ENHANCED GLOBAL NUCLEAR EVENT LOCATION AND ITS UNCERTAINTY ANALYSIS BASED ON VARIOUS ADJOINT ENSEMBLE DISPERSION MODELLING TECHNIQUES

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Abstract: After the detection of treaty-relevant radionuclides in filters or air samples, atmospheric backtracking techniques are employed by the Provisional Technical Secretariat (PTS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to trace back the measured substances to their potential areas of origin. In the case of an underground nuclear test, potential sources are co-located with the epicentres of seismic events that may have been triggered by the explosions. Previous studies have shown that predictions or analyses of atmospheric transport can be significantly improved by ensemble techniques.

Within the CTBT environment it is important to build confidence in the source-receptor sensitivity (SRS) field based backtracking products issued by the PTS in the case of the occurrence of treaty relevant radionuclides. Therefore the PTS has set up a highly automated response system together with the Regional Specialized Meteorological Centres of the World Meteorological Organization in the field of dispersion modelling. These Centres have committed themselves to provide the PTS with the same standard SRS fields as calculated by their systems for CTBT relevant cases.

The SRS field data standard allows for ensemble dispersion modelling. The parametric inter-comparison among ensemble members has been integrated into the decision making software tool WEB-GRAPE (CTBTO Newsletter Spectrum, 7, page 19). In sensitivity studies we varied the choice of LPDM, and the kind and source of wind field utilized to demonstrate the potential of the following two ensemble dispersion modelling (EDM) methods:

a) Multi-model EDM in order to improve the accuracy of a global scale source attribution based on joint CTBTO-WMO experiments in January 2005 (Becker et al., 2007) and December 2007 (Wotawa and Becker, 2008).
b) Single-model EDM with different lead times of the wind fields utilized in order to estimate the relative error of forecasted source attribution results in comparison to the analyzed ones
c) Single-model EDM with different choices of wind field resolutions for the source receptor sensitivity fields of the same station at Schauinsland in order to assess quality of the PTS standard backtracking results based on the rather coarse 1º×1º horizontal resolution.

Key words: *Lagrangian Particle Dispersion Models, receptor oriented modelling, ensemble dispersion modelling, FLEXPART, model evaluation, quality assurance, decision making tools.*

1. INTRODUCTION

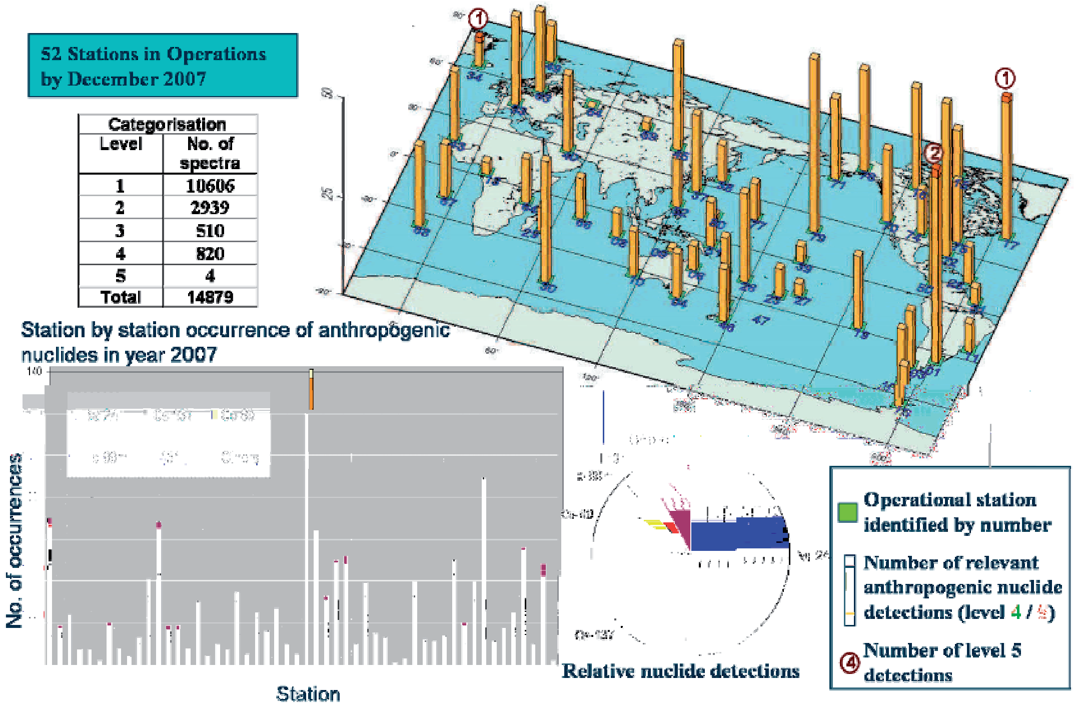
The Provisional Technical Secretariat (PTS) of the CTBTO Preparatory Commission maintains and permanently updates a source-receptor matrix (SRM) describing the global monitoring capability of a highly sensitive 80 stations radionuclide (RN) network in order to verify states signatories' compliance of the comprehensive nuclear-test-ban treaty (CTBT). Each RN station is equipped with a germanium detector ready to detect radionuclide particulates down to minimum detectable concentration (MDC) of 0.3×10^{-4} Bq/m^3 with regard to a 24 hour sampling period. During each period 500 m^3 of air are sucked through a filter with an effective cross section of 1 m^2. 52 RN particulate stations were already in operations by end of 2007 thus sending data to the Vienna based PTS for further analysis and categorization. A 5-Level categorization is applied whereby only Levels 3, 4 and 5 indicate the occurrence of at least one or more CTBT relevant nuclides. For a Level 3, however, the nuclide has occurred already too often before, so it is associated to the background concentration. On the other side a Level 5 categorization requires additional appearance another relevant nuclide, and one of the two needs to be a fission product. A resume for the 14879 samples categorized in 2007 is given in Figure 1.

50% of the RN particulate stations are also equipped with noble gas sampling systems that feature MDCs ranging from 0.1 - 1.0×10^{-3} Bqm^{-3} according to experiences gathered within the so-called International Noble Gas Experiment (INGE).

In support of this, receptor-oriented Lagrangian particle dispersion modelling (LPDM) is performed in 24h/7d operations to help determine the region from which suspicious radionuclides may originate. In so doing the two LPDM systems FLEXPART_5.1 (Stohl et al., 2005) and HYSPLIT_4.8 (Draxler and Rolph, 1998) are integrated backward in time based on two different global analysis wind fields yielding global source-receptor sensitivity (SRS) fields stored in three-hour frequency and at 1º horizontal resolution (Wotawa et al., 2003).

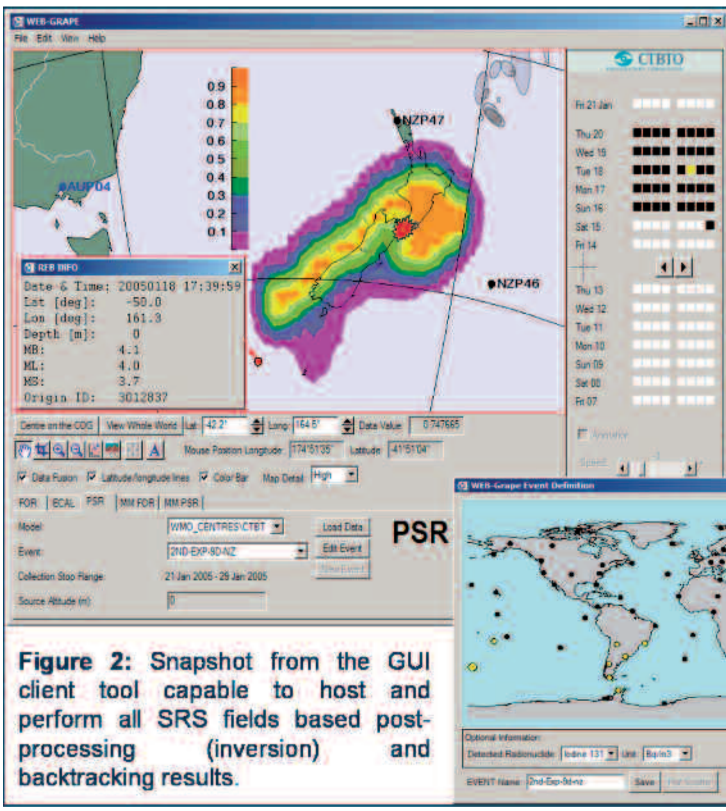
2. SOURCE ATTRIBUTION FOR THE RADIONUCLIDE NETWORK

A database of these SRS fields substantially helps to improve the interpretation of the RN samples' measurements because it enables a time efficient testing of source hypotheses. Applying the source-receptor concept introduced by Wotawa et al. (2003) and introduced to HARMO9 by Becker et al. (2004) an inversion problem is solved on basis of the SRS data base in order to determine the so called possible source region (PSR, Figure 2, left) of a scenario of treaty relevant RN measurements (Fig. 2 bottom). Provided a user has access to the relevant SRS fields, the global source attribution can be performed in a pure post-processing step even bundled within a "thick client" visualisation tool such as WEB-GRAPE (CTBTO, 2005) developed by the PTS (Fig. 2, left). The example of Figure 2 examines the data exchanged during the 2nd CTBTO-WMO experiment introduced to HARMO10 by Becker et al. (2005).



Categorisation	
Level	No. of spectra
1	10606
2	2939
3	510
4	820
5	4
Total	14879

The WEB-GRAPE based analysis is feasible on hardware with specifications comparable to currently available PC/Notebook, and allows also for a parametric inter-comparison among SRS fields calculated by different LPDM systems on the same backtracking problem.



Left: Displayed is the colour coded PSR field in term of correlation coefficients. The higher the PSR value the more consistently a singular source there would reproduce the event scenario (**bottom**). The actual* source location (red object) of the virtual nuclear scenario conducted during the 2nd CTBTO-WMO Experiment is spotted very well by the PTS source location methodology.

*Geo-temporal event location: 18 Jan 2005 from 16:12 to 19:12 UTC at λ=174.86E, φ=41.89S

Figure 2: Snapshot from the GUI client tool capable to host and perform all SRS fields based post-processing (inversion) and backtracking results.

3. ENSEMBLE DISPERSION MODELLING APPROACHES FOR THE RADIONUCLIDE MONITORING STATION SCHAUINSLAND, GERMANY (DEP33)

Based on the CTBTO-World Meteorological Organization Cooperation Agreement the IDC has created the CTBTO – WMO response system providing PTS with the capability to perform backward ensemble dispersion modelling (EDM) yielding so-called multi-model versions of the FOR and PSR products in case of treaty relevant RN detection (Becker et al., 2007). In addition to addressing the uncertainties inherent to any kind of dispersion modelling, these products also serve quality assurance purposes. The SRS field concept provides for this purpose the ideal standard to harmonize the backtracking results delivered by the external meteorological centres and the different PTS in-house systems (Becker et al., 2004). The latter constitute the experimental PTS in-house EDM system. As detailed in Table 1, the members of this system distinct by the wind-field and the LPDM utilized. Three example EDM set ups shall be examined with regard to the SRS field pertaining to the 24 hour RN sample collected until 3 April 2007, 6 UTC at the German monitoring station DEP33 (Schauinsland, Black Forest):

Table 1. Members of the CTBTO-WMO response system in backward ensemble dispersion modelling.

LPDM	ID	Mode	# of particles	Met. Input Data	Resolution	z-coord.	# of levels
FLEXPART_5.1	FECA	3D-particle	240 000	ECMWF, 4DVAR	1^0x1^0, 3h	eta	91
FLEXPART_5.1	FE20	3D-particle	500 000	ECMWF, 4DVAR	0.2^0x0.2^0, 3h	eta	91
FLEXPART_5.1	FE50	3D-particle	500 000	ECMWF, 4DVAR	0.5^0x0.5^0, 3h	eta	91
FLEXPART_5.1	FGDA	3D-particle	240 000	US-NCEP, GDAS	1^0x1^0, 6h	eta	26
FLEXPART_5.1	FGF1	3D-particle	240 000	US-NCEP, GFS	1^0x1^0, 6h	eta	26
FLEXPART_5.1	FGF3	3D-particle	240 000	US-NCEP, GFS	1^0x1^0, 6h	eta	26
FLEXPART_5.1	FGF5	3D-particle	240 000	US-NCEP, GFS	1^0x1^0, 6h	eta	26
FLEXPART_5.1	FGF7	3D-particle	240 000	US-NCEP, GFS	1^0x1^0, 6h	eta	26
HYSPLIT_4.7	HGDA	3D-particle (part.)	50 000	US-NCEP, GDAS	1^0x1^0, 6h	p	26
HYSPLIT_4.7	PECA	z-part./hor.-puff	2 500	ECMWF, 4DVAR	1^0x1^0, 3h	p	91
HYSPLIT_4.7	PGDA	z-part./hor.-puff	2 500	US-NCEP, GDAS	1^0x1^0, 6h	p	26

Single-model EDM "Forecast": **Calculate the SRS field with the same LPDM and the same wind-field source, however with different lead times with regard to the wind-field forecast while using the wind field analysis of the same NWP as reference.**

Figure 3 demonstrates that for the single-model EDM the SRS fields of the analysis run FGDA and the forecast runs FGF1, FGF3, FGF5, and FGF7 remain surprisingly congruent for the case regarded, even for lead times of 5 and 7 days (FGF5, FGF7). Predicted SRS fields can also be interpreted as 'vulnerability maps' for the target (receptor) area considered. For example the 7 days forecast (FGF7) would still give 104, 80, 56, 32, and 8 hours notice to warn for hazardous emissions released 1, 2, 3, 4 and 5 days prior to their arrival at the target area. The strongest deviations among the runs occur across the alpine bow in all EDM examples, but these deviations partly recover (re-converge) for longer backward ranges when the predicted areas of high source-receptor sensitivity reside across rather flat terrain.

Multi-model EDM**: The backward pendant to the approach of Galmarini et al. (2004): Calculate the SRS field with entirely different LPDM systems in terms of LPDM and wind field utilized.**

Figure 4 demonstrates the same inter-comparison for the multi-model EDM case where the same analysis run is performed with five different model systems and/or set ups. The deviations in this inter-comparison are substantially stronger, although none of them utilizes forecasted wind fields. The differences due to the source of the analysis wind field (FECA vs. FGDA and PECA vs. PGFA) are much smaller than due to the LPDM system chosen (HYSPLIT vs. FLEXPART).

The astonishing congruence of the SRS predictions in the single-model EDM case versus the multi-model EDM case is also reflected with regard to the standard inter-comparison metrics fractional bias (FB), Pearson-Correlation (R^2) and Overlap (Figure of Merit in Space, FMS) and its aggregation value calculated by equation (1) as follows:

$$RIK = R^2 + (1 - |FB/2| + FMS/100) \qquad (1)$$

The resulting cross-comparison matrices as shown in Figure 5 for the single-model (left) and the multi-model EDM case (right) confirm the much higher model agreement in the first case also in terms of the metrics of Equation (1).

Single-model EDM "Resolution": **Calculate the SRS field at different horizontal resolutions of the same LPDM system**

Increasing the re-solution of the LPDM system applied is important for the correct description of the transport across topographically structured terrain (here the alps) and to resolve small scale emission patterns. This is also demonstrated in the in Figure 6. However, after two days of backward simulation the 0.2^0 vs. 0.5^0 deviations diminish, compared to the ones vs. the original FECA run at 1^0 resolution.

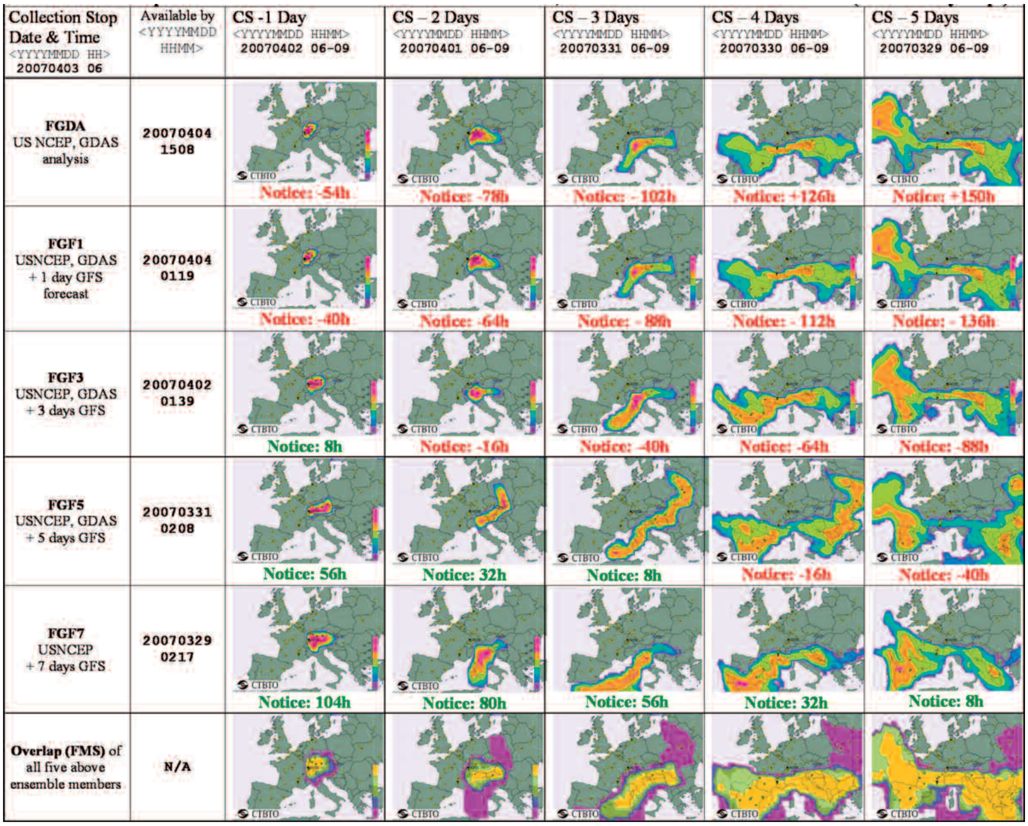


Figure 3. Inter-Comparison of forecasted SRS fields for the station DEP33, Schauinsland with different lead times applied.

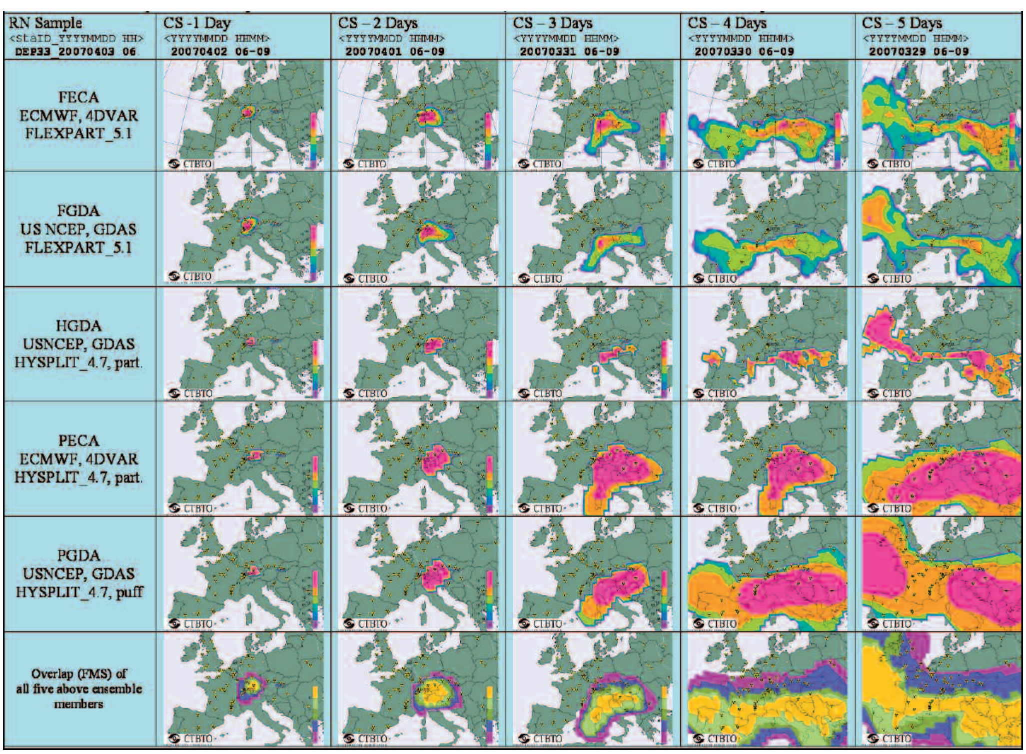


Figure 4. As Figure 3 but for the multi-model EDM case.

RNK	FGDA	FGF1	FGF3	FGF5	FGF7		
FGDA	3	2.82	2.00	1.97	1.96		
FGF1	2.82	3	2.00	1.98	1.96		
FGF3	2.00	2.00	3	2.09	2.34		
FGF5	1.97	1.98	2.09	3	2.27		
FGF7	1.96	1.96	2.34	2.27	3	*AV*	*σ*
Agreement	**72.93**	**72.98**	**70.2**	**69.27**	**71.08**	**71.290**	**1.648**
Anomaly	***1.64***	***1.69***	***-1.09***	***-2.02***	***-0.21***	***0.000***	***1.648***

FMS	FGDA	FGF1	FGF3	FGF5	FGF7		
FGDA	100	82.5	73.7	65.5	67.9		
FGF1	82.5	100	73.6	65.8	68.2		
FGF3	73.7	73.6	100	64.6	65.3		
FGF5	65.5	65.8	64.6	100	60		
FGF7	67.9	68.2	65.3	60	100	*AV*	*σ*
Overlap	**72.37**	**72.54**	**69.3**	**63.96**	**65.36**	**68.71**	**3.943**
Anomaly	***3.66***	***3.83***	***0.59***	***-4.75***	***-3.35***	***0.000***	***3.943***

RNK	FECA	FGDA	HGDA	PECA	PGDA		
FECA	3	2.05	0.59	0.47	0.48		
FGDA	2.05	3	0.62	0.50	0.46		
HGDA	0.59	0.62	3	1.26	0.75		
PECA	0.47	0.50	1.26	3	1.89		
PGDA	0.48	0.46	0.75	1.89	3	*AV*	*σ*
Agreement	**29.86**	**30.32**	**26.86**	**34.39**	**29.84**	**30.250**	**2.691**
Anomaly	**-0.39**	**0.07**	**-3.39**	**4.14**	**-0.41**	**0.000**	**2.691**

FMS	FECA	FGDA	HGDA	PECA	PGDA		
FECA	100	67.1	34.1	37.1	39.2		
FGDA	67.1	100	35.3	37.2	39.6		
HGDA	34.1	35.3	100	14.7	15.8		
PECA	37.1	37.2	14.7	100	82.6		
PGDA	39.2	39.6	15.8	82.6	100	*AV*	*σ*
Overlap	**44.36**	**44.79**	**24.96**	**42.89**	**44.31**	**40.260**	**8.584**
Anomaly	***4.10***	***4.53***	***-15.30***	***2.63***	***4.05***	***0.000***	***8.584***

Figure 5. Inter-comparison metrics for the single model EDM "Forecast" (left) and the multi model EDM case (right).

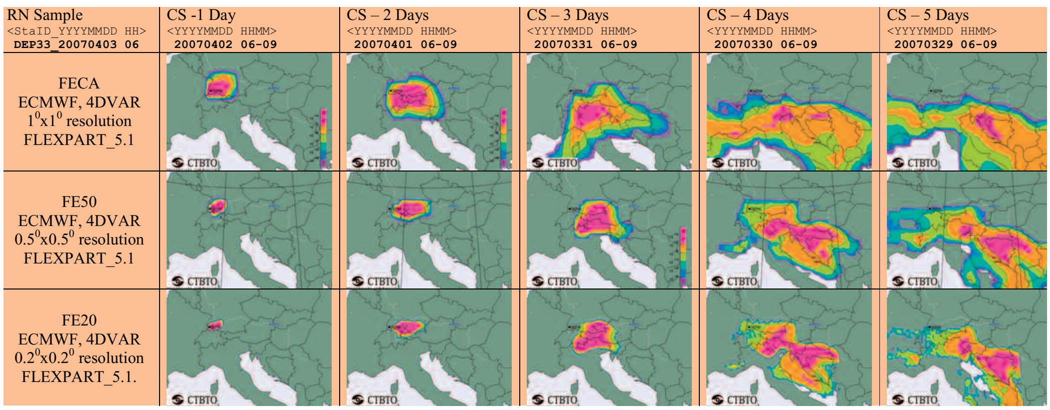


Figure 6. Inter-comparison of the analysis run FECA (Table 1) with two re-runs at higher resolutions of the LPDM system.

4. SUMMARY

Three different ensemble modelling techniques are applied for the backtracking of one specific 24hour radionuclide sample taken at the station DEP33, Schauinsland, Germany, from 2-3 April, 6 UTC. In doing so, three different sources of uncertainty with regard to backward modelling are investigated: (i) the error of forecast wind fields, (ii) the deviations between different wind fields and LPDM systems, (iii) and the discretisation error (related to the model resolution). For the case examined here the deviations between different model systems, in particular between the transport modules is stronger than the deviation between the analyses wind fields utilized. Moreover the deviation resulting from the use of wind fields with different forecast lead times is small in comparison to the deviation between different LPDM systems that are very wide spread in the community. The resolution error diminishes with the temporal range of the backtracking simulation.

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