to 5 m/s) and constant relative amount of active data to all data indicate good performance of the radar. Though there may appear exceptions e.g. due to strong wind shear situations. An example of an exception was presented in Montmerle and Faccani (2009).

Considering the number of observations it is easy to distinguish periods of precipitation activity when the counts of data relatively increase. The following Figure 3.5a represents the number of active (dark blue) and all (light blue) data from the radar located in Feldberg in south-west Germany. The amount of radial wind measurements can be compared to the OPERA composite maps (Fig: 3.5b, 3.5c and 3.5d) representing the reflectivity from precipitation.



(a) defbg - Feldberg, south-west Germany



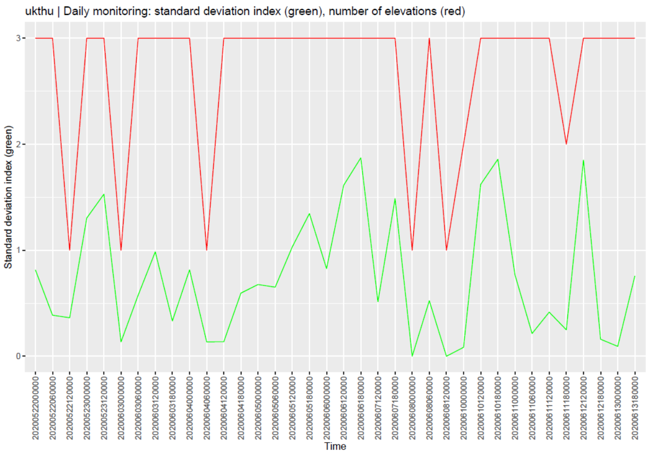
(b) 2020-05-22__12 (c) 2020-05-25__18 (d) 2020-06-04__00

Figure 3.5: Number of active (dark blue) and all (light blue) radial wind radar observations and OPERA composite of maximum radar reflectivity (available from CHMI remote sensing department).

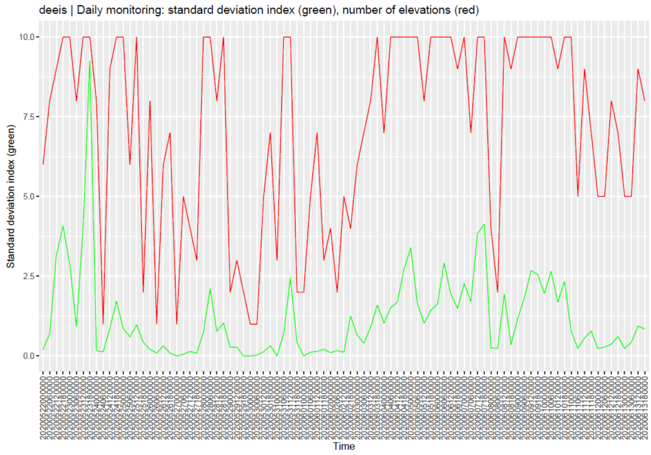
The diagnostics according to Montmerle and Faccani (2009) revealed differences in radar measurements quality between countries.

The eight UK radars (an example is shown in Fig. 3.6a) reached the best results, because the averaged standard deviation index is below 3 m/s for most of them most of the time. On the other hand, there are several missing datasets along the period. The corresponding number of active (dark blue) and all (light blue) measurements is plotted below in Fig. 3.6c.

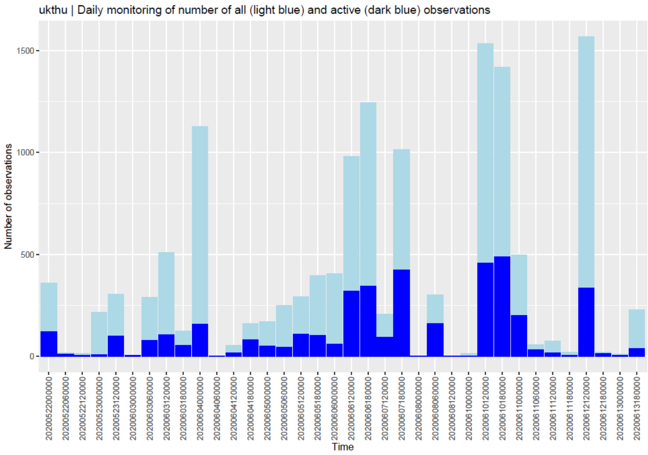
The issue related to missing UK data was then examined further. The UK radar provide only few low elevation angles whilst FR, DE or SK radar data contain a wider range of elevation angles. So only low elevations from FR, DE and SK datasets were selected to be compared to UK measurements (not shown). Generally, the standard deviation index was slightly lowered for FR, DE and SK data because of the truncation. On the other hand the overall pattern remained noticeable.



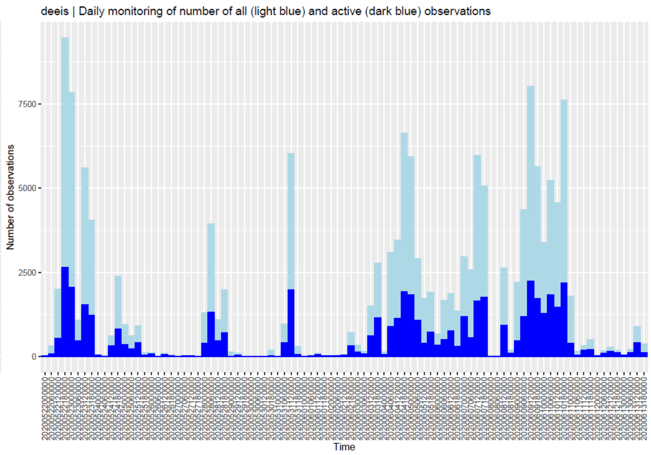
(a) ukthu - Thurnham, south-east UK



(b) deeis - Eisberg, south-east Germany



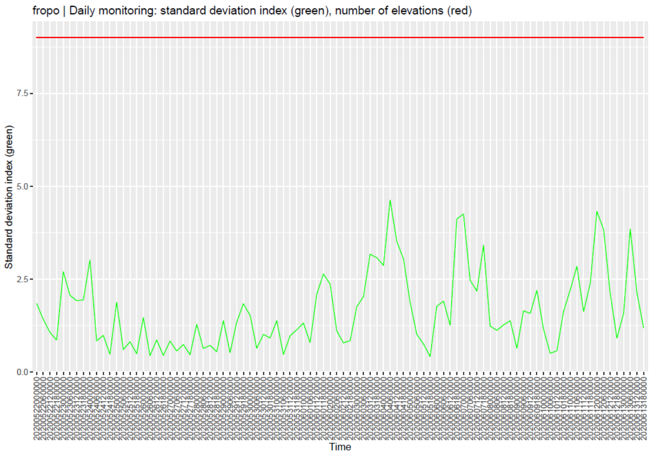
(c) ukthu - Thurnham, south-east UK



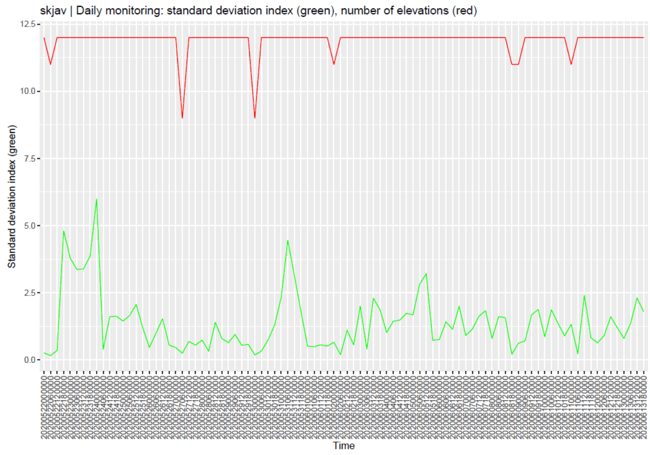
(d) deeis - Eisberg, south-east Germany

Figure 3.6: Standard deviation index (green), number of elevations considered (red), number of active (dark blue) and all (light blue) radial wind radar observations for UK and Germany.

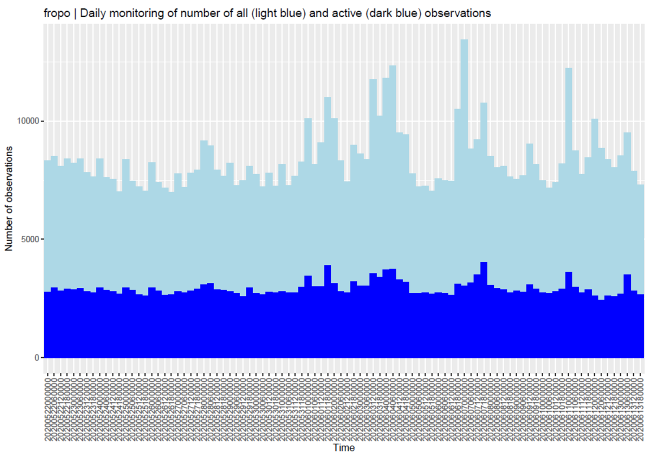
The monitoring of German (an example from German radar in Eisberg), French (an example from French radar in Opoul is in Fig. 3.7a, Fig. 3.7c) and Slovak (Fig. 3.7b, Fig. 3.7d) meteorological radars indicated desired values of averaged standard deviation index. However, there is a short interval at the beginning of the studied period where the standard deviation increased relatively to its average. A similar pattern is noticeable for the majority of radars from these three countries.



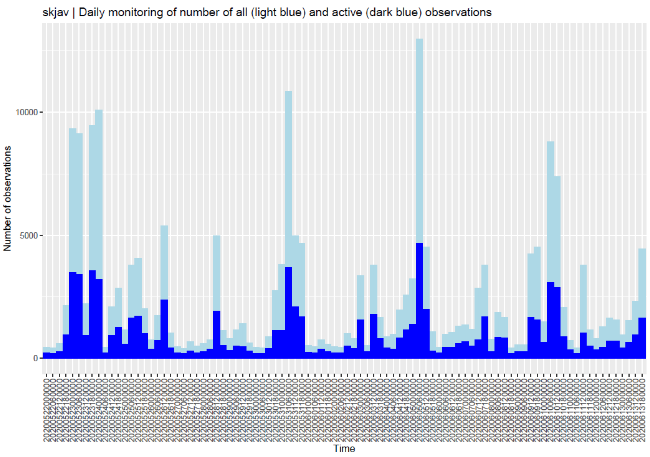
(a) fropo - Opoul, south France



(b) skjav - Maly Javornik, south-west Slovakia



(c) fropo - Opoul, south France



(d) skjav - Maly Javornik, south-west Slovakia

Figure 3.7: Standard deviation index (green), number of elevations considered (red), number of active (dark blue) and all (light blue) radial wind radar observations for France and Slovakia.

Danish and Slovenian data are not representative enough for these statistics due to lots of missing datasets and because of the coding approach.

The purpose of the diagnostics was to compare the data quality among the studied countries. The VAD (velocity-azimuth display) profiles calculation and pseudo TEMP soundings computation were also considered but finally the method of standard deviation index was selected.

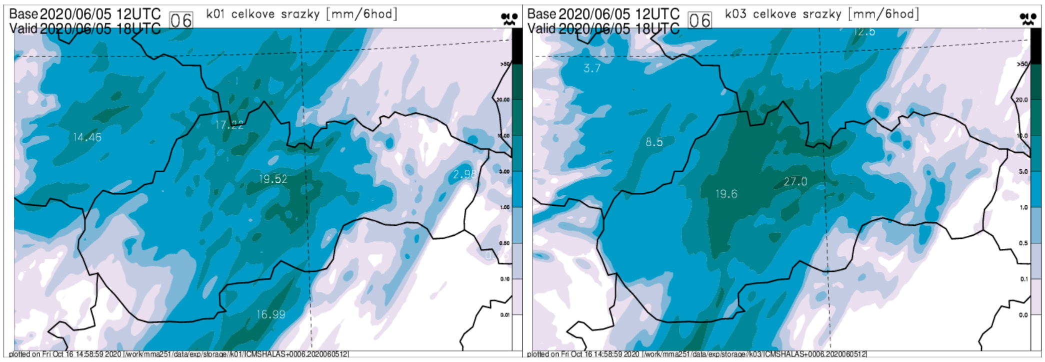
The quality of the analysed data is comparable in the studied sample.

4 Case study

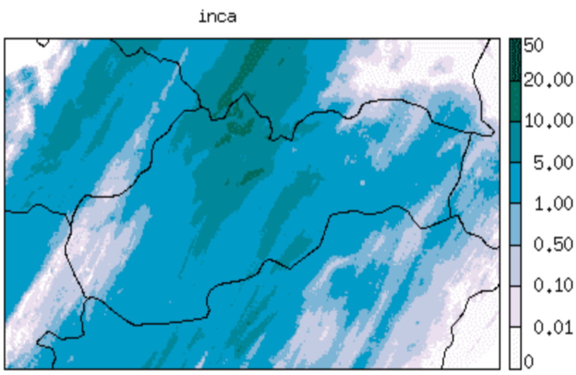
The final experiment during the stay was a case study where a comparison of a passive and active assimilation experiment was performed. The passive experiment without radial wind assimilation is denoted as $k01$ experiment and the active one including the radial wind data is denoted as $k03$ experiment. Both experiments were computed on ALARO NH-v1B cy43t2pt op1 model. The model setup is detailed in Table 3.1.

The case study was selected from 2020-06-05 in the afternoon when a cold front passed through the region of Slovakia. The Figures 4.1a on the left represents the passive data assimilation experiment $k01$ without radial wind while the figure on the right stands for the active data assimilation including the radial wind data. The accummulated rainfall forecast for 6 hours is depicted in both maps. There is an obvious impact due to radial wind assimilation.

The assimilation of radial winds indicated a slight improvement in the case presented in Figure 4.1a. Taking into account the INCA analysis in Figure 4.1b the pattern of increased rainfall gauges over the mountain area in central Slovakia seem to be expressed more precisely in the $k03$ experiment with radial wind assimilation.



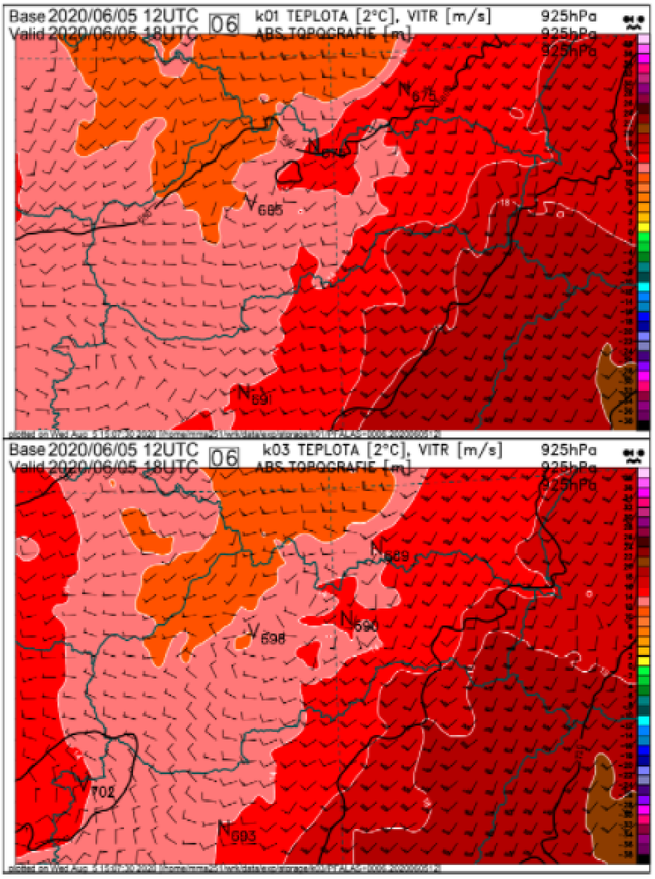
(a) k01, k03



(b) inca

Figure 4.1: Case study for accumulated 6 h precipitation forecast.

The impact of radial wind assimilation on several other meteorological parameters was also observed. An illustration of temperature at 925 hPa level and wind field is presented in Figure 4.2a. It indicates the potential to improve weather forecast thanks to radar radial wind measurements.



(a) k01, k03

Figure 4.2: Case study for wind and temperature field at 925 hPa level.

The active assimilation performed to get the case study includes the Slovenian and Danish dataset which although were small they were significantly biased. Therefore the results might be influenced by the incorrect measurements.

Though the preliminary results from upper-air verification scores with respect to TEMP observations (not shown here) showed overall deterioration due to radial wind data assimilation a deeper analysis should be completed.

5 Conclusion

To summarize, the main outcomes from the work realized during the stay are related to HOOF, statistical analysis of the studied data and a case study in the end.

Several bugs in HOOF tool were discovered. The incorrect quantity name reading when the option splitMeasurement=False was fixed. An error which led to HOOF crash when a dataset contains only TH (raw reflectivity) but no DBZ (corrected reflectivity) was reported and fixed in HOOF_v1.9. A bug in HOOF for radars with special scanning strategy was reported.

The statistical characteristics of OMG departures computed for Slovenia and Denmark did not correspond to the general pattern for other considered countries (namely Germany, France and Slovakia). The issue might me related to lower amount of data or a special data coding (in case of Slovenia) but it should be investigated further to understand better the incorrect behaviour.

On the other hand the averaged standard deviation index computed according the the method presented in paper by Montmerle and Faccani (2009) did not support the hypothesis of not accurate Slovenian radial wind data. In spite of several missing datasets for UK radars, the standard deviation index reached values corresponding to high quality radar performance, as well as for Germany, France and Slovakia.

In closing a case study was elaborated to investigate the impact of radial wind assimilation on weather forecast. The special case of accumulated precipitation forecast from 2020-06-05 in the afternoon indicated a slight improvement in the forecast thanks to radial wind assimilation. However a systematic verification scores analysis should be still completed.

Apart from the work done there remained some open questions which were not tackled more deeply due to lack of time.

Regarding the scanning strategy, it was observed that UK radar do not contain radial wind in the volume scan closest to the assimilation time. This was manually fixed thanks to Alena Trojáková so HOOF processed the second closest to the assimilation time volume scan where the radial wind is already involved.

The reason why Hungarian radars are excluded in bator was spotted but not explained because of missing information in the listing files.

Some preliminary experiments with sampling setting (detailed in Section 2.2.1) in bator were done but further analysis should continue. Besides the impact of median filter and filter cleaner on bator pre-selection of data is not understood completely and should be analysed.

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