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RESEARCH ARTICLE

Simulation of nuclear accident caesium-137 contamination Using FLEXPART model

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Abstract

This paper analyzes Chernobyl accident caesium-137 (^{137}Cs) contamination over the European region. The simulation was performed to identify the long-range dispersion transport of ^{137}Cs contamination patterns and its motions. The transport of ^{137}Cs over Europe is simulated by using the FLEXPART Lagrangian particle dispersion model coupled with the Mesoscale Model, MM5 for the first two weeks after the beginning of the release. The accident scenario employed in the simulation was estimated using published data from the Atmospheric Transport Model Evaluation Study (ATMES). The results and the performance of the model simulation are discussed and evaluated by comparison with observations over twelve European locations. The results demonstrated that the FLEXPART model coupled with MM5 is able to predict the ^{137}Cs plume integral advection from the Chernobyl accident and indicate a relatively high level of agreement with observations. Also the analysis of the weather patterns and using trajectory analyses give another significant demonstration for the model capability and its accurate results. .

Introduction

The hazardous impacts due to a nuclear accident were unimaginable until the Chernobyl accident occurred in 1986. The accident at Chernobyl Nuclear Power Plant showed transparently a large quantity of radioactive materials were released and can spread widely across the world resulting in contaminated vast geographical areas, a huge damage and long-term effect on the environment (Tschiersch and Georgi 1987; IAEA 1991; Balonov, 2007; Pollanen et al., 1997; Saenko et al., 2011; Pöllanen et al. 1999). From the experience gained in European countries after the Chernobyl accident, most countries in Europe developed national nuclear dispersion or accidental release models linked to weather prediction models of varying types and resolutions for early warning and monitoring of radioactivity in the environment (Galmarini et al., 2008). Therefore, essential advances have been added to development of the dispersion models and the software that are able to simulate the transport and transformation of radioactive or toxic materials in the atmosphere.

Dispersion models play an important role as fundamental technical support for decision makers at all level to protect human health and the environment. In this context, several papers have been published concerning the Chernobyl radioactive cloud simulation (ApSimon and Wilson, 1987; de Leeuw et al., 1987; lange et al. 1988; Albergel et al., 1988; Pudykievicz, 1988). The simulation outputs were generally presented in terms of calculated radioactive cloud patters and evaluation by comparison between observed and calculated radionuclides concentration over a limited number of locations and times.

For the purpose of review and development of atmospheric dispersion models, twenty-one participants in ATMES were provided with sets of released data and meteorological data and computed caesium-137 and ioden-131 air concentrations. In order to identify the approaches which would be the more successful for the simulation of long-range radionuclides transport, the ATMES evaluation was based on a large number of measured data stored into the Radioactivity Environmental Monitoring (REM) data bank, using several statistical methods (Girardi et al. 1987; Klug et al. 1991).

Another evaluation for the performance of a number of dispersion models has been done against the European Tracer Experiments (ETEX) impetus for the development of accidental release models and several intercomparisons between different model types have been made (Galmarini et al., 2001; Van Dop et al., 1998; Wendum, 1998). From second ETEX experiment it was clear that issues still remain about the appropriate strategies for predicting the impacts of an accidental release. Since most of the codes failed to predict the location of the tracer plume correctly. ETEX evaluations and comparisons showed significant impacts of both input data (e.g. three dimensional wind-fields and boundary layer descriptions) and model structure, such as the choice of numerical solution method and model resolution on output predictions accuracy.

The predominant model types that used in the accidental release simulations are Eulerian and Lagrangian. In Eulerian models grid based methods are used. As advantage they may take into account fully 3D descriptions of the meteorological fields instead of single trajectories (Wendum, 1998; Langner et al., 1998). However, Eulerian models show difficulty in resolving large gradients near to the point source when it used traditionally with fixed meshes. This will lead to particular problems for simulating dispersion from a single point source. As a result of this, very large gradients and numerical error near the release will be created because of numerical diffusion. Such problem can be adjusted by nesting a finer resolution grid or using an adaptive gridding method to resolve better and handle steep gradients (Lagzi et al., 2004). In a Lagrangian model, particles with dispersed mass of pollutants are moved along trajectories determined by the advection field taking into account the effect of turbulence. The advantage that Lagrangian models have is that they can allow using high spatial resolution although they depend on the interpolation of meteorological data (Stohl et al., 1998).

Dispersion models that especially simulate the accidental release of radioactive and its consequences must have a high degree of accuracy and must be achieved faster than real time to be of use in decision support. Therefore, the purpose of this study is verifying the prediction capability of the FLEXPART as Lagrangian model for prediction the released plume of ^{137}Cs from nuclear accidents. Also the results are valuable for assessing the model performance and its capability to accurately predict ^{137}Cs surface concentrations by comparison with results of other studies and measurements.

2. Numerical Models

2.1 Atmospheric model

MM5 is a non-hydrostatic atmospheric dynamic model developed by the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) (Grell 1994). This model has the advantage that it can provide Arakawa-B horizontal grid staggering, terrain following sigma vertical coordinates, a second-order leapfrog time integration scheme, nesting of multiple domains, and has a number of parameterization schemes for atmospheric physical processes. MM5 is used for research and other purposes because of its flexibility, easy-operation and high performance of prediction. Also MM5 can predict meteorological fields with high resolution in time and space by resolving atmospheric dynamic equations numerically.

In this study, MM5 (version 3.7) model is configured with two nested domains of 36 km, and 12 km horizontal resolution and 34 vertical σ (sigma) levels. The σ is defined by the following equation:

$$\sigma = (p - p_t)/(p_s - p_t)$$

where p is the pressure, p_t the specified constant top pressure, and p_s the surface pressure. The physics schemes options that used in this study are the Eta Mellor-Yamada second order turbulence closure scheme for Planetary Boundary Layer, five layer soil diffusion scheme for surface temperature prediction, Monin-Obukhov similarity theory for surface layer, Kain–Fritsch scheme for convective parameterization, simple Ice scheme for cloud microphysics, Rapid Radiative Transfer Model (RRTM) scheme for radiation transfer in the atmosphere (Mellor and Yamada 1982; Kain and Fritsch 1993; Dudhia 1989; Mlawer et al. 1997). The model is integrated for 384 h from 12 UTC 25 April 1968 to 12 UTC of 11 May 1968.

2.2 Lagrangian particle dispersion model FLEXPART

FLEXPART is a Lagrangian dispersion model developed by Andrea Stohl for Austria emergency response system (Stohl et al., 2005; Eckhardt et al., 2008). This model simulates forward transport and dispersion of air particles within the atmosphere over short or long distances. It can also be used backward with time to identify the sources of sampled air masses as potential source of the pollutant. FLEXPART model can be driven with meteorological data from both the European Center for Medium-Range Weather Forecasts (ECMWF) and Global Forecast System (GFS) model of the National Center for Environmental Prediction (NCEP).

FLEXPART was validated by using data from continental scale tracer experiments and used for a large range of applications such as fire emissions, emergency response, simulating the dispersion of volcanic plumes, and urban dispersion (Stohl et al., 2008; Kasischke et al., 2005; Wotawa and Trainer, 2000; Forster et al., 2001; Spichtinger et al., 2001; Pechinger et al., 2001; Wenig et al., 2003; Arnold et al., 2008; Prata et al., 2007; Prata et al., 2009; Eckhardt et al., 2008; Kristiansen et al., 2010; Stohl et al., 2011; Fast and Easter, 2006c). Its advantage is that the numerical accuracy is only limited by the number of particles released and by the resolution of meteorological input data and so gives more reliable estimates even near the source unlike Eularian models.

In this study Lagrangian particle dispersion model FLEXPART (version 6.2) was used to simulate the released ^{137}Cs from Chernobyl accident. FLEXPART was run in forward mode and driven with hourly meteorological data from MM5 model with a horizontal resolution of 12 km × 12 km, and 34 vertical sigma levels.

3. Meteorological input fields and source term

3.1 Meteorological input fields

The MM5 model was driven here by operational analysis data from the ECMWF model with a temporal resolution of 6 hours, horizontal resolution of $1^o \times 1^o$ in latitude–longitude grid, and 60 vertical levels. For Sea Surface Temperature (SST), the National Center for Environmental Prediction (NCEP) Reynolds optimally interpolated weekly SST dataset is used with resolution $1^o \times 1^o$ in latitude–longitude grid.

3.2 Source term

The source term describes the accidental release of radioactive material from a nuclear facility to the environment. Not only the levels of radioactivity released are important, but also their distribution in time as well as their chemical and physical forms.

The daily variation of ^{137}Cs release rates shown in Table 1 is deduced from the ATMES (Atmospheric Transport Model Evaluation Study) which is an international project to evaluate the performance of long-range transport models by using Chernobyl data (Klug, et al., 1992). The data in Table 1 are consistent with several other publications for the total release of activity from ^{137}Cs. This source term is broken into 11 release periods of 24 hours each started from 00 UTC 26 April 1986 to 00 UTC 7 May 1986, with an additional specification that the first release period can be further divided into two release periods; an initial release lasting 6 hours at an effective stack height of 1500 meters and containing 20% of the first day's release, and the second release period of 18 hours at a height of 600 meters containing the remaining.

Table 1: Release rates of ^{137}Cs used for Chernobyl simulation

Time interval (UTC)	Release rate (Bq/day)	Effective initial plume height (m)
04/26 00 - 04/26 24	2.2×10E+16	600*
04/27 00 - 04/27 24	7.0×10E+15	600
04/28 00 – 04/28 24	5.5×10E+15	300
04/29 00 - 04/29 24	4.1×10E+15	300
04/30 00 - 04/30 24	3.0×10E+15	300
05/01 00 - 05/01 24	3.0×10E+15	300
05/02 00 - 05/02 24	5.5×10E+15	300
05/02 00 - 05/03 24	6.3×10E+15	300
05/04 00 - 05/04 24	8.1×10E+15	300
05/05 00 - 05/05 24	8.9 ×10E+15	300
05/06 00 - 05/06 24	1.1×10E+14	300

Table 2: Statistical results from comparison of predicted ^{137}Cs surface concentration with measurements

NMSE	MBE	RMSE	FB	FA 2(%)	FA 5(%)	R
3.87	-0.153	0.668	-0.128	43	53	0.524

4. Model simulation and impact of local meteorological conditions

FLEXPART simulate the transport and the distributions of ^{137}C over Europe for 374 hours represent the period from the start of release, 0000 UTC 26 April to 1200 UTC 11 May in 1986. While the Meteorological fields prediction by MM 5 were started 12 hours before the release.

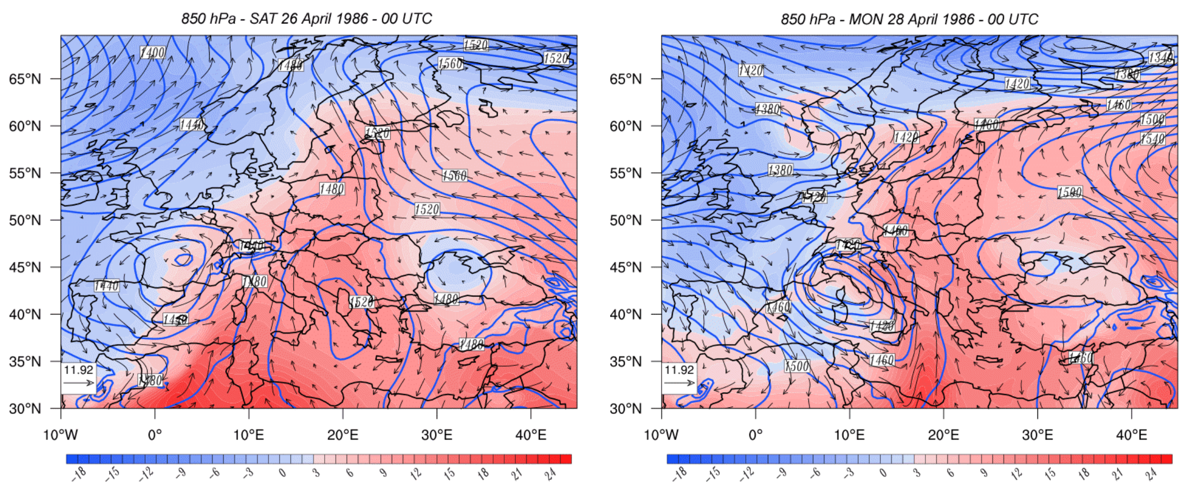
In Fig.1, the 0000 UTC 850 hPa weather charts predicted by MM5 model indicate that the initial stage of the transport occurred in a synoptic situation dominated by a prevailing strong cold continental high pressure system was centre over the northeast of Chernobyl site and a low pressure system located in the vicinity of Iceland. As a result, exceptionally worm air flowed from the Chernobyl site are towards Scandinavia. This situation pattern remained quasi-stationary for the next two days of the transport. Therefore the radioactive cloud transported towards Scandinavia. The model simulation indicates that the radioactive materials released in early hours of 26 April were transported mostly to the north of Chernobyl towards the Scandinavian countries as shown in Fig. 2.

One the 28 April, as shown in Fig.2, the simulated radioactive cloud crossed the Scandinavia countries in a north-westerly direction and later entered the cyclonic circulation system located over the north-eastern sector of the Atlantic Ocean. Therefore, a very strong flow spread the radioactive material in the direction of Iceland and Greenland. The part of the radioactive cloud that originally spared over Finland was later transported in the south-east direction.

During 29 and 30 April, the prevailing Azores high pressure system extended a ridge eastwards across France and Central Europe as shown in Fig.1. The 30th can considered as a critical day in the movement of the radioactive cloud as it has previously been moving toward the northwest found itself on the southern flank of the advanced ridge forcing it along a new route towards the southwest across Poland (see Fig.2). Subsequently on 1 and 2 May, this ridge became a detached feature centered over Denmark and extended a broad of west-moving air over most of Central Europe as shown in Fig.1. Because of this change in the weather patterns over the Baltic Sea and the Central Europe, the core of the simulated radioactive cloud moved in a southwesterly direction crossing initially over Poland and finally covering the southern part of Germany, Austria and north of Italy (see Fig.2).

On 1 May the radioactive cloud reached France and initially covered the southern part. Finally by the end of May 3rd the radioactive cloud covered France totally. The results agree with the previous studies (Thomas and Martin, 1986).

The radioactive cloud on 3 May moved towards the British island and covered it totally during 4 and 5 May as shown in Fig.2. The release of the radioactive isotope ^{137}C during about 4-6 was firstly transported to the south and southwest of Chernobyl site. It covered Eastern Europe, Greece and Turkey and also transported northward. The radioactive cloud was finally stretched lengthwise and thinly from north to south, covering eastern and northern Europe.



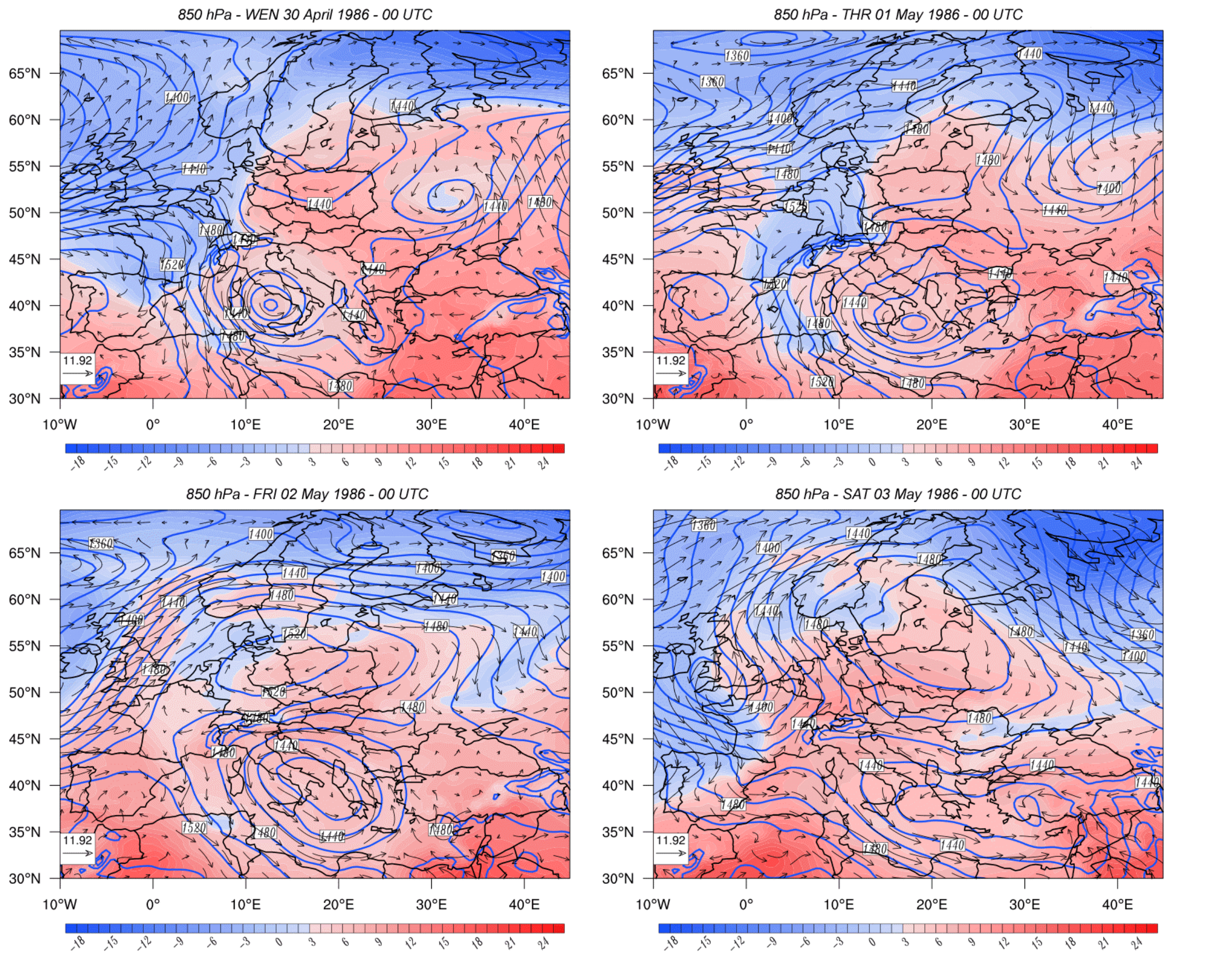
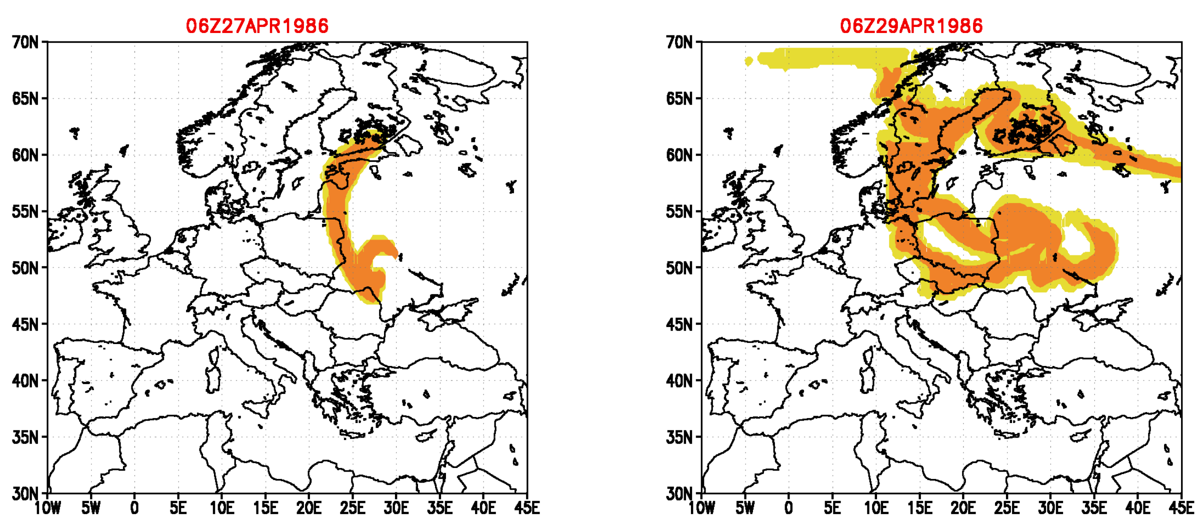


Figure 1: The 850 hPa pressure surface weather charts at 0000 UTC predicted by MM5 model during the week following the accident.



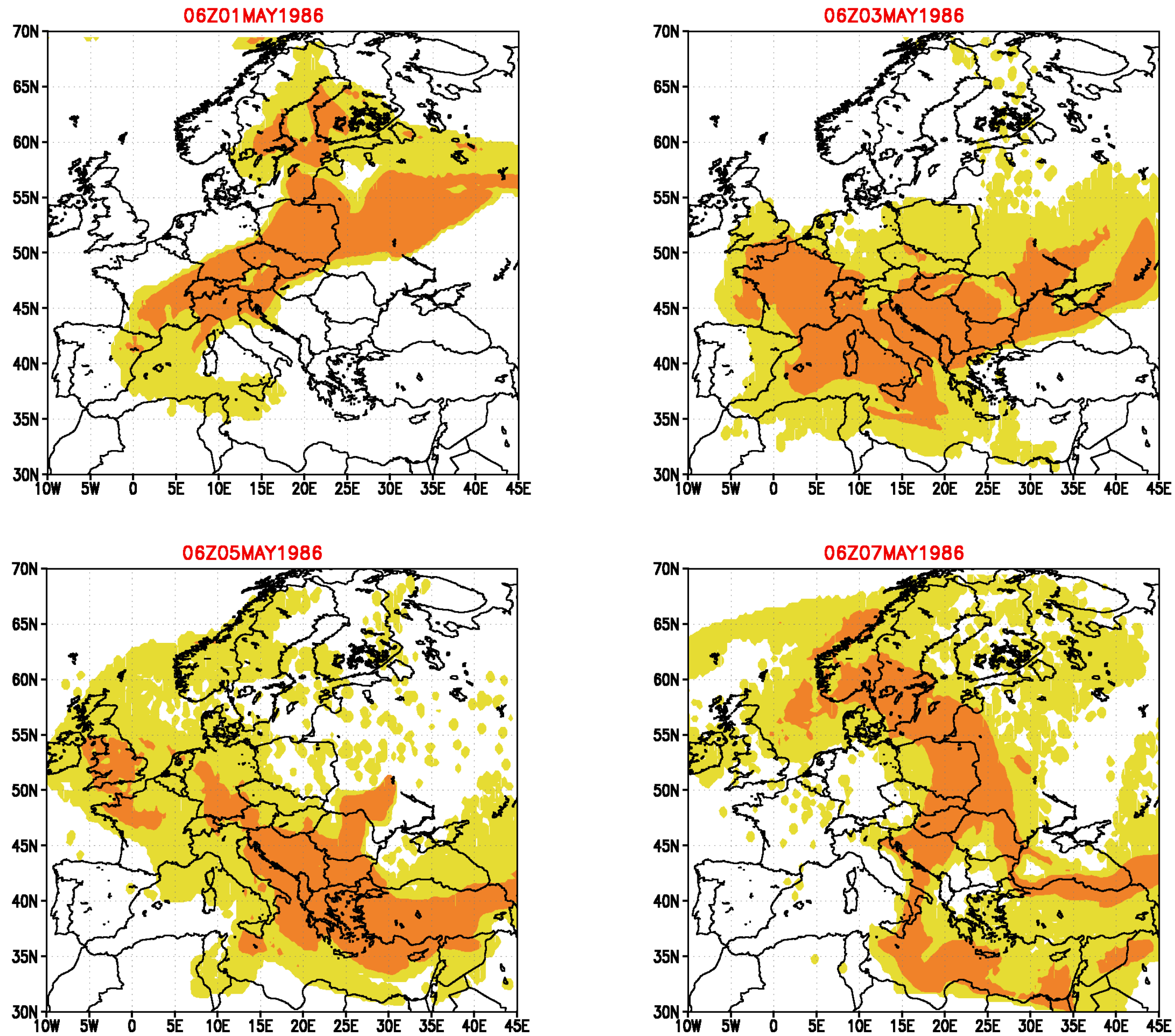


Figure 2: Distributions of surface air concentrations of 137Cs at 0600 UTC from 27 April to7 May 1986.

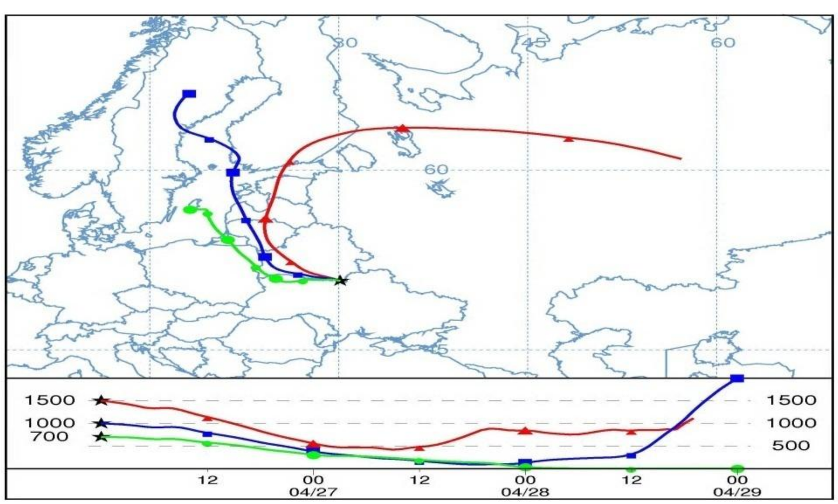
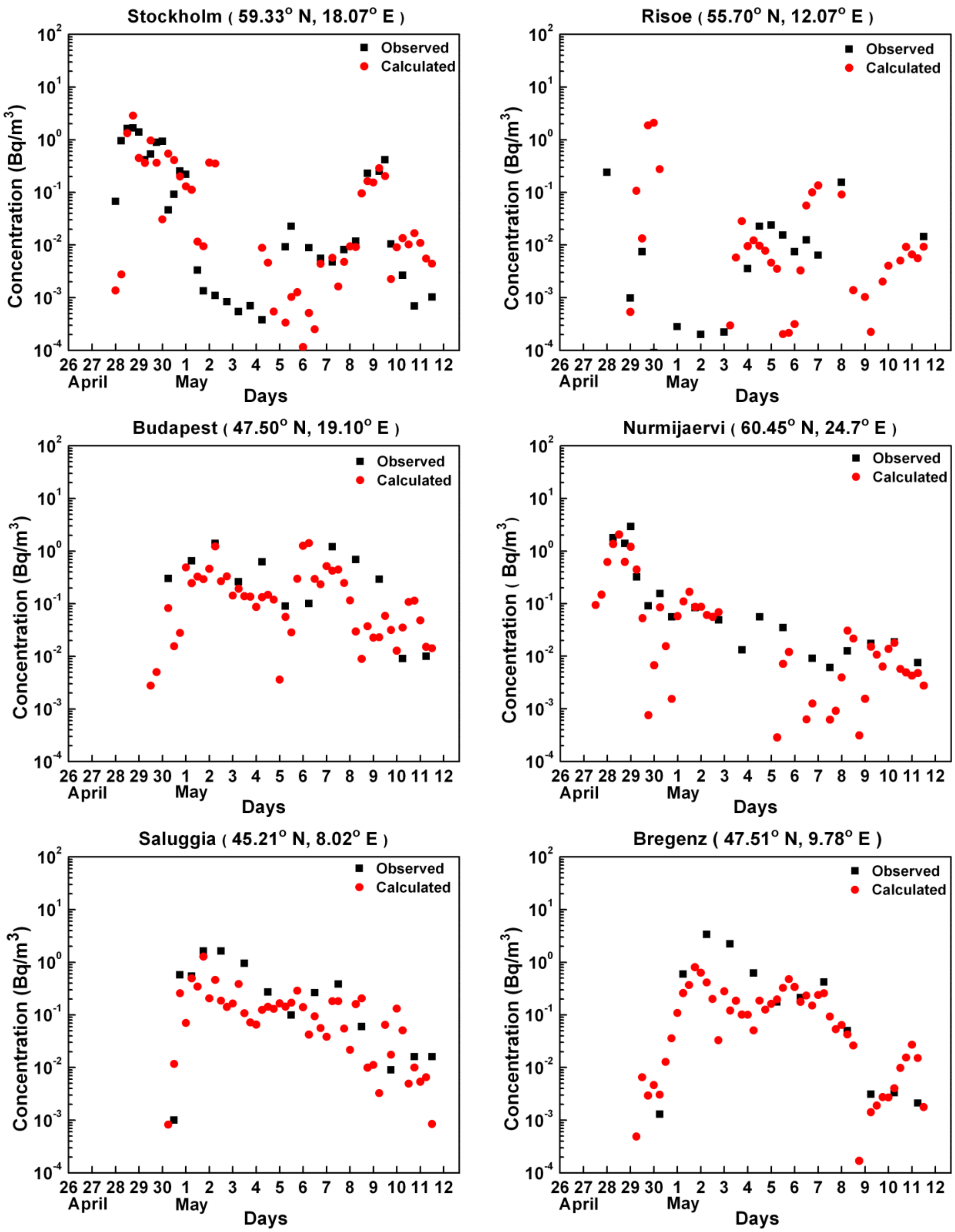


Figure 3: Air mass trajectories for 72 hours from Chernobyl on 26 April 0000 UTC. Starting height are 700, 1000, 1500 m.

Figure 4: Time series of the measured and the predicted concentration of ^{137}Cs.



5. Models Evaluation and discussion

In this study, the FLEXPART particle dispersion model has been applied to simulate the release of the radioactive isotope ^{137}C due to Chernobyl accident from 26 April 0000 UTC to 11 May 1200 UTC in 1986. The general feature of the movement of the radioactive cloud was similar the consequence of previous studies as show in Fig.2 (Ishikawa 1995, Ishikawa and Chino 1991). Also the air parcel forward trajectories originating from the Chernobyl at the time of the accident supported and demonstrated that the initial simulated movement of the radioactive cloud was towards the Scandinavian countries (see Fig.3).

The evaluation of the FLEXPART model results can be preformed by comparison the predicted surface air concentrations of ^{137}Cs with measurement data. The measurement data used for the comparison are from REM (F. Raes et al. 1989). Hence, as shown in Fig.4, measured data from eight locations over Europe were compared with modeled ^{137}Cs surface concentrations values to discuss the characteristic stages of the model performance with emphasis on the initial arrived time for radioactive cloud. The calculated results agree well with measurements at all measurement sites in Fig.4. Also the time difference of first arrival of the simulated radioactive cloud is about half a day or less at the maximum.

The observed air activity over Scandinavia region is compared with the predicted ^{137}Cs at Nurmijaervi, Stockholm, and Risoe sites. At Nurmijaervi, the predicted cloud arrival time for the Nurmijaervi region was around 1200 UTC on 27 April, just about 36 hours after the released. And the maximum ^{137}Cs that predicted during 27-29 April is closed to the measurements. From then the observed and the predicted surface ^{137}Cs concentrations decrease until 8 May with a small intermediate increase for predicted values around 1 May. Form 8 to 11 May another increase in the predicted values close to the measured.

At Stockholm, model simulated the occurrence of two major peaks of the surface ^{137}Cs concentrations. These two peaks are in good agreement with measurements. The first peak is predicted during 28-30 April while the second one is around 9 May. The predicted cloud arrival time for Stockholm area is identified on 28 May and it is agree with the start time of high observed surface ^{137}Cs concentrations.

At Risoe, similar to Stockholm area the model simulated the occurrence of two major peaks of the surface ^{137}Cs concentrations. The simulation detected first peak during 28-30 April while the second one detected around 7 May. However, the results were simulated well compared to measurements.

At Budapest, Saluggia, and Bregenz, the predicted values of surface ^{137}Cs concentration are generally in good agreement with measurements. The simulations also demonstrated its ability to capture the peak values which are in closest agreement with the measurements through all these time periods.

Also totally 130 pairs of predicted and measured values of surface ^{137}Cs concentration are compared using statistical indicators such as such as Mean Bias Error (MBE), Root Mean Square Error (RMSE), Normalized Mean Square Error (NMSE), Fractional Bias (FB), the Pearson's correlation coefficient (R) and the fractions of FA2 and FA5 that represent the proportion of the calculated values, which are within a factor of 2 and a factor of 5 of the measurements values. The results of the statistical analysis are summarized in Table.2**.** The statistical analysis shows that the spatial distribution of the predicted ^{137}Cs surface concentration has high accuracy.

6. Conclusions

The numerical model FLEXPART (V6.2) coupled with MM5 (v 3.7) predictions was used to simulate the transport of the ^{137}Cs radioactive cloud form Chernobyl accident. The simulation results indicate that this coupled numerical model works relatively well for the prediction of the arrival time and the general patterns of the transport of the radioactive cloud. The air parcel trajectories emphasize the model performance for simulating the movement of the radioactivity cloud towards Scandinavia countries during the first phase after accident. This reflects that FLEXPART has been driven by a good quality of the high resolutions meteorological fields predicted by the MM5 and the accuracy of the employed MM5 physical schemes.

The predicted surface ^{137}Cs concentration from 0000UTC April 26 to 1200 UTC 11 May was compared with measurements from the REM data bank over eighth sites. From this comparison, it is concluded that the coupled numerical model MM5-V3.7-FLEXPART (V6.2) can predict the surface ^{137}Cs contamination with high accuracy within one order in differences from measurements.

The results of the statistical evaluations showed very good model performance compared to former studies (H. Terada. et al. 2004, Kyung-Suk Suh et al. 2009). A significant positive correlation 0.524 is seen between the predicted and the measurements over individual sites (REM data Bank). Also the deviations (NMSE = 0.668) and (RMSE = 3.78) were clearly demonstrated that the model perform reasonably well in space and time. The agreement between the predicted and the measurements is 43 % within a factor 2 and 53 % within a factor 5.

The simulation has also illustrated the enhancement impact of the high resolution output meteorological fields from MM5 on the prediction accuracy of the radioactive cloud transportation and the surface air concentrations of ^{137}Cs values.

It is concluded that the model FLEXPART (V6.2) has the capability to simulate the Chernobyl nuclear accident and could be recommended for standard use in emergency response situations.

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