PROCESSING OF RADAR REFLECTIVITIES IN SCREENING

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Model cycle: cy43t2_bf10
4 BATOR routines updated by MF cycle cy43t2_op1.12:
bator_decodhdf5_mod.F90, bator_module.F90, bator_init_mod.F90, bator_namelist.nam.h

1. Introduction

The aim of the stay was to get familiar with screening procedure of Radar Reflectivity Data in AROME/ALARO configuration, i.e. to get familiar with 1D+3D-Var assimilation method proposed by Wattrelot et *al.* (2014). This means to learn how pseudo observed relative humidity columns are computed, and to learn how radar thinning works. The functionality of reflectivity observation operator was out of scope of this stay.

It was proposed to run sensitivity tests on size of box for selection of model simulated profiles, on number of model simulated profiles, on value of prescribed reflectivity error which has influence on computation of pseudo observed relative humidity. The other proposed topics were to estimate effect of superobing on resulting pseudo observed relative humidity column and to assess vertical vs slanted reflectivity columns by comparison of resulting pseudo observed RH after screening.

The process of calculating pseudo observed relative humidity columns from observed reflectivity is the following: First step is definition of N neighboring model simulated profiles for each observation column in routine radar_profs.F90, see section 2. The next step is calculation of pseudo observed relative humidity column in routine inv_refl1dstat.F90, see section 3. Afterwards signs of reflectivity and relative humidity innovations are compared in routine flgtst.F90. If signs differ then both innovations are rejected, see more details in section 4. Final step is thinning of pseudo observed relative humidity, see section 5. The pseudo observed relative humidity is then assimilated by standard 3D-Var.

Note: In the following text there is strict distinction between column and profile. The column denotes all elevations of one observation report (i.e. set of observations approximately above one horizontal point). The profile denotes all elevations of one of model simulated profiles.

2. Search for model profiles

Routine: `arpifs/obs_preproc/radar_profs.F90`

Input: `lat, lon` of observation column
`NOBSPROFS` number of simulated profiles to define

Output: `array PLAT(NOBSPROFS), PLON(NOBSPROFS)` Array of lats and lons of defined simulated profiles, `error code`

Calling tree: `cnt0 > cnt1 > suobsb > sugoms > gom_mod:gom_create_glob > mkglobstab_obs > radar_profs`

For computation of pseudo observed relative humidity we need to define sufficiently large sample of model simulated reflectivity profiles and model relative humidity profiles. This routine defines NOBSPROFS model profiles for each observed reflectivity column. The variable NOBSPROFS is set in namelist NAMNPROF and its default value is 1.

The NOBSPROFS profiles are regularly distributed in hardcoded square box of size 200x200 km (was 100x100km in cy40t1), which means meridional/zonal distance between two nearest profiles is $200/\left(\sqrt{\text{NOBSPROFS}}-1\right)$ km. The profiles are defined from 1 to NOBSPROFS in a way illustrated on the Fig.1. First simulated profile is at observation column point.

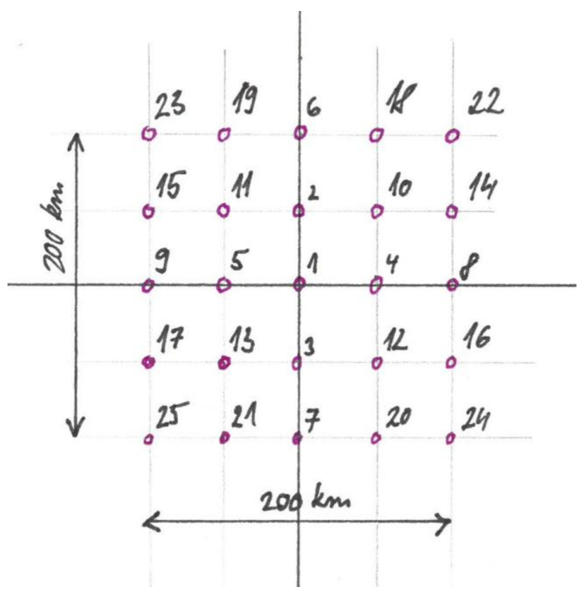

Fig1: Order of positions of defined model simulated reflectivity profiles when NOBSPROFS=25 for one column of observed reflectivity. First profile (No. 1) lies at location of observation column.

Note: NOBSPROFS should be square of some odd number!! We used 225 profiles as Météo-France (MF used 81 profiles until cy40t1).

3. Inversion of observed reflectivity to pseudo observed relative humidity

Routine: `arpifs/op_obs/inv_refl1dstat.F90`

Input: `PREFL2D` model simulated reflectivity profiles (M_{refl})
many other variables

Output: `ZREHU` pseudo observed relative humidity column
`PREFL2D` model simulated reflectivity profiles

Calling tree: `cnt0 > cnt1 > cnt2 > cnt3 > cnt4 > obsv > taskob > hop > obsop_radar > inv_refl1dstat`

The intent of this routine is to compute pseudo observed relative humidity column for each observed reflectivity column. The routine could be split to three parts: quality control, pseudo observed relative humidity computation and final check of values. Before we look at the details, it is worth noting possible scenarios of assimilation of observed reflectivity (O_{refl}) versus model simulated reflectivity (M_{refl}) according to Wattrelot et *al.* (2014), see table 1:

Table 1 Summary of various cases of rain assimilation

Cases	Definition	Decision
No rain observed / no rain simulated	O_{refl} == Noise && $M_{refl} \leq$ Noise	No assim if this is valid for all elevations in the observation column, see point 1) in quality control
No rain observed / rain simulated	O_{refl} == Noise && M_{refl} > Noise	Drying
Rain observed / no rain simulated	O_{refl} > Noise && $M_{refl} \leq$ Noise	Moistening
Rain observed / rain simulated	O_{refl} > Noise && M_{refl} > Noise	Adjustment of rain (drying or moistening)

Quality control

The quality control removes reflectivity observations which are dry and model is dry as well in all elevations of the observation column. It removes rain observations with low height (<3600m) and low values (<15dBZ) that are likely contaminated by ground effects. It removes higher level rain observations (>3600m) which have low values (<0dBZ or for French S-band radars <8dBZ). It removes observations below last model level and above first model level. And it also removes reflectivity observations at a certain elevation for which model reflectivity is not defined at observation location (i.e. the first M_{refl} profile is not defined at that elevation).

Note: Explanation of flgdyn flags valid for MF cycle cy43t2_op4.03. This helps with understanding of the code:

`satbody%flgdyn_at_radar_body==0`	means dry observation, i.e. undetect, which means that the observed radar signal was at or below noise level, but Bator redefined that value to noise level (Detection threshold)
`satbody%flgdyn_at_radar_body==8`	means observation with observed rain
`satbody%flgdyn_at_radar_body==1`	these obs are rejected (OPERA flag < 0.7) see Maud Martet (2019)

The above mentioned quality control is in the code written closely to the following lines:

1) `IF satbody%flgdyn_at_radar_body==0 and first` M_{refl} `profile (at observation column) <` O_{refl} `for all elevations THEN reject full` O_{refl} `column.`
2) `IF (satbody%flgdyn_at_radar_body > 0) THEN`

    `IF obs height < 3600m AND` O_{refl} `< 15dBZ THEN reject` O_{refl}`;`
    This if removes observations likely spoilt by ground effects; Is OPERA QC able to remove observations contaminated by ground effects?

    `ELSEIF obs height > 3600m AND` O_{refl} `< 8dBZ AND one of listed radars:`
    `7108 – frpla, 7510 – frbor, 7436 – frgre,`
    `7569 – frbol, 7645 – such wmo id does not exists,`
    `7745 – fropo, 7671 – frcol, 7774 – frale THEN reject Orefl;`
    Low values of O_{refl} for French S-band are removed, see Wattrelot et al. (2014).
    Is it necessary to add LACE radar? Is OPERA QC able to remove observations contaminated by anaprop?

    `ELSEIF obs height > 3600m AND` O_{refl} `< 0dBZ THEN reject` O_{refl}`;`
    Low values for O_{refl} are removed. Is OPERA QC able to remove observations contaminated by anaprop?

3) `IF obs height < last model level OR obs height > first model level THEN reject` O_{refl}.
   Elevations for which it would be necessary to extrapolate model RH are removed.
4) `IF first` M_{refl} `profile (at obs location) is not defined for a certain elevation THEN reject` O_{refl} `at that elevation;`
   The M_{refl} could be defined at other profiles (2…NOBSPROFS)! This check is before writing pseudo observed relative humidity to ODB. According to me this check could be moved to the beginning to avoid unnecessary computation of pseudo-observed relative humidity.

Specific treatment is for dry observation columns (flgdyn==0) when model is not completely dry at observation column, it means that at least one elevation of the first M_{refl} profile is not dry. In this case we would like to dry out a model so we search for dry model profiles (2..NOBSPROFS) and give them the largest possible weight in computation of pseudo observed relative humidity. This is done as following:
`IF satbody%flgdyn_at_radar_body==0 AND` M_{refl} `<` O_{refl} `THEN redefine` M_{refl} `(`M_{refl} `==` O_{refl}`).`

Before the pseudo observed humidity is computed it is necessary to interpolate relative humidity from model levels to elevations in each model profile.

Computation of pseudo observed relative humidity

The pseudo observed relative humidity column at observation location is computed as weighted average of humidity profiles at locations defined by radar_profs.F90. The weight for one profile is defined as Gaussian function of difference between observed reflectivity and model simulated reflectivity summed over all elevations. This means the larger the difference is the lower the weight is for that profile. See the exact formula for pseudo observed relative humidity:

jl observed column (JLEN in the code)
jc column elevation (JCOUNT in the code)
jp serial number of model simulated reflectivity profile (JPROF in the code), jp ∈(1..NOBSPROFS)
ZHU relative humidity at each simulated profile
ZREHU pseudo observed relative humidity column
ZREFRETR reference, pseudo analyzed reflectivity at obs column
N(jp) number of defined elevation for jp profile
σ sigma of reflectivity, hardcoded, ZXSIG=5.0 dBZ (was 0.2 dBZ until cy40t1)
O_{refl} observed reflectivity
M_{refl} model simulated reflectivity

$$\mathrm{ZREHU(jl,jc)} = \frac{\sum_{\mathrm{jp}} \mathrm{ZHU(jl,jc,jp)}\exp\left(\frac{-\sum_{\mathrm{jc}}\left(O_{\mathrm{refl}}(\mathrm{jl,jc}) - M_{\mathrm{refl}}(\mathrm{jl,jc,jp})\right)^2}{2\sigma^2 N(\mathrm{jp})}\right)}{\sum_{\mathrm{jp}} \exp\left(\frac{-\sum_{\mathrm{jc}}\left(O_{\mathrm{refl}}(\mathrm{jl,jc}) - M_{\mathrm{refl}}(\mathrm{jl,jc,jp})\right)^2}{2\sigma^2 N(\mathrm{jp})}\right)}$$

Very similar formula is used for computation of pseudo-analyzed profile of reflectivity, this values are written to the ODB (q_1dv@radar_body).

$$\mathrm{ZREFRETR(jl,jc)} = \frac{\sum_{\mathrm{jp}} M_{refl}(\mathrm{jl,jc,jp})\exp\left(\frac{-\sum_{\mathrm{jc}}\left(O_{\mathrm{refl}}(\mathrm{jl,jc}) - M_{\mathrm{refl}}(\mathrm{jl,jc,jp})\right)^2}{2\sigma^2 N(\mathrm{jp})}\right)}{\sum_{\mathrm{jp}} \exp\left(\frac{-\sum_{\mathrm{jc}}\left(O_{\mathrm{refl}}(\mathrm{jl,jc}) - M_{\mathrm{refl}}(\mathrm{jl,jc,jp})\right)^2}{2\sigma^2 N(\mathrm{jp})}\right)}$$

Final check

At the end of the routine there are a few safety checks. The consistence between pseudo-analyzed reflectivity and observed reflectivity is checked. If differences between pseudo-analyzed reflectivity and observed reflectivity are large then the reflectivity inversion is not able to provide pseudo observed relative humidity consistent with observation in terms of reflectivity and corresponding column is not assimilated (Wattrelot et *al.*, 2014). The limits of pseudo observed relative humidity are also checked:

IF $\frac{\sum_{jc}\left(O_{\mathrm{refl}}(\mathrm{jl,jc}) - \mathrm{ZREFRETR(jl,jc)}\right)}{N_{ZREHU}(jl)}$ >400 or
ZREHU(jl,jc) <0 or
ZREHU(jl,jc)>120 THEN reject O_{refl}(jl,jc).

Performed test

To test if removal works as expected a single radar observations (czbrd) were used. The result could be seen in Table 2. About 70 % of observations are removed because they belong to dry observation columns when model is also dry, 5.6 % of observations are removed due to other reasons.

Table 2 Example of number of rejected observation from one radar station (czbrd) on 21.2.2020 at 0utc.

Number of input observations (reflectivities)	25855 obs	100 %
Flgdyn=0 and first M_{refl} profile < O_{refl} for all elevation	18036 obs	~70 %
(Flgdyn>0 and obs_height<3600 and O_{refl}<15) or (flgdyn>0 and obs_height>3600 and O_{refl}<0)	930 obs 121 obs	3.6 % ~0.5 %
Denom<tiny(1) or zrehu==rmdi or M_{refl}==rmdi 462 obs has obsgeop <geop(klev) or obsgeop>geop(**lev10**) so rhu not defined this result in denom==0 6 obs has not defined M_{refl} at first profile (M_{refl}==rmdi)	468 obs	~1.8%
Number of rejected reflectivity obs (sum of row 2,3,4)	19555 obs	~75.6 %
Number of created humidity obs (row1 –row5)	6300 obs	~24.4 %

Found bugs

1. At humidity interpolation, line 153 in cy43t2_bf10
   `ROBODY%DATA(IBODY,ROBODY%VERTCO_REFERENCE_2_AT_BODY)<(PGEOPF5(JLEN,10,JPROF)/RG))`
   I think there should be 1 instead of 10. There is no reason to interpolate only between last model level and model level 10. Every country has different distribution of levels so if there is a reason to stop before model top it should be in pressure not in model level. If I put 1 in the code I get more humidity observations.
2. At final consistency check, line 264 in cy43t2_bf10
   `ZREHU(JLEN,JCOUNT)>120._JPRB`
   The model relative humidity is defined in interval <-0.2;1.2> in obsop_radar.F90 so the pseudo observed relative humidity should not exceed **1.2** as well. In reality this check will be used only when there is a bug in weighted average!
3. At final consistency check, not real bug but suboptimal code, line 263 in cy43t2_bf10
   `ZREHU(JLEN,JCOUNT)<0._JPRB`
   This is fulfilled even ZREHU==RMDI (-2147483647) which was set earlier in the process. It is not necessary to go in this if! So it would be better to make
   `(ZREHU(JLEN,JCOUNT)<0._JPRB .AND. ZREHU(JLEN,JCOUNT)!=RDMI)`

4. Removal of radar column and innovation sign check

Routine: `Arp/obs_preproc/flgtst.F90`

Calling tree: `cnt0 > cnt1 > screen > decis > flgtst`

Purpose: flgtst will transform datum/report flag information to a status (i.e. active, passive, rejected, blacklisted).

For radars observations there is specific check of sign of reflectivity and relative humidity innovation (fg_depar), if reflectivity and relative humidity innovation have opposite sign for particular observation then this observation is rejected from assimilation.

For radar observations there is also removal of dry columns, i.e. reflectivity innovation equal zero (fg_depar=0) for all observations in one obs column. This can only happen when O_{refl} column is dry and M_{refl} was not completely dry at beginning of inv_refl1dstat.F90 but due to other checks in the inv_refl1dstat.F90 the non-dry elevations were removed.

Note: reflectivity innovations (fg_depar) are computed as difference between observed reflectivity and model simulated reflectivity in the first profile (i.e. at obs location and elevation).

Continuation of test performed in section 3 is summarized for flgtst.F90 in table 3:

Table 3 Example of number of rejected RH observations from one radar (czbrd) on 21.2.2020 at 0utc.

Number of created humidity obs	6300 obs	~24.4 %
Obs removed due to opposite sign of innovation	187	~1 %
Obs removed due to dry column (fg_depar=0)	1936	~7.5 %
Active humidity observations (row1 - row2 - row3)	4177	~16 %

5. Thinning

Routine: `arpifs/obs_preproc/new_thinn.F90 (pre_thinn_rad_reflec, new_thinn_rad_reflec)`

Calling tree: `cnt0 > cnt1 > screen > decis > new_thinn`

Thinning of radar observations could be influenced by keys RMIND_RADAR, RFIND_RADAR (in m) in block NAMSCC Default setting is:

RMIND_RADAR = 0.037_JPRB*RA/RDEGREES ! cca 4km, Min distance between RADAR obs,
RFIND_RADAR = 0.075_JPRB*RA/RDEGREES ! cca 8km, Avg distance between RADAR obs.

Thinning works in two loops. At first domain is split to RMIND size boxes and only one observation column is allowed in a box, then domain is split to RFIND size boxes and again only one observation column is allowed in a box. The observations are ordered by thinningtimekey and some random number in case thinningtimekey is the same for two observation columns. First observation column in the ordered list for the specified box is selected the other observations in the box are rejected. Definition of thinningtimekey (thinningtimekey@hdr) is:

mdb_thinningtimekey_at_hdr = 5*rhoer/obslev +0.001*azimut(radians), where

rhoer [0-1] = 0.25*distance/160km + 0.15 [bator_ecriture_mod.F90:1646],
obslev -- number of levels in observation column,
azimuth -- of the observation column with respect to the radar.

The boxid is stored in mdb_thinningkey_at_hdr (thinningkey@hdr). From the above formula is obvious that observation columns which are nearer to the radar, observation columns with more elevation and observation columns with lower azimuth are preferred.

Time dependence

Time of the observations is not handled by thinning. The Bator is processing one ODIM file at a time and selects the observations nearest to the analysis time. Time of observation is set in ODB as analysis time even it was measured before or after the analysis time. So if two files from the same radar are processed by Bator then two observations with analysis time enters screening!

This can easily happen if you use HOOF (Homogenization Of Opera Files) tool. HOOF by default splits one opera ODIM file to separate files for each radar volume scan. If Bator reads all files created after HOOF then screening will have select one of the scans in thinning procedure. Or user has to select one of the volume scans before screening!

Found bugs (problems)

Thinning is not reproducible when two ODIM files from the same radar are processed by Bator! If you run thinning twice you will get two different selections of active observations. The problem is due to allocated but not initialized field ZKEYPRE in routine arpifs/obs_preproc/new_thinn_rad_reflec.F90. This field is later used for sorting of obs columns, i.e. to make random order of observations. One would like to have pseudo random order, not totally random! As a temporal fix I propose to switch off sorting over this field, see my modification to the routine new_thinn_rad_reflec.F90:

```
!INTEGER(KIND=JPIM), PARAMETER   :: I_MKEY(ICOLUMNS-1)=(/IBX,ITM,IRN/)
INTEGER(KIND=JPIM), PARAMETER   :: I_MKEY(ICOLUMNS-2)=(/IBX,ITM/) !abuc
```

6. Conclusion

Only the processing of reflectivity observation in screening was investigated during this stay, so no sensitivity tests were performed. The reason was that I got flu during the stay so I returned to the Czech Republic and when I got well, the situation with Corona virus pandemic got so serious, that it was not possible to get back to Austria.

Only test performed was to observe how reflectivity observations are converted to relative humidity and where observations are removed from processing. It was found a reason for each removal of observations.

There were found a few minor bugs in routine inv_refl1dstat.F90, please see section 3. One problem was also found in the thinning is section 5.

I propose to run a few additional tests beside the ones mentioned in the introduction:

1) Harmonie WW 2016 SHMI (https://hirlam.org/trac/raw-attachment/wiki/HarmonieWorkingWeek/UseObs201605/SMHI_status_may2016.pdf) reported drying effect of assimilation of radar data when no observed precipitation and no model precipitation. The problem appears when model is not able to make reflectivity values lower than radar detection threshold it can have consequence on artificial drying effect!!!! So it would be worth to test if model minimal values of reflectivity are low enough.
   By the way solution of Hirlam colleague's is not correct, since minimal detection threshold is dependent on distance from radar and can be larger than 30dBZ, see Watterlot et *al.* (2014).
   MF fixed this problem in AROME by microphysics tuning of autoconversion threshold, in cy43op2 they use modified threshold RCRIAUTC=0.001 instead 0.0005 in their 001 namelist (personal communication with Florian Meier).
   For ALARO it is worth to investigate this issue.
2) Test correlation between O_{refl} versus pseudo-analyzed reflectivity – similarly to Watterlot et *al.* (2014).
3) Investigate if OPERA QC is able to remove observations contaminated by anaprop and ground effects. The question is if LACE radars should be added to the QC of inv_refl1dstat.F90 as the Croatian and Serbian and some Romanian radars are S-Band. How much OPERA flags solve this anaprop and ground effects when we assimilate observations which have total OPERA flag > 0.7?

7. Comments

1) Hydrometeors should be in the guess!
2) In ALARO, if you do not read prognostic graupels from the guess (NREQIN=1), do not rely on default settings but initialize graupels to zero!!! (personal communication with Alena Trojakova)

```
&NAMGFL
  YG_NL%LGP=.T.,
  YG_NL%LREQOUT=.F.,
  YG_NL%NREQIN=0,
/
```

3) Memory consumption becomes a problem when trying to assimilate all radar observation without pre-thinning in BATOR! However this was valid for the HARMONIE-Bator reader, which took not into account QI<0.7 and DBZH/TH-3 check. With the MF BATOR the amount of observations is already significantly less after BATOR. So it might become less an issue. (personal communication with Florian Meier)

8. References

Maud Martet (2019): OPERA radar data use in AROME-France model, http://www.umr-cnrm.fr/gmapdoc/IMG/pdf/201906_arome-france_opera.pdf

Wattrelot E., Caumont O., Mahfouf J. F. (2014). Operational implementation of the 1D+ 3D-Var assimilation method of radar reflectivity data in the AROME model. *Monthly Weather Review*, *142*(5), 1852-1873.