

# **The Application of Atmospheric Modeling to the Design and the Verification of the CTBT - an Historical Perspective and Current Areas of Work**

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## **1. Introduction**

The concepts surrounding a Comprehensive Test Ban Treaty can be traced back to the early 50's and are well described in Sullivan (1998). The verification regime of the Comprehensive Nuclear-Test-Ban Treaty requires the establishment of an International Monitoring System (IMS) based on four different monitoring technologies: seismic, hydroacoustic, infrasound and radionuclide. The first three technologies are based on the propagation of various waves in the Earth's mantle, oceans and atmosphere and are designed to detect and locate the site of an explosion and its magnitude. The monitoring of radionuclide is based on the atmospheric transport of radioactive material possibly released by the explosion. The propagation of infrasonic waves and the transport of radionuclides are critically dependent on the three dimensional structure of the atmosphere. This has an impact on the actual verification work and we can also take advantage of our knowledge of the atmosphere to help design a monitoring network.

The purpose of this contribution is to provide an overview of the role of meteorology in CTBT verification work. In section 2 we will briefly present approaches that have been used to support past and present IMS radionuclide network design work. In section 3, the role of atmospheric transport modeling in contributing to the determination of a source area and the concept of data fusion will be explored. Concluding remarks will be provided in section 4.

## **2. Atmospheric modeling tools and the design and performance of an IMS radionuclide network**

Various studies have been done to resolve the issues associated with the development of an appropriate configuration of a radionuclide monitoring network either in general terms or in the context of a CTBT (Rodhe and Hamrud, 1985; Pudykiewicz, 1991, 1994 and 1998; Sornatale, 1994; Mason et al., 1994; Jean et al., 1995)<sup>1</sup>. The current IMS radionuclide network represents a compromise between various elements such as detection performance, geographical locations, presence of infrastructure, operating costs and geopolitical considerations. Long range transport and dispersion models, such as NOAA ARL

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<sup>1</sup> The author acknowledges that this list is far from being exhaustive and relates to work which has been presented within verification forums or the CTBT Preparatory Commission (including Working Group B).

HYSPLIT (Draxler, 1992) or CMC's CANERM (Pudykiewicz, 1987) amongst others, have played a significant role in assessing the detection performance of proposed network configurations which led to the establishment of the current network of 80 particulates samplers and 40 radionuclides samplers.

A potential issue that the Preparatory Commission might have to deal with in the future is geographical coordinate changes for radionuclide stations. A country might want to change a Treaty location because of lack of appropriate infrastructure or for safety and security considerations (civil war for example). In this case, atmospheric transport modeling tools might be used to assess the impact of the coordinate change on network performance. Various approaches can be used, either involving forward or backward atmospheric transport modeling. In section 2.1 we will consider the use of forward in time modeling and in section 2.2 we will consider backward in time modeling.

## **2.1 Using forward in time atmospheric transport modeling tools using an Eulerian approach**

To demonstrate the concept, we chose one of the long-range transport and dispersion simulations used by Canada during the network design work, namely the Spring 1993 simulations (Jean et al., 1995). This case corresponds to the fire at the Tomsik radiochemical facility in April 1993. The numerical simulation goes forward in time for 240 hours after the accident. The radionuclide stations which were hit by the modeled plume were moved by +/- 1 degree latitude (1 degree latitude is approximately 100 km at 60N) and +/- 1 degree longitude (the distance from the initial position will vary with latitude) for each of the stations.

The results for this case show that:

1. Non-zero values are recorded at 27 stations over a 240-hour period;
2. Using a measurement threshold of 1 :Bq we observe that
  - 14 stations experience concentration values always below measurement threshold
  - 11 stations experience concentration values always above measurement threshold (see Figure 1 for Beijing as a typical example)
  - 2 stations experience concentration values above measurement threshold when moved;
3. At stations where no detection occurred (when the station is located at initial Treaty position), no detection occurred at the modified positions; that is when only 'zeros' are detected, you still detect 'zeros' in the vicinity of the station;
4. At stations where detection occurred (when the station is located at the initial Treaty position), detection still occurred at the modified positions - timing or amplitude of the signal could change, but detection (that is non zero values) would still happen.

This preliminary analysis has a few shortfalls, one being that it is based on only one case. On the other hand, the fundamental nature of the problem and the inherent tendency of the atmosphere to well mix constituents are arguments supporting our preliminary assessment, which is that from a practical point of

view the performance of the IMS radionuclide monitoring network would not be significantly altered when stations are moved within a few degrees latitude/longitude in the context of large scale transport and dispersion of tracers. More work is needed to assess these results for problems which are more regional in nature, such as the venting and subsequent transport and dispersion of noble gases in the atmosphere.

## **2.2 Using backward in time atmospheric transport modeling tools using Lagrangian methods**

Another approach would be to use a simple three dimensional backward trajectories of a non-reactive tracer (D'Amours et al., 1995) or a more sophisticated backward stochastic Lagrangian model (Flesch et al., 2000) to compare climatological airshed; that is we want to compare the climatological origins of the air being sampled at a given site with those of an alternate site. As an example, we look at the issue of moving one station located in North Africa in the eventuality that a country would not accept to host an IMS monitoring station<sup>2</sup>. One such example is the Misratah radionuclide monitoring site located on the coast of Libya (32.5N, 15.0E). Based on this approach, one of the criteria to be met by the substitute site is that it should be sampling air from comparable domains of origin. Three alternate sites were considered (Figure 2): El Golea (Algeria, 30.58N and 2.87W), El Kahzra (Egypt, 25.2N and 30.2E) and a site named 'Tunisia 1' located at the boundary of Tunisia, Libya and Algeria (30.51N and 9.27E).

We first examined the use of simple three dimensional backward trajectories of a non reactive tracer to determine climatological airshed, or possible source regions which could be sampled by the detector. For this simple experiment we ran backward trajectories for 5 days starting at the 4 sites, Misratah and the 3 alternate sites. The backward trajectories have been computed 4 times a day (at 0, 6, 12 and 18 UTC) for the months of January, April, July and October 1998. The results indicate a relative level of homogeneity between the stations El Golea, Tunisia 1 and Misratah. El Kahzra, being quite distant from the other stations, is generally sampling air coming from a different domain. This behavior is shown in Figure 3.

Finally we examined preliminary results using a more sophisticated approach based on the use of zeroth order backward stochastic Lagrangian model. To achieve this, backward simulations of a stochastic Lagrangian model starting at the monitoring sites have been performed. Backward integrations were done for specific 5-day periods for the months of January, April, July and October for 30 years using NCEP re-analyzed meteorological fields. This provides an approximation of the climatology of the domain being sampled by the various monitoring stations (Figures 4 to 7).

These preliminary results seem to indicate that the El Kahzra locations is sampling air from a different domain. This is not to say that the site is not good, it only states the fact that it will impact on the level of

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<sup>2</sup> It is important to note that we are looking at the technical aspects of the issue, the political undertakings and implications of such a decision being left to the appropriate decision-making forums.

performance of the existing network, while the other two alternate sites won't. More work would be required to assess if the change in network performance would be negative or positive.

### **3. Atmospheric modeling tools and their contribution to real-time verification work**

The use of atmospheric modeling tools for the detection of possible source area dates back to the times when USSR began atmospheric testing. Following a positive detection from an airborne sampler, hand-derived backtrajectories were used to help locate the source area. In the context of CTBT verification involving the radionuclide monitoring network, three scenarios can be envisaged:

1. Supposing that an anomalous event is detected by either the seismic, hydroacoustic or infrasound networks, which radionuclide stations are the most likely candidates for detection?
2. Supposing suspicious radionuclides are detected at one or more IMS radionuclide stations, how can the source location be determined if it cannot be associated with any event detected by the other IMS sensors?
3. By what objective process can a radionuclide event be associated with one of many other (particularly seismic) events that may have occurred several days earlier?

These scenarios and various concepts of operations have been tested through various case studies using nuclear events (Chernobyl, Toms, Algeciras, Tokaimura) or large-scale field experiments such as the European Tracer Experiment (ETEX; Van Dop et al., 1998 and Nodop et al., 1998) and have been discussed at the Montréal informal workshop (1996)<sup>3</sup> and the Paris informal workshop (1998)<sup>4</sup>. The different scenarios involve forward and/or backward atmospheric transport modeling. A proposed concept of operation has been described in Jean (1999a). Preliminary testing of the concepts of operation for the three scenarios have been done between World Meteorological Organization Regional Specialized Meteorological Centres (WMO RSMCs for the provision of real-time atmospheric transport and dispersion modeling products during nuclear emergencies) and the CTBTO International Data Centre (IDC) and results have been presented in Jean (1999b) and Kalinowski et al. (2000).

#### **3.1 The use of forward in time atmospheric transport modeling tools**

A typical event would be the detection of characteristic signals associated with a nuclear explosion either through the seismic, hydroacoustic or infrasound signals monitored by the IMS network. Forward in time simulations using simple trajectory models or complex transport and dispersion models can be run using different emission scenarios to determine which of the IMS radionuclide stations are likely to detect

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<sup>3</sup> Informal Meeting to Discuss the Application of Atmospheric Modelling to CTBT Verification - Group Report and Proceedings (Montréal, Canada, 15-16 October 1996). Non-Proliferation, Arms Control and Disarmament Division (Department of Foreign Affairs and International Trade), and Canadian Meteorological Centre (Environment Canada). Montréal, January 1997, 280 pp.

<sup>4</sup> Proceedings of the Informal Workshop on Radionuclides (Paris, France, 28 September to 2 October 1998), Département d'Analyse et de Surveillance de l'Environnement (Commissariat à l'Énergie Atomique).

possible released material and when. Under this scenario, the nuclear test would be detected and the geolocation be performed through a combination of the information acquired through the wave technologies. Detection of radionuclides of interest would help characterize the nuclear test and atmospheric modeling would provide the verification mechanism to link all the pieces of the puzzle together.

This scenario has been tested, on a few hypothetical cases and is not fundamentally different from regular emergency response simulations of the atmospheric transport and dispersion of pollutants. A detailed description of an hypothetical case and an in-depth analysis is provided in Kalinowsky et al. (2000). Figure 8 displays a simple trajectory model output simulating the 3-D advection of a non-reactive parcel of air . Figure 9 shows a simulation for the same hypothetical event using a sophisticated Eulerian atmospheric long range transport and dispersion model, the Canadian Emergency Response Model in this case.

### **3.2 The use of backward in time atmospheric transport and dispersion modeling tools**

A number of applications can be thought of for this new generation of modeling tools. In CTBT context, there might be cases for which radionuclides of interest are being measured without any prior warnings from the other three IMS networks. Figure 10 shows an example of a backtrajectory model output for a hypothetical detection of radionuclides of interest in Stockholm (Sweden) at a specific time. This can provide general information on the origin of the air mass being sampled at a specific radionuclide monitoring station. It is interesting to note that depending on the height at which the backward calculations are initialized, the origin of the air mass can be significantly different. It should be clear that in the context of verification, this simple tool cannot provide accurate geolocation unless other informations are used.

More sophisticated approaches can be used to better assess the potential origin of an air mass being sampled at monitoring sites. One approach involves inverse methods based on the adjoint of an Eulerian transport and dispersion model (see the paper by Idelkadi, Hourdin and Issartel; also Pudykiewicz, 1998). Another approach involves inverse methods based on the use of Stochastic Lagrangian Particle Dispersion model (see the paper by Seibert; also Wilson and Sawford, 1996). Outputs from a simple backward Stochastic Lagrangian Particle Dispersion model are shown in Figure 11. A hypothetical detection of radionuclides of interest on 3 May 2000 12 UTC is assumed in Stockholm. The integrations have been carried backward in time until 30 April 00 UTC. For this simulation, 60 000 particles have been emitted during the 24 hour period extending from 4 May 00 UTC to 3 May 00 UTC. The release of particles takes place in the layer extending from the ground to a height of 2 kilometers. The upper picture shows the position of the particles at 00 UTC 30 April. The heights of the particles are indicated by a color code, blue being close to the surface and dark red being above 4000 meters. The lower picture shows the surface field of regards for the same time. The various areas correspond to the probability that a particle

arriving at the detection site (Stockholm in this case) would originate from those regions. The values for the field of regard at a given point are proportional to the concentration of particles within the layer extending from the surface to a height of 500 meters.

In the eventuality that a nuclear test is conducted in a fully decoupled way, venting of radioxenons into the atmosphere might be the only way to identify a Treaty violator. In this context, Phase II of the xenon sampler inter-comparison experiment conducted at the Institute for Atmospheric Radioactivity (Freiburg, Germany) provided an opportunity to apply real-time atmospheric transport and dispersion modeling with radioxenon measurements. In this case, the problem involves a high degree of complexity since there are numerous anthropogenic sources of radioxenons associated with the operation of nuclear power plant throughout Europe. Figure 12 shows a field of regard associated with one of the radioxenon peak detected in Freiburg. Work is currently underway to further develop concepts around the use of backward atmospheric transport and dispersion modeling for verification purposes using the data collected during the Freiburg experiment.

#### **4. Concluding remarks**

Meteorological modeling has accomplished considerable and remarkable progress during the past fifty years. Meteorological modeling tools are increasingly used in air pollution source-receptor studies. In this context, the use of this new generation of modeling tools provides supplementary benefits to the verification community. It should be understood that the uncertainties associated with the chaotic nature of atmospheric processes impose natural limitations to the estimation of source locations. On the other hand, the development of new data assimilation techniques, continuous both in space and in time, is expected to reduce significantly those uncertainties. In this context, the development of objective approaches to fuse the data from all the CTBT technologies with meteorological modeling becomes essential.

The emphasis of this paper has been on the use of meteorological modeling in support to the radionuclide technology. It is important to note that meteorological modeling will become increasingly important to the infrasound technology. A detailed knowledge of the current and predicted structure of the atmosphere was not critical in infrasound propagation models when events involved weapon yields in the 100-1000 kilotons range. For smaller events in the 1 kiloton range, this will be a different matter and high resolution meteorological datasets (both in diagnostic and prognostic mode) should be taken into account by scientists involved in infrasound propagation modeling.

## 5. References

- D'Amours, R., M. Jean, J.P. Toviessi and S. Trudel, 1995: Atmospheric Transport models for environmental emergencies. Internal report, Atmospheric Environment Service, Environment Canada, 4 pp.
- Draxler, R., 1992: Hybrid Single-Particle Lagrangian Integrated Trajectories (HYSPLIT) Version 3 - User's Guide and Model Description. NOAA Tech Memo, ERL ARL-195, June 1992.
- Flesch, T., R. D'Amours and J. Wilson, 2000: A long range Lagrangian stochastic dispersion model - Model details and validation. Internal report, Meteorological Service of Canada, Environment Canada, 51 pp.
- Jean, M., R. D'Amours, R. Servranckx, P. Button, and B. Tracy, 1995: Evaluation of the performance of a 71 stations global radionuclide monitoring network. Internal report, Canadian Meteorological Centre, 45 pp (incl. Figures).
- Jean, M., 1999a: Atmospheric Transport Model Data, Products and Expertise: A Look Towards Future Comprehensive Test Ban Treaty Organization – World Meteorological Organization Collaboration., Preparatory Commission internal document (limited distribution), CTBT/WGB-8/CA/1, Vienna, 10 pp.
- Jean, M., 1999b: Report on an informal test between the prototype IDC and WMO Regional Specialized Meteorological Centres, March 15 and 18 1999. Preparatory Commission internal document (limited distribution), CTBT/WGB-9/TL-2/25, Vienna, 6 pp plus Appendices.
- Kalinowski, M.B., L.E. DeGeer, and M. Jean, 2000: Informal test between the International Data Centre and WMO Regional Specialized Meteorological Centers conducted on 3 and 4 May 2000. CTBTO Technical Report PTS/IDC-2000/01, Vienna, 78 pp.
- Mason, R.L., 1995: Comprehensive design analysis for an international radionuclide monitoring system. Final report, Pacific-Sierra Research Corporation, 96 pp.
- Nodop, K., R. Connolly and F. Girardi, 1998: The field campaigns of the European tracer experiment (ETEX) - Overview and results. *Atmospheric Environment*, 32, 24, 4095-4108.
- Pudykiewicz, J., 1991: Environmental prediction systems - Design, implementation aspects and operational experience with application to accidental releases. In 'Air Pollution Modeling and its Applications VIII', H. Van Dop editor, Plenum Press, New York, 789 pp.
- Pudykiewicz, J., 1994: Evaluation of performance of radionuclide monitoring network. Internal report, Atmospheric Environment Service, Environment Canada, 22 pp.
- Pudykiewicz, J., 1998: Application of adjoint tracer transport equations for evaluating source parameters. *Atmospheric Environment*, 32, 17, 3039-3050.
- Rodhe, H., and M. Hamrud, 1985: The design of a global detection system for airborne radioactivity. Report No. CM-68, ISSN 02080-445X, Stockholm University.
- Sornatale, F., 1994: CTBT network density project. In 'CTBT Monitoring Technologies Conference Proceedings', San Diego.
- Van Dop, H., R. Addis, G. Fraser, F. Girardi, G. Graziani, Y. Inoue, N. Kelly, W. Klug, A. Kulmala, K. Nodop and J. Pretel, 1998: ETEX A European tracer experiment; Observations, dispersion modelling and

emergency response. *Atmospheric Environment*, 32, 24, 4089-4094.

Wilson, J.D., and B. L. Sawford, 1996: Lagrangian stochastic models for trajectories in the turbulent atmosphere. *Boundary Layer Meteorol.*, 78, 191-210.

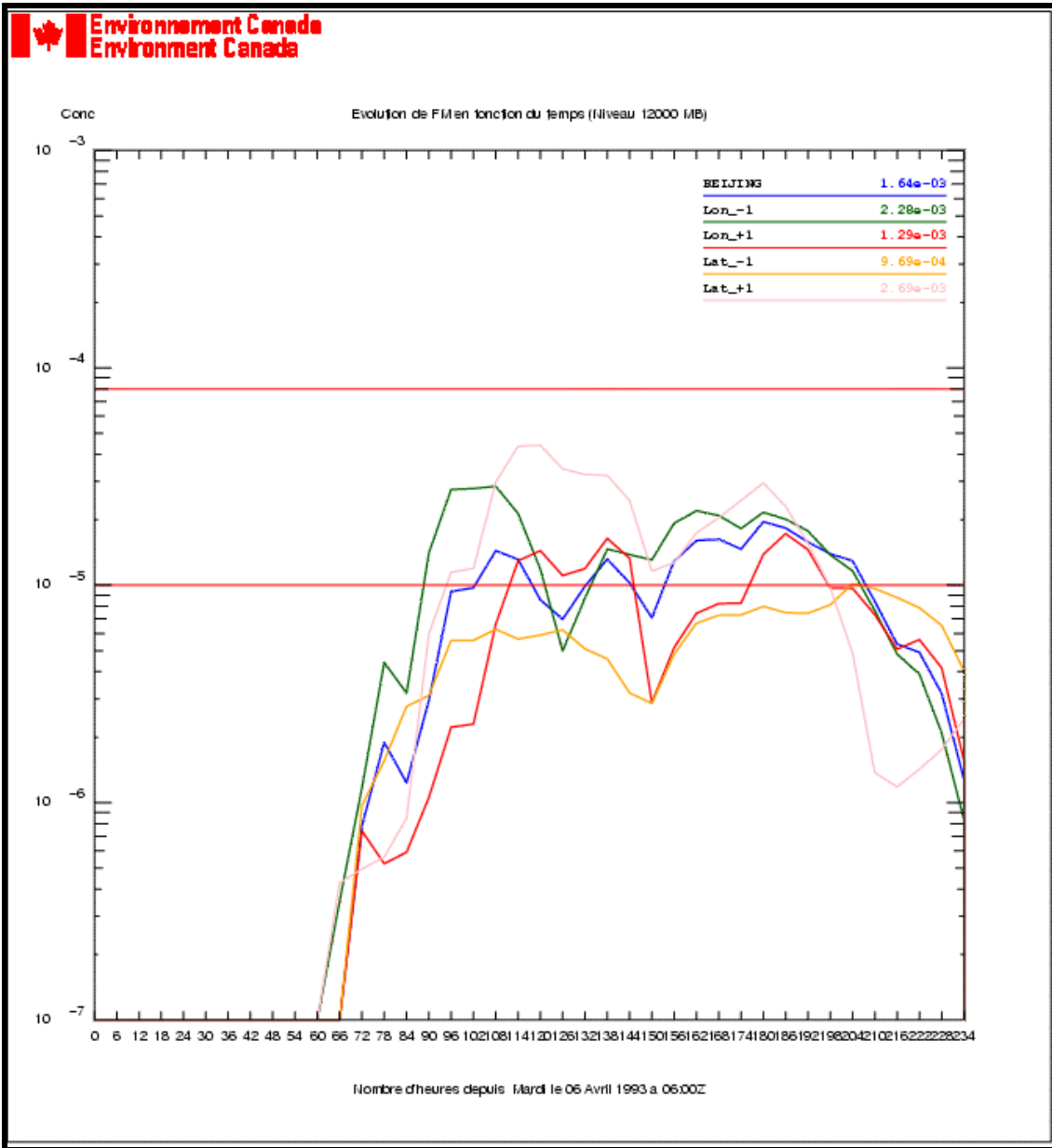


Figure 1. Time series of 0-500 meters modeled concentration for Beijing (PRC) following the release at the Tomsk radiochemical facility in April 1993. The blue curve corresponds to the Treaty location; the other curves correspond to modification to the Treaty location by +/- one degree latitude/longitude.

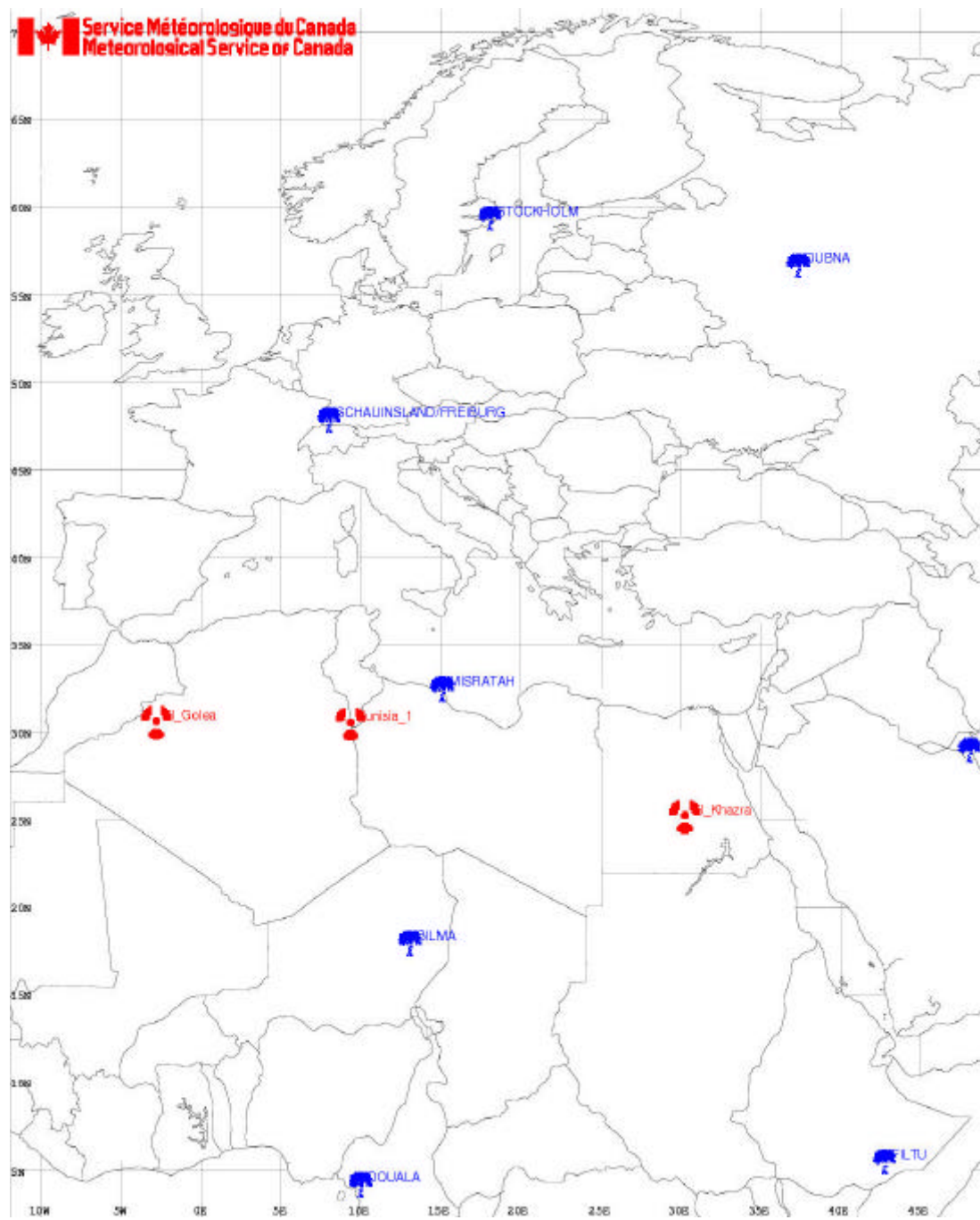


Figure 2. Location of the simulations done for the displacement of an IMS radionuclide station in North Africa

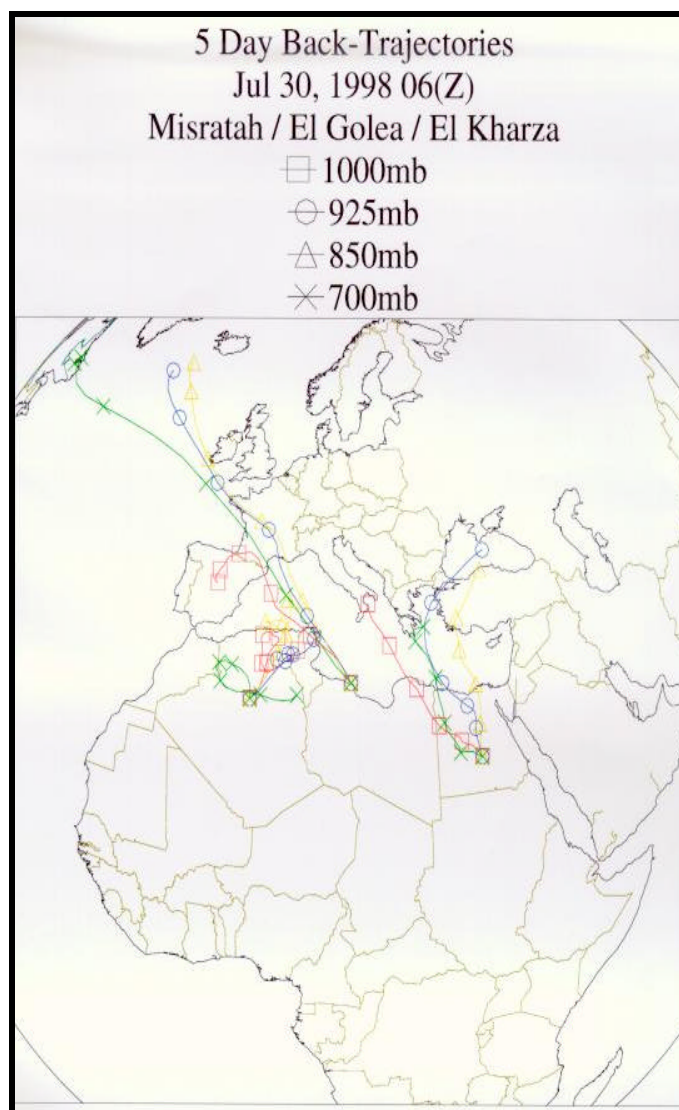
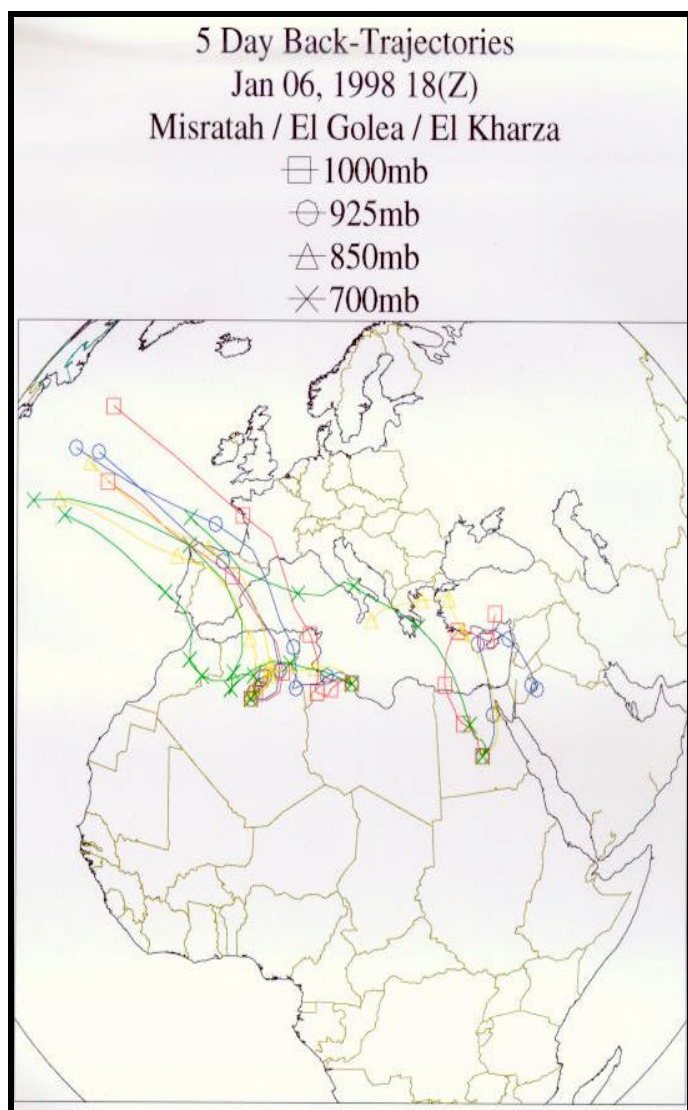


Figure 3. Five days backtrajectories for stations located at Misratah, El Golea and El Khazra starting at 18 UTC 6 January 1998 (upper pannel) and starting at 06 UTC 30 July 1998 (lower pannel). Similar calculations were performed 4 times a day for the months of January, April, July and October 1998. The results, shown here for two individual cases, are representative of the average situation which indicates that the stations at El Golea and Misratah are sampling air from comparable geographic domains while El Khazra, located further to the southeast, is sampling air originating from a different domain.

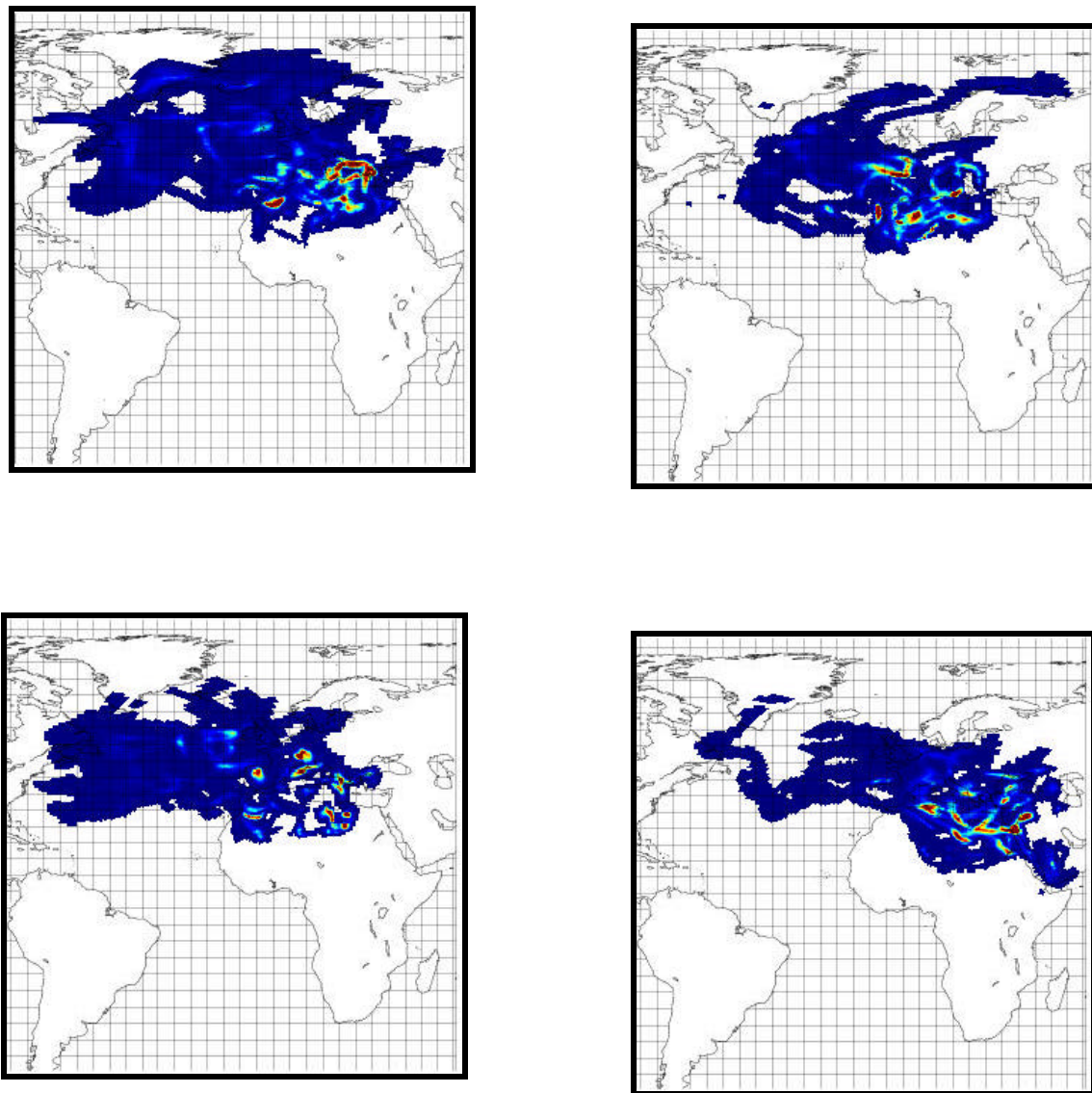


**Figure 4.** Climatological domain for air sampled at Misratah (upper left), El Golea (upper right), Tunisia1 (lower left) and El Kahzra ((lower right) for a period of 7 days in January for 30 years. For each backward simulations 43200 particles were released over a 24-hour period. The field depicted corresponds to the relative density of particles in the layer 0-500 meters above the surface of the Earth.

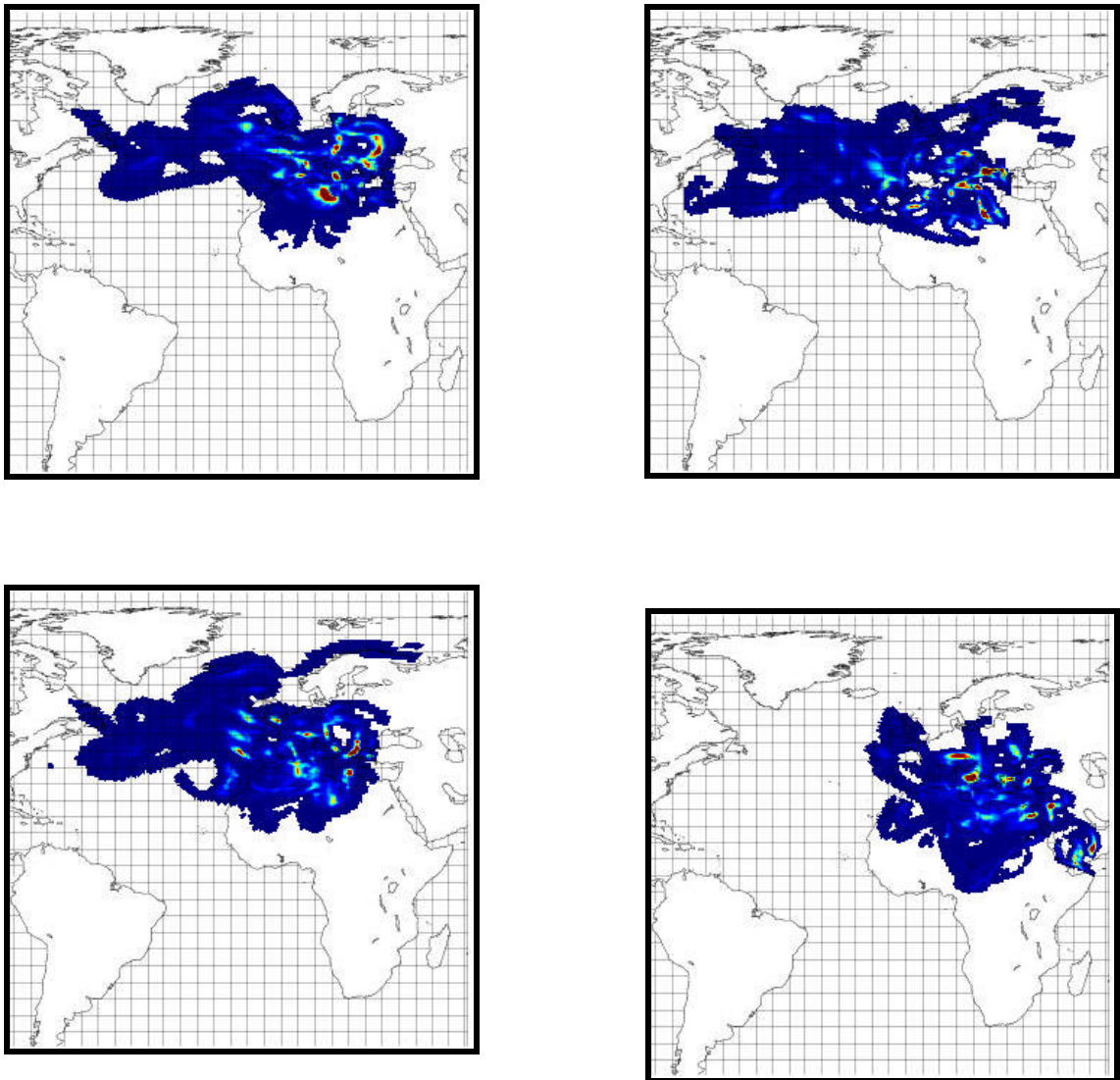


**Figure 5.** Climatological domain for air sampled at Misratah (upper left), El Golea (upper right), Tunisia1 (lower left) and El Kahzra ((lower right) for a period of 7 days in April for 30 years. For each backward simulations 43200 particles were released over a 24-hour period. The field depicted corresponds to the relative density of particles in the layer 0-500 meters above the surface of the Earth.

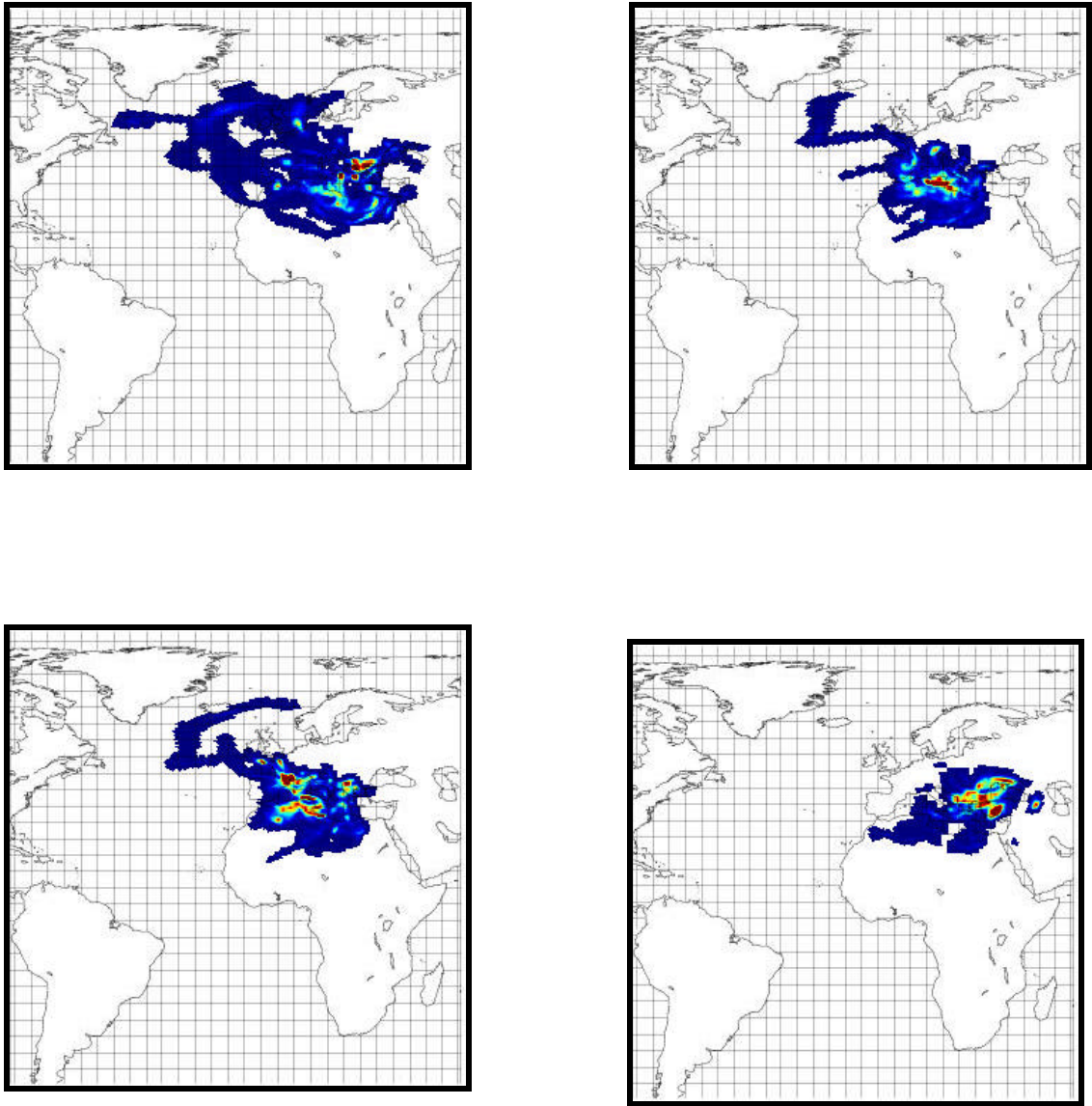


**Figure 6.** Climatological domain for air sampled at Misratah (upper left), El Golea (upper right), Tunisia1 (lower left) and El Kahzra ((lower right) for a period of 7 days in July for 30 years. For each backward simulations 43200 particles were released over a 24-hour period. The field depicted corresponds to the relative density of particles in the layer 0-500 meters above the surface of the Earth.

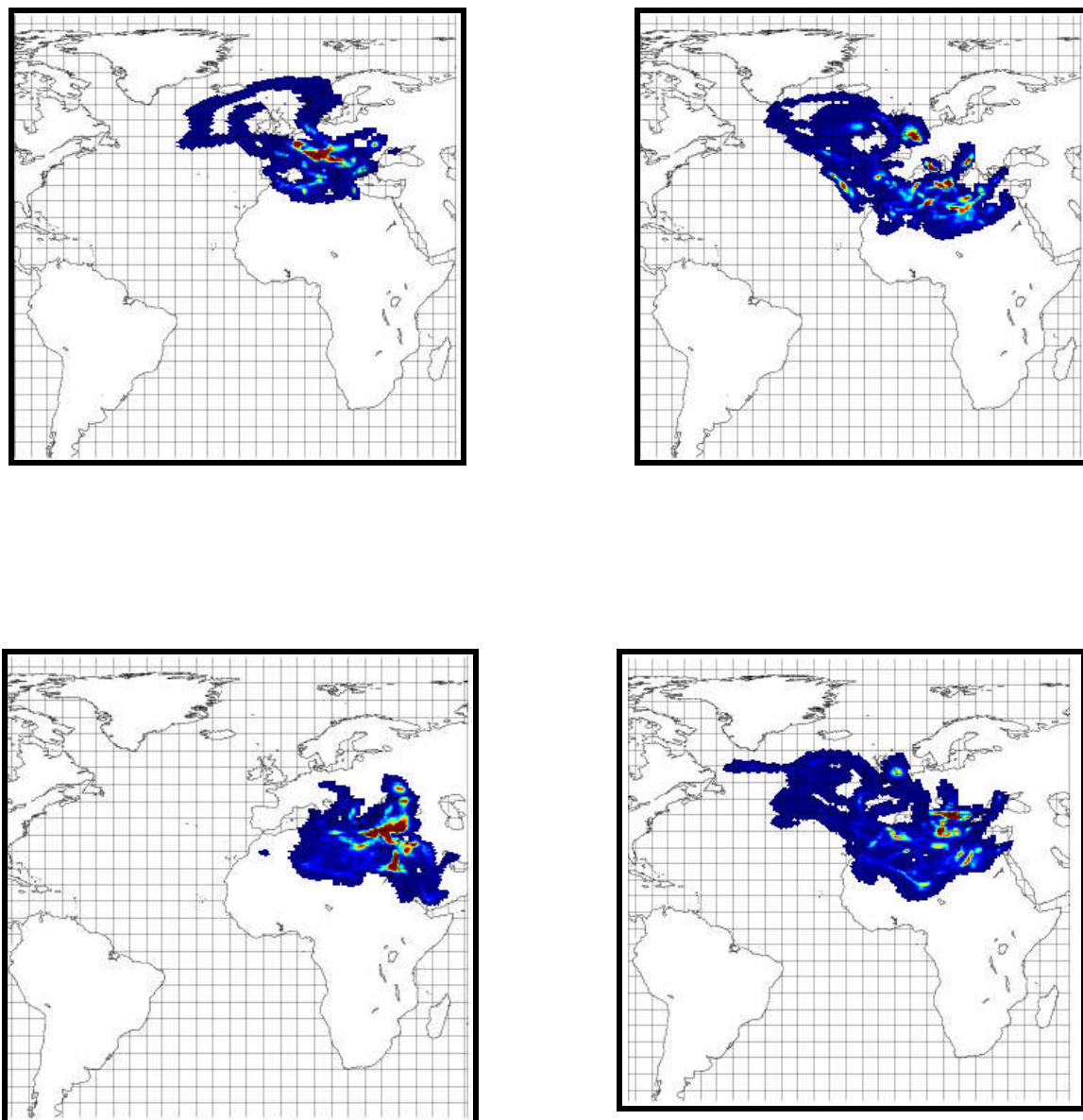


**Figure 7.** Climatological domain for air sampled at Misratah (upper left), El Golea (upper right), Tunisia1 (lower left; missing) and El Kahzra ((lower right) for a period of 7 days in October for 30 years. For each backward simulations 43200 particles were released over a 24-hour period. The field depicted corresponds to the relative density of particles in the layer 0-500 meters above the surface of the Earth.

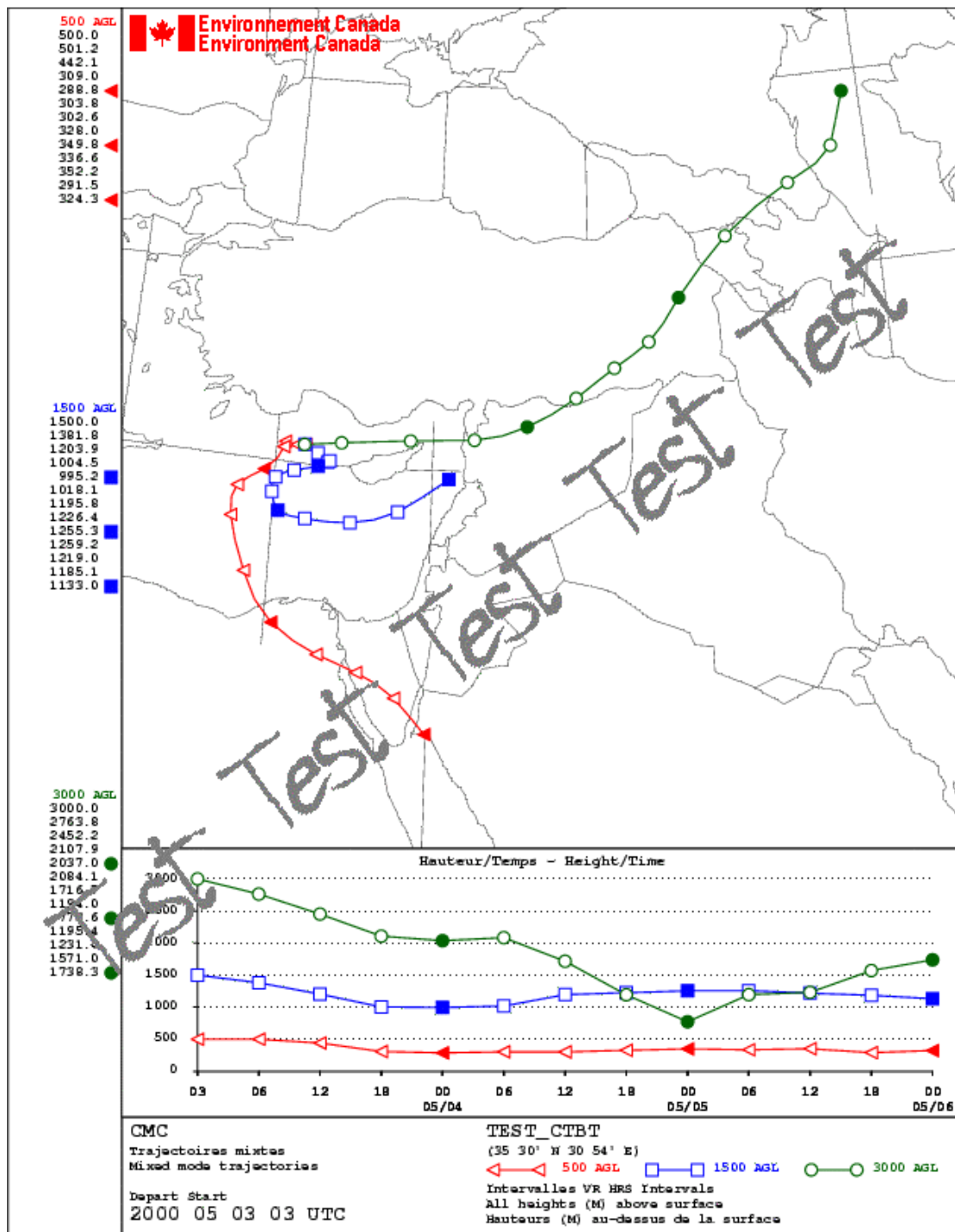


**Figure 8.** Trajectory model output for a hypothetical event in the eastern Mediterranean sea. Non-reactive parcel of air are followed in prognostic mode from the hypothetical site. Three parcels of air are followed from an initial height of 500, 1500 and 3000 meters respectively.

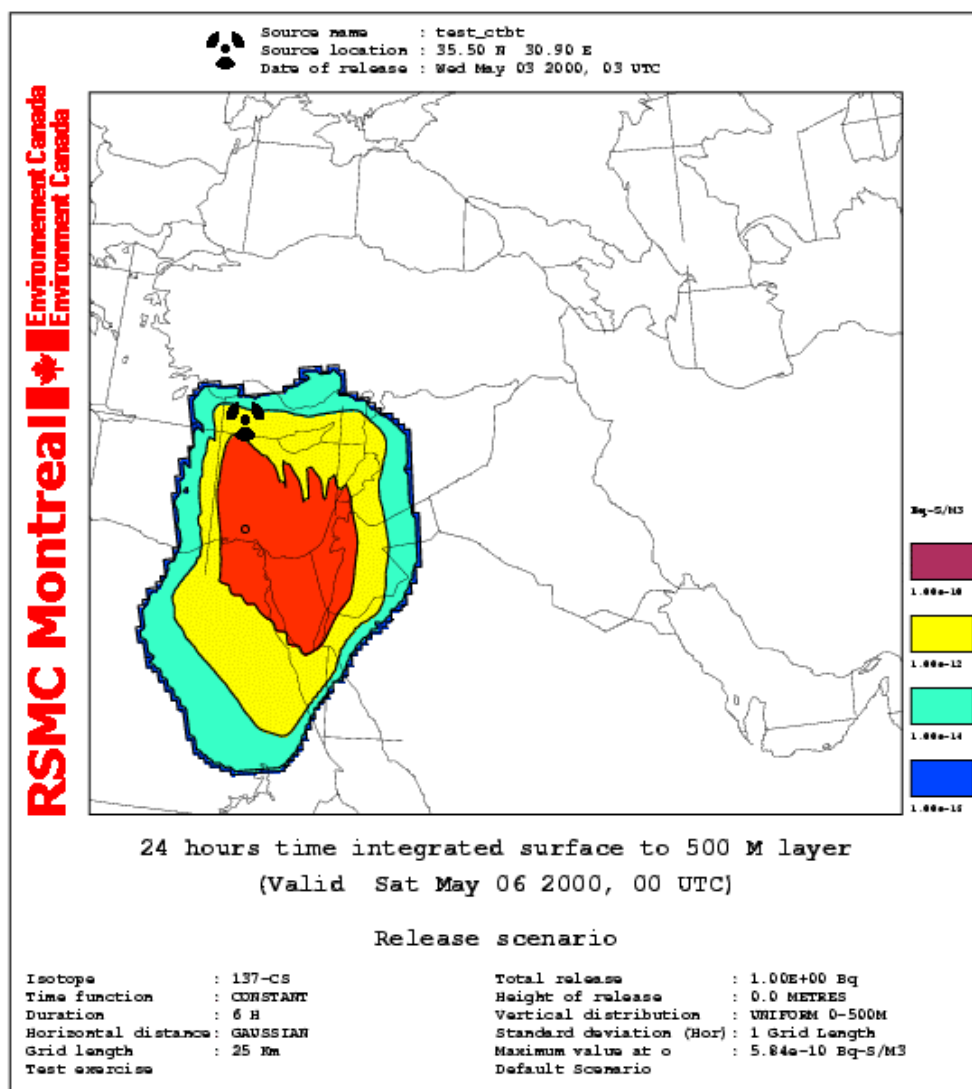


**Figure 9.** Long range atmospheric transport and dispersion model output from the Montréal Regional Specialized Meteorological Centre for the same hypothetical event as depicted in Figure 8. Isopleths of 24-hour integrated concentration valid for the period 48-72 hours after detection of the event. Units are in Bq/m<sup>3</sup>.

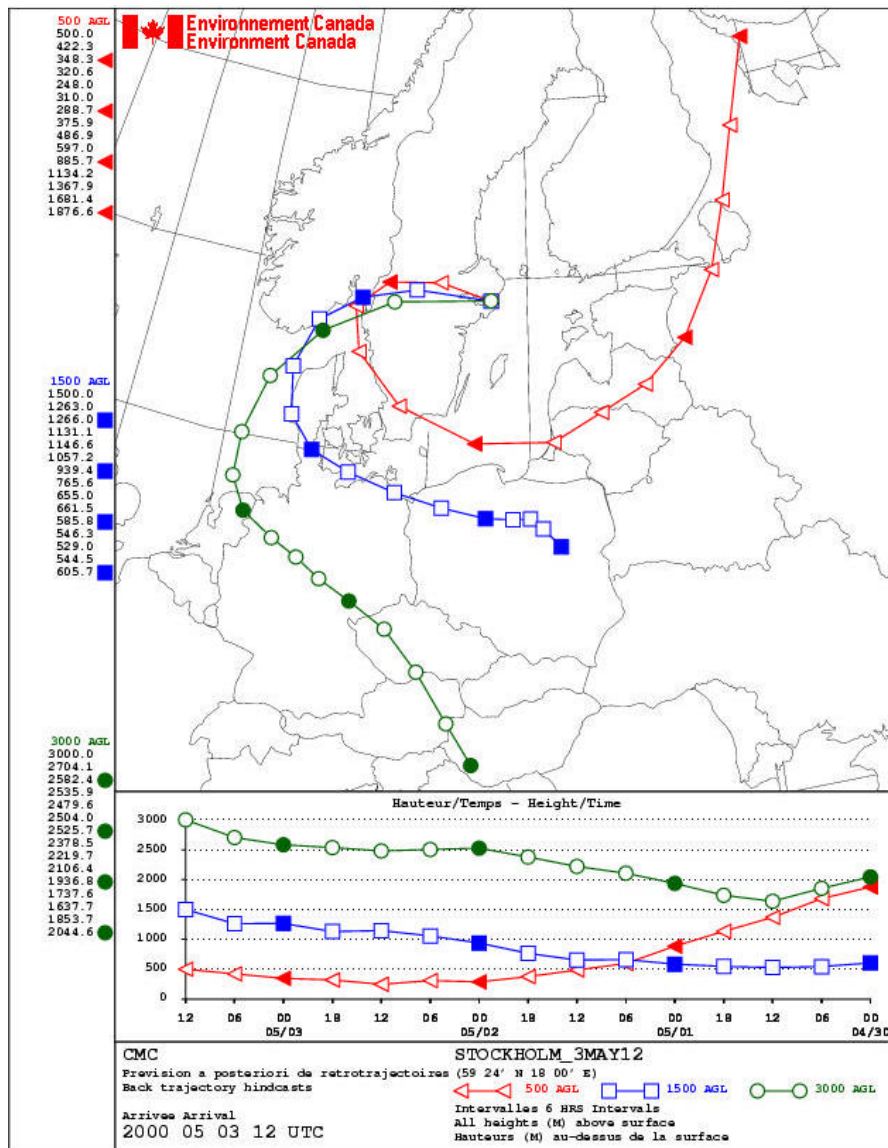


**Figure 10.** Backtrajectory model output (backward in time trajectories) for an hypothetical detection of radionuclides of interest in Stockholm on 3 May 2000. We are following non-reactive parcel of air backward in time until 30 April .

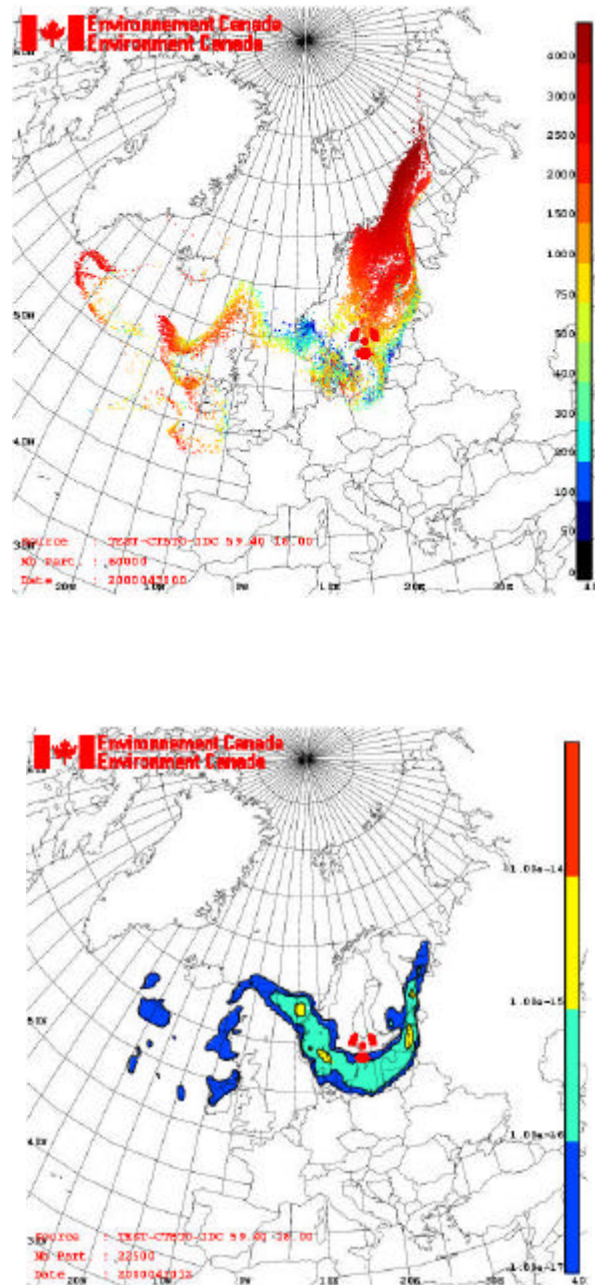


**Figure 11.** Outputs from a simple backward Stochastic Lagrangian Particle Dispersion model. A hypothetical detection on 3 May 2000 12 UTC is assumed in Stockholm. The integration have been carried backward in time until 30 April 00 UTC. For this simulation, 60 000 particles have been emitted during the 24 hour period extending from 4 May 00 UTC to 3 May 00 UTC. The release of particle takes place in the layer extending from the ground to a height of 2 kilometers. The upper picture shows the position of the particles at 00 UTC 30 April. The height of the particles are indicated by a color code, blue being close to the surface and dark red being above 4000 meters. The lower picture shows the surface field of regards for the same time. The various areas correspond to the probability that a particle arriving at the detection site (Stockholm in this case) would originate from those regions. The values for the field of regard at a given point are proportional to the concentration of particles within the layer extending from the surface to a height of 500 meters.

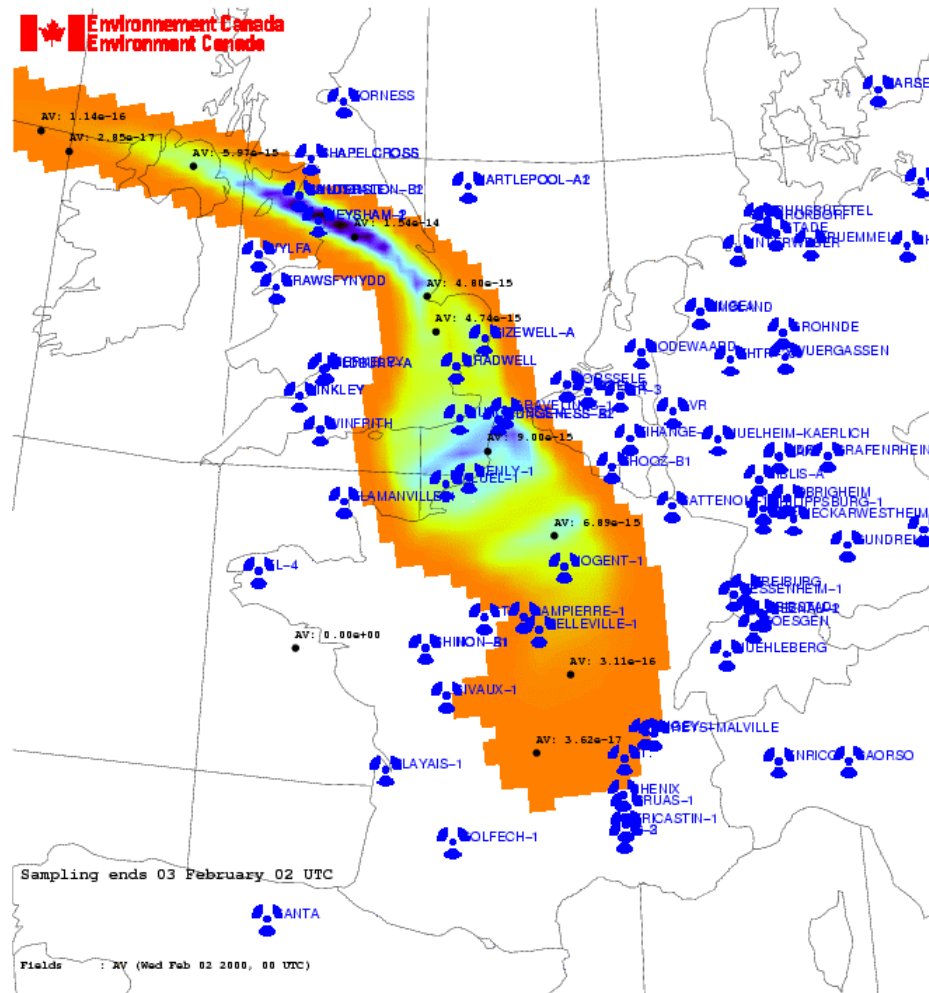


**Figure 12** Outputs from a simple backward Stochastic Lagrangian Particle Dispersion model for the radioxenon peak measured in Freiburg, Germany, on 2-3 February 18-02 UTC. The integration have been carried backward in time until 2 February 10 UTC. For this simulation, 60 000 particles have been emitted during the 8 hour period extending from 3 February 02 UTC to 2 February 18 UTC. The release of particle takes place in the layer extending from the ground to a height of 2 kilometers. The interpretation of the plot is similar to the one described in the lower picture of Figure 11. Commercial nuclear power reactors are depicted in blue.