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ENHANCED INVERSE DISPERSION MODELLING BY COLOCATION WITH WAVEFORM EVENTS: AN ANALYSIS OF THE NATIONAL DATA CENTRE PREPAREDNESS EXERCISE 2009

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Abstract: Inverse modelling for the phenomenon of atmospheric dispersion is often hindered by a limited number of measurements which makes the problem severely underdetermined. Superimposed are inaccuracies in the meteorological fields which drive the atmospheric transport models, simplifications in the models themselves and the errors intrinsic to the measurement procedures. Consequently, obtaining informative and reliable results of inverse modelling requires additional information which needs to be provided to an inversion algorithm. Mathematical techniques could be employed in order to constrain the underdetermined inverse problem, or, in case of a simple source characterised by a small number of parameters, the estimation could be limited to those parameters. In the context of monitoring compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) yet other pieces of information are taken advantage of. Large regions indicating a possible presence of a source of radionuclides can be overlaid with an accurate location of the phenomena emitting seismic, infrasound or hydroacoustic signals. Ultimately, under the hypothesis that the source of radioactivity coincides in space and time with one of the detected phenomena, the atmospheric transport modelling (ATM) aids to discriminate between those which could have been and could not have been at the origin of a detected release.

Key words: *atmospheric dispersion, inverse modelling, airborne radionuclides.*

INTRODUCTION

The principal mission of the CTBTO consists in monitoring compliance with the Comprehensive Nuclear Test Ban Treaty (CTBT). For this purpose, CTBTO operates a network of 321 monitoring stations constituting the International Monitoring System (IMS). According to their design, the stations aim at detecting either seismic, infrasound or hydroacoustic, referred to as waveform, signals, or concentrations of radionuclides in the atmosphere.

The stations monitor different, yet complementary, phenomena, all of which might be an indication of a nuclear test. Thorough analysis of all the signals registered by the waveform monitoring stations is carried out in order to specify a location in space and time of the events emitting those signals. Inferring such location for a source of airborne radionuclide measurements is a much more complex task. The time of propagation of a cloud of radionuclides is of the same order of magnitude as the changes in the medium in which the cloud is propagated (Earth's atmosphere). Moreover, these changes are subject to an important forgetting factor constituted by turbulence.

The results of data analysis provided by the CTBTO are transmitted to the signatories of the treaty to whom the judgement on the true nature of the events detected by the monitoring network is reserved. Some of the treaty signatories operate National Data Centres (NDCs) having technical capacity of accommodating data analyses provided by the CTBTO and of carrying out their own analyses to support such judgements. The NDCs perform periodically preparedness exercises in order to test their own capacities as well as the performance of the IMS network. The rest of this paper is devoted to an analysis of the most recent NDC Preparedness Exercise 2009 (NPE 2009) from the point of view of inverse modelling for atmospheric dispersion.

SELECTION OF A WAVEFORM EVENT FOR AN EXERCISE

A phenomenon emitting signals detected by either seismic, infrasound or hydroacoustic network is referred to as waveform event. A waveform event scrutinised during an NPE is not accompanied by a release, or production even, of radioactive material. For the needs of an exercise it is, nevertheless, hypothesised to be so. An instantaneous release of 10^{15} Bq to the atmosphere coinciding in space and time with the waveform event is supposed to take place. The quantity of the emitted radioactivity corresponds to 10% of the yield of a 1kt nuclear explosion. It implies that for the needs of an exercise the event is considered to be an underground nuclear test characterised by a 90% containment. The event also constitutes a source term for an atmospheric transport model which is used to produce a fictitious scenario of detections in the radionuclide stations of the IMS network. In order to enable testing the performance of a source attribution algorithm used at the CTBTO, as well as data fusion capacity, the scenario should be formed by detections in a few stations on several consecutive days. Thus, the atmospheric transport requirements add to a complexity of selection of a waveform event for an NPE.

For the NPE 2009 it was required for the waveform event to be characterised by both seismic and infrasound detections. Several potential candidates have been considered and rejected since they did not meet the requirement of predicting an appropriate radionuclide measurement scenario. The event eventually selected for the exercise by the German NDC (BGR – the Federal Institute for Geosciences and Natural Resources) was a blast near Kara-Zhyra mine (77.45°E, 50.19°N) near Semipalatinsk region, Kazakhstan. The event occurred on 28 November 2009 at 07:20:31 UTC. The hypothesised release of radionculides accompanying the event resulted in 93 detections (above the assumed minimum detectable concentration of 0.1 mBq m^{-3}) in the IMS radionuclide network during the period of two weeks after the event.

RADIONUCLIDE MEASUREMENT SCENARIO FOR THE NPE 2009

A fictitious radionuclide measurement scenario created for the needs of the NPE 2009 was computed by the Austrian NDC (ZAMG - Central Institute for Meteorology and Geodynamics). The detections (Table 1) were predicted using the atmospheric dispersion model FLEXPART (Stohl *et al.*, 2005) driven by the analysed ECMWF meteorological fields. A sequence of snapshots illustrating the evolution of the shape of the modelled plume is shown in Figure 1.

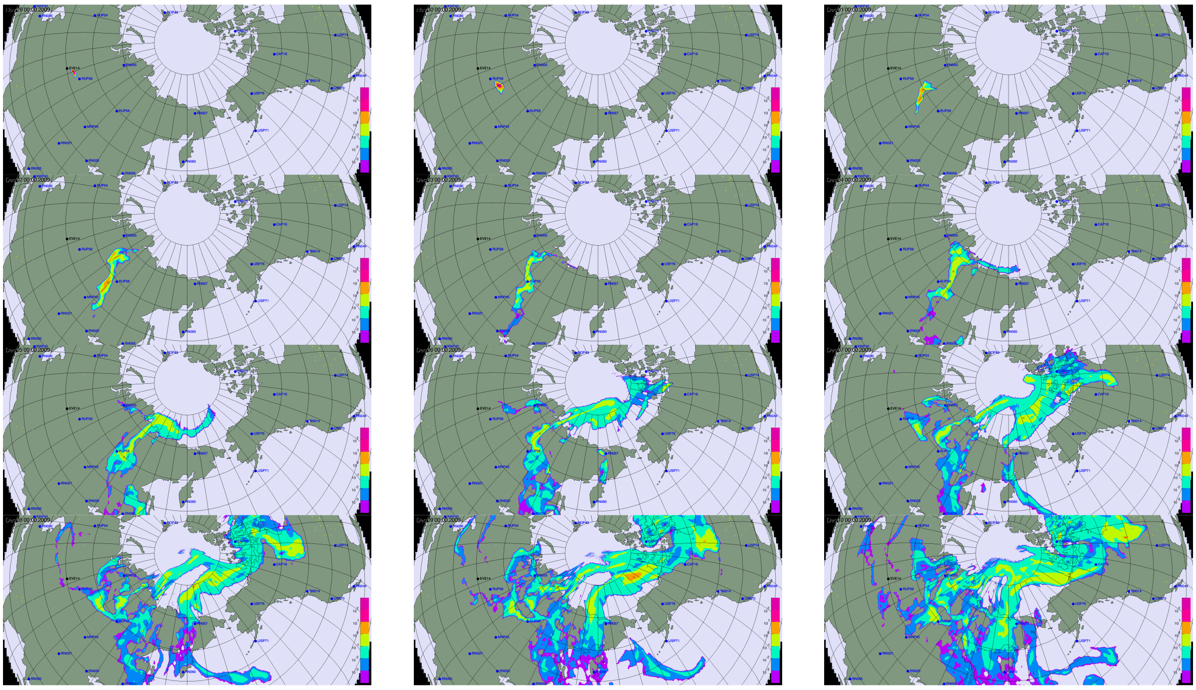

Figure 1. Snapshots of the results of a forward atmospheric transport model (courtesy of ZAMG) giving rise to the fictitious scenario of radionuclide detections presented in Table 1. The snapshots are organised row-wise and the time interval separating two successive plots is 24 hours. The first snapshot (top left-hand corner) illustrates the shape of the plume at 00 UTC on 29 November, the last one at 00 UTC on 10 December 2009 (bottom tight-hand corner).

First fictitious detection was recorded on 30 November 2009 at a radionuclide station in Zalesovo (RUP59) in the Russian Federation. The activity concentration was elevated (9530 mBq m^{-3}), an order of magnitude higher than any further detection in the scenario. The passage of the cloud was brief with no detection at this station, nor any other station of the radionuclide network for the following two consecutive days. It could be inferred from this fact that the source of radionuclides was likely to be located not far away upwind from Zalesovo. Second and third detection come respectively on 3 and 4 December 2009 in Peleduy (RUP56), also in the Russian Federation. Starting from 5 December 2009 there were multiple detections on a single day present in the radionuclide network. These measurements indicated a diluted plume of a considerable spatial spread. It should, nevertheless, be noted that such a detection scenario is also consistent with several weak sources located upwind of the detecting stations. During the days which followed, the presence of the fictitious cloud was detected not only in the Russian Federation but also in Japan and in the north of Canada. For the needs of the source attribution algorithm only the detections up to 8 December 2009 have been taken into account and only those are reported in Table 1.

Table 1. Scenario of the radionuclide measurements which result from a fictitious instantaneous release of 10^{15} Bq coinciding with the blast near Kara-Zhyra mine, Kazakhstan on 28 November 2009. Only the values above the assumed minimum detectable concentration (0.1 mBq m^{-3}) are reported. The table is organised column-wise and the columns are placed in two rows. Each column specifies a symbol of a detecting station (first record), the date of a detection (second record) and the activity concentration (third record) expressed in mBq m^{-3}.

Station	RUP59	RUP56	RUP56	RN55	RUP56	RN55	RUP56	RN57	RUP58	CAP15
Date	30 Nov	3 Dec	4 Dec	5 Dec	5 Dec	6 Dec	6 Dec	6 Dec	6 Dec	7 Dec
mBq m^{-3}	9530	31.9	146.0	0.694	61.6	9.999	61.6	4.14	0.696	8.14
Station	CAP16	JPP38	RN55	RUP56	RUP58	CAP15	RN55	RUP56	RN57	RUP58
Date	7 Dec	7 Dec	7 Dec	7 Dec	7 Dec	8 Dec	8 Dec	8 Dec	8 Dec	8 Dec
mBq m^{-3}	0.234	0.196	7.52	0.244	8.37	30.0	33.4	0.917	0.402	0.195

POSSIBLE SOURCE REGION INFERRED FROM RADIONUCLIDE DETECTIONS

For a specified source term, there are two equivalent ways of computing activity concentration at a measurement station (receptor). One is based on a forward atmospheric transport modelling when the output field of activity concentration is sampled according to the spatio-temporal location of a measurement. The other makes appeal to an adjoint solution of an atmospheric transport model. It arises from a model which is run backwards in time, is fed by the spatio-temporal characteristics of the measurement, and is driven by the wind fields whose directions have been inverted. The sensitivity field produced in this way is in turn probed with the characteristics of the source term in order to predict the value of the activity concentration.

The relationship between the source of radionuclides S (indexed by j running over all the grid-cells which potentially contain the source) and the activity concentrations c (indexed by i running over all the grid-cells containing a radionuclide measurement station) is expressed by the linear relationship of the form (Wotawa *et al.*, 2003)

$$c_i = M_{ij}S_j$$

where j is a summation index.

The two above-mentioned ways of performing the ATM computations refer to the way the matrix M in this formula is constructed. For the first option it is built column by column and for the second option row by row. The second way is by far more efficient if the number of the measurements is significantly lower than the number of the potential sources, which is the case for the CTBT verification regime. Whereas the output of an ATM operating in the forward mode is a field of activity concentration, the output computed in the backward mode is rather interpreted in terms of sensitivity. The CTBTO calculates those sensitivity fields (Source-Receptor Sensitivity (SRS) fields), also called retroplumes, for each of the radionuclide measurements on a daily basis using FLEXPART 5.1 driven by the ECMWF and NCEP meteorological fields. The SRS fields are hence, ready to use on the next day following any detection.

Attribution of a fictitious source of radionuclides during the NPE 2009

The retroplumes which are associated with the radionuclide measurements involved in the fictitious scenario, but also zero activity concentrations from the neighbouring non-detecting stations, have been used as input information for the source attribution algorithm. The algorithm runs over all possible source locations (currently the grid-cells of the size of one geographical degree) and computes the value of a correlation coefficient. The correlation coefficient is a measure of consistency between the measurements which would have arisen from the source located at a specified point and the measurements constituting the fictitious scenario. The most probable source locations are those characterized with the highest values of the correlation coefficient and are called Possible Source Regions (PSRs). The regions with the elevated values of the correlation coefficient (>0.1) constructed on the basis of the first detection in the fictitious scenario and zero measurements in the four neighbouring stations are shown in Figure 2. It is clearly visible how the region of possible source locations become broader and broader the further one looks backward in time adding uncertainty to the source attribution process.

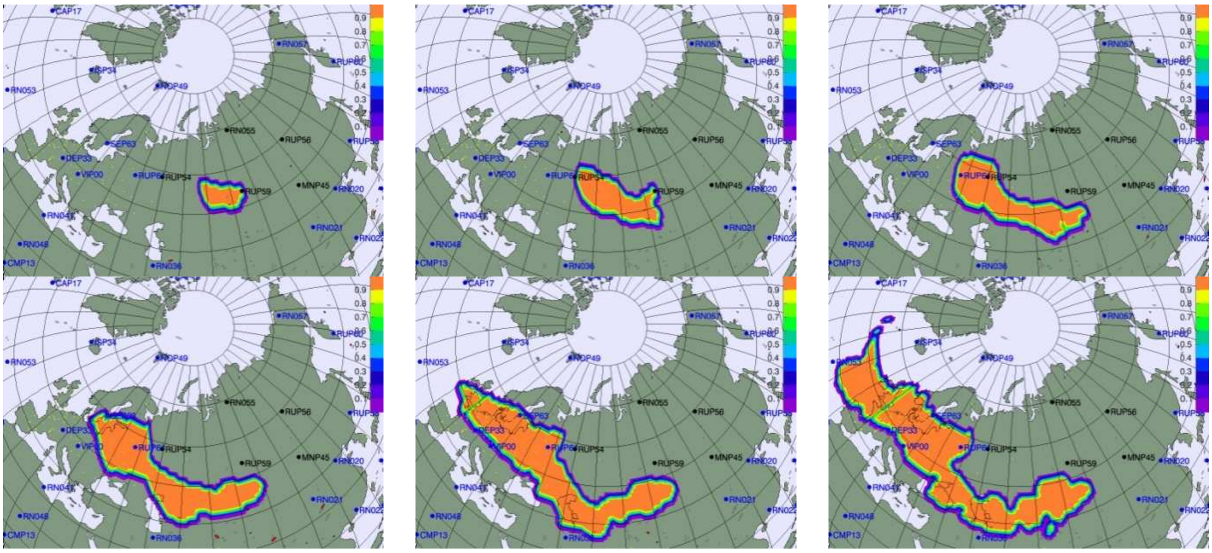

Figure 2. The regions of possible locations of a source of radionuclides (PSRs) constructed on the basis of the first fictitious detection (30 November 2010) in the considered scenario. Additionally, four neighbouring non-detecting stations are also included in the inversion algorithm. The results have been obtained with the CTBTO retroplumes. Each plot illustrates an interval of 24 hours in the period preceding the first detection - starting from 29 November (top left-hand side corner), through 28 November (second in the top row), etc., to 24 November 2009 (bottom right-hand side corner).

In parallel, for a specified time interval preceding the first detection of the fictitious scenario, Figure 3 illustrates how a PSR for a given one-day period (28 November 2009) becomes more confined as more detections (and neighbouring zero measurements) are integrated into the source attribution algorithm.

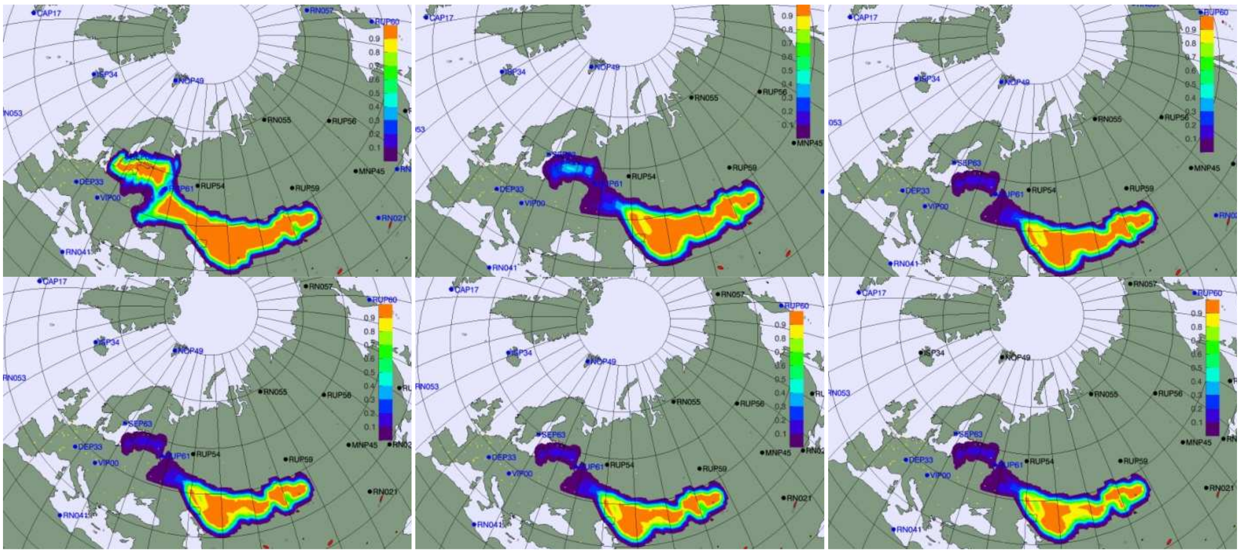

Figure 3. Evolution of the PSR for a given day (26 November 2009) preceding the first detection in the measurement scenario. The detections integrated into the inversion algorithm were made on 3, 4, 5 December (top row) and 6, 7, and 8 December 2009 (bottom row).

Data fusion

Possible Source Regions identified with the help of ATM have a considerable spatial extension (Figure 2), even for the day immediately preceding the first detection. Under the hypothesis that the detections originate necessarily from a waveform event, source attribution algorithm can benefit from the high accuracy of the location of those events. Consequently, the ATM-based source attribution is mainly used to discriminate between the waveform events which could and could not have been at the origin of production and subsequent venting of the radioactive material detected by the radionuclide IMS stations. The procedure is referred to as data fusion and it is the CTBTO's responsibility to maintain it during an NPE. In favourable circumstances, data fusion is capable of restricting the set of suspicious waveform events to one. Not only are the waveform events used to narrow down the region of interest indicated by the PSRs but also gradual confinement of the PSRs (Figure 3), as more and more measurements participate in the inversion, could eliminate some of the waveform events from the list of possible sources of radionuclides.

During the NPE 2009 there were initially (inversion algorithm using only the first detection of the scenario together with four zero measurements) 3 waveform events intersecting in space and time one of the PSRs during a period of 6 days preceding the first detection. At the end of the exercise (inversion algorithm using the detections gathered up to the ninth day of the scenario together with some zero measurements) there was only one waveform event whose location overlapped with one of the six PSRs. At this stage, the event in Kazakhstan was correctly identified as the only waveform event in the considered period to be possibly at origin of the fictitious release of radionuclides.

CTBTO-WMO RESPONSE SYSTEM

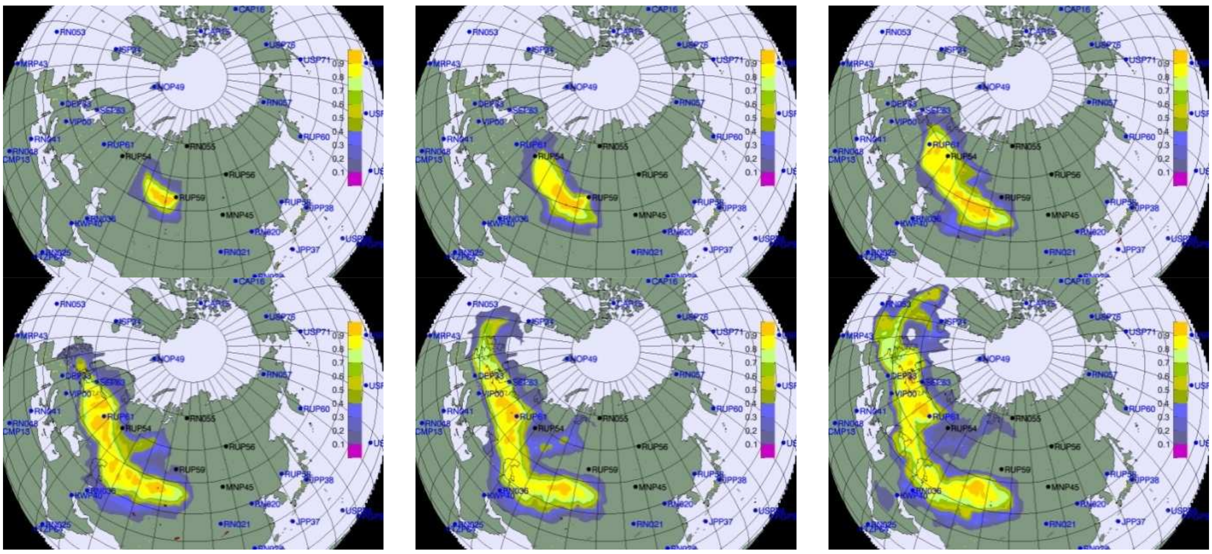

Figure 4. Similar to Figure 2. PSRs averaged over the results provided by the cooperating meteorological centres.

In the framework of cooperation with the World Meteorological Organization (WMO), the CTBTO has a possibility to trigger the requests for support in case of anomalous activity concentrations detected in the IMS radionuclide network. An NPE provides an opportunity to test this response system as each of the fictitious detections constituting the scenario is considered to be anomalous. Following a request for support, the cooperating meteorological centres provide the CTBO with the SRS fields computed using their own means, within 24 hours of a notification. The resulting ensembles of the SRS fields are checked for consistency. The ultimate PSRs (Figure 3) are computed by averaging those obtained independently for each of the cooperating meteorological centres (Becker *et al.*, 2007). Furthermore, the PSRs and data fusion results based exclusively on the supporting SRS' computations are also made available to the signatories of the treaty.

Due to a larger spatial extension of the PSRs computed on the basis of an ensemble of retroplumes (Figure 4), there might be more overlapping waveform events than in case of the PSRs inferred from single realisations of the retroplumes (see Figure 2 and 3). Indeed, for the NPE 2009, first data fusion analysis indicated as many as 15 suspected waveform events in the period of 6 days preceding the first detection. Taking into account all the fictitious detections and some zero measurements up to 8 December 2009 results in confining the spatial extension of the PSRs (Figure 5). Consequently, for the NPE 2009 the number of the relevant waveform events was reduced to two for the last one of data fusion analyses. It is worth mentioning that one of the two relevant events was the source of a fictitious release of radionuclides – the blast near Kara-Zhyra mine in Kazakhstan.

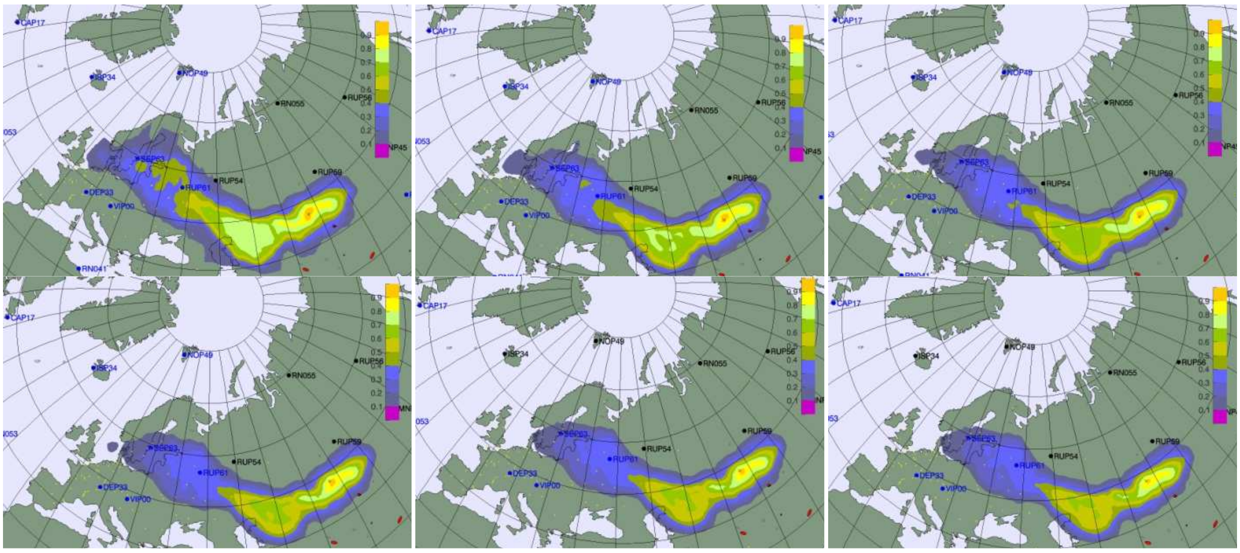

Figure 5. Similar to Figure 3. Evolution of the PSR for 26 November 2009 computed as an average of the retroplumes provided by the cooperating meteorological centres.

SUMMARY

Under the hypothesis that the detections in the IMS radionuclide network are the results of a release of radioactivity accompanying one of the detected waveform events, the accuracy of the location in space and time of the waveform events could be used to enhance inverse atmospheric dispersion modelling. As illustrated during the NPE 2009, the PSRs indicate large areas on the surface of the Earth as possible locations of a fictitious release of radionuclides. Nevertheless, they can be used to pinpoint, among all the considered waveform events, those (or the one, in an ideal case) which could have given rise to this fictitious scenario. It should, however, be borne in mind that the scenario selected for the needs of an NPE aims at ensuring testing of the performance of the source location algorithm. In case of a real event accompanied by a release of radionuclides, the number of detections might be lower than the number used in a fictitious scenario adding complexity to the problem of attribution of the source of radionuclides to one of the waveform events.

REFERENCES

Becker, A. et 17al., 2007: Global backtracking of anthropogenic radionuclides by means of receptor oriented ensemble dispersion modelling system in support of nuclear-test-ban treaty verification, *Atmos. Env.*, **41**, 4520-4534.

Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa, 2005: Technical Note: The Lagrangian particle dispersion model FLEXPART version 6.2. *Atmos.Chem.Phys.*, **5**, 2461-2474.

Wotawa, G., L.-E. De Geer, P. Denier, M. Kalinowski, H. Toivonen, R. D'Amours, F. Desiato, J.-P. Issartel, M. Langer, P. Seibert, A. Frank, C. Sloan and H. Yamazawa, 2003: Atmospheric transport modelling in support of CTBT verification – overview and basic concepts. *Atmos. Env.*, **37**, 2529-2537.