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Short communication

Short and long term dispersion patterns of radionuclides in the atmosphere around the Fukushima Nuclear Power Plant

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ABSTRACT

The Chernobyl accident and unfortunately the recent accident at the Fukushima 1 Nuclear Power Plant are the most serious accidents in the history of the nuclear technology and industry. Both of them have a huge and prolonged impact on environment as well as human health. Therefore, any technological developments and strategies that could diminish the consequences of such unfortunate events are undisputedly the most important issues of research. Numerical simulations of dispersion of radionuclides in the atmosphere after an accidental release can provide with a reliable prediction of the path of the plume. In this study we present a short (one month) and a long (11 years) term statistical study for the Fukushima 1 Nuclear Power Plant to estimate the most probable dispersion directions and plume structures of radionuclides on local scale using a Gaussian dispersion model. We analyzed the differences in plume directions and structures in case of typical weather/circulation pattern and provided a statistical-climatological method for a “first-guess” approximation of the dispersion of toxic substances. The results and the described method can support and used by decision makers in such important cases like the Fukushima accident.

1. Introduction

The accident at Chernobyl Nuclear Power Plant (NPP) in 1986 showed transparently that radioactive materials from a nuclear accident can spread from continent to continent and across the world resulting in huge damage and long-term effect on the environment (Balonov, 2007; Pollanen et al., 1997; Saenko et al., 2011). This accident resulted in substantial advances in the development of dispersion models and software that are able to simulate the transport and transformation of radionuclides or toxic chemical substances in the atmosphere, hence supporting decision makers at all level. The Chernobyl disaster also stimulated the development of complex decision making software (e.g., RODOS) that can simulate and predict the consequences of such events in a transboundary framework (Ehrhardt et al., 1993; Lepicard et al., 2004).

Environmental model simulations – especially simulation of an accidental release 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. For simulating the dispersion of air pollutants, different modelling approaches are applied and widely used. In a Lagrangian model, particles with assigned mass of pollutants are moved along trajectories determined by the advection field taking into account the effect of turbulence. Lagrangian models have the advantage that they can afford using high spatial resolution although they rely on the interpolation of meteorological data (Stohl et al., 1998).

Eulerian models use grid based methods and have the advantage that they may take into account fully 3D descriptions of the meteorological fields rather than single trajectories. However, used traditionally with fixed meshes, Eulerian models show difficulty in resolving steep gradients near to the point source. This causes particular problems in case of simulating spread of chemical species during an accidental release from a single, but strong point source, which will create very large gradients and numerical errors due to the “numerical diffusion” near the release. This problem can be addressed by nesting a finer resolution grid or using an adaptive gridding method to resolve better and handle steep gradients (Lagzi et al., 2004).

In spite of the enormous effort to provide fast and accurate predictions using special numerical techniques, solvers and parallelization of the models on supercomputers, clusters, GRIDs (Dabdub and Seinfeld, 1996; Alexandrov et al., 2004) or even on graphical processing units (Molnár et al., 2010), the recent unfortunate accident at the Fukushima NPP (Bowyer et al., 2011; Manolopoulou et al., 2011; Pittauerová et al., 2011; Diaz Leon et al., 2011; Sinclair et al., 2011; Bolsunovsky and Dementyev,

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2011) showed that even sophisticated model results cannot be efficiently used in decision support because of lack of detailed information of the release. Unlike Chernobyl, the impact of the Fukushima accident was concentrated on a local scale, but the duration of radioactive release was longer than a month. Although the exact amount and composition of the released material is not known, the spatial distribution of the pollution can be estimated based on meteorological observation data throughout the release time. A possible solution could be using a statistical approach based on several thousand or even million model runs in the past incorporating all possible meteorological and dispersion scenarios. These huge numbers of simulations are hardly feasible with sophisticated Eulerian or Lagrangian models, however a simple Gaussian model could be adequate for this task. A "first-guess" probability approximation on plume direction and structure can be made based on these statistical inventories.

The main aim of this study is to investigate the typical plume structures at the Fukushima 1 NPP (Japan) after the accident on12 March, 2011 and over an 11-year period assuming an accidental release every day using observed meteorological data to explore the most probable plume directions of the radionuclides. Moreover, we present a new statistical approach based on the results of this long time period model evaluation to provide a new strategy for decision makers.

2. Model and method description

The ALOHA (*Areal Locations of Hazardous Atmospheres*) Gaussian air dispersion model developed by the National Oceanic and Atmospheric Administration (NOAA) (NOAA and EPA, 2007) was used to simulate the transport of the gas phase substances from the Fukushima 1 NPP (Japan) on local scale. This model has an advantage of extremely short runtime, simplicity and predictive power. ALOHA provides the authorities with an easy-to-use tool for estimation of the consequences of an accidental release within 1 h and 10 km from the source. This simple Gaussian approach (compared to Eulerian and Lagrangian models) was chosen for statistical analyses of dispersion properties because of the high number of runs. As it has been discussed earlier, simulating accidental release for statistical purposes using either Eulerian or Lagrangian models undisputedly requires huge computational time (several months or years) and represents a very challenging computational task. Although the two-dimension Gaussian model cannot handle complex terrain and the spatial variability of meteorological fields, its fast runtime and simple algorithm makes Gaussian models an effective tool for sensitivity and statistical studies (Bubbico and Mazzarotta, 2008). The model requires the following input data and parameters: time and location, atmospheric data (wind speed and wind direction, air temperature, relative humidity, cloud cover, mixing layer height), stability category of the atmosphere (proposed by the model based on meteorological data), roughness length and information about the release (air pollutant, duration of release, amount of released material, source height). ALOHA assumes a Gaussian concentration distribution both in crosswind (y) and vertical (z) direction. The σ_y and σ_z diffusion parameters are defined as a function of the stability class and the downwind (x) distance from the source. Vertical g_z distribution of the plume assumes total reflection from the ground and the inversion layer. Concentration distribution with Q source strength and a uniform u wind speed is given by the following relation:

$$c(x,z,y) = \frac{Q}{u}\frac{1}{\sqrt{2\pi}\sigma_y}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]g_z(x,z). \quad (1)$$

Solution of the Eq. (1) provides with a "Gaussian" plume, where the transport of a chemical compound in vertical and horizontal directions occurs by turbulent diffusion along the direction of the mean wind (advection).

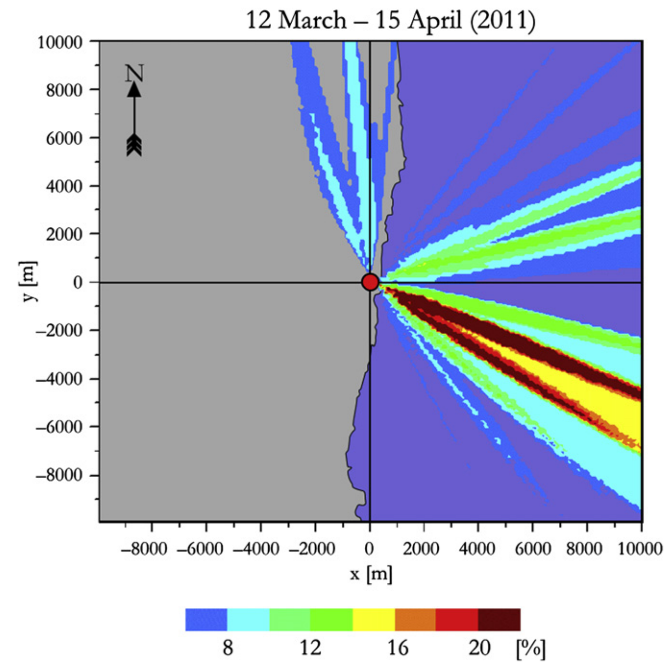

Fig. 1. Average relative distribution of the plume of a passive tracer based on 101 independent simulations released from the Fukushima 1 NPP between 12/March/2011 and 15/April/2011.

3. Results and discussion

A hypothetical release of an inactive tracer gas (xenon) was assumed with an emission rate of 10 kg/h in each 6 h from the Fukushima 1 NPP. Dispersion of this tracer was simulated with the

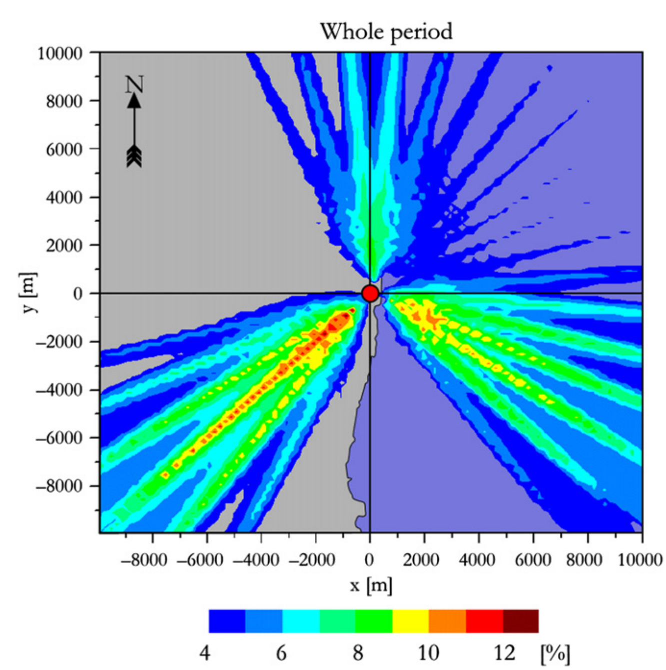

Fig. 2. Average relative distribution of the plume of a passive tracer based on 10,192 independent simulations released from the Fukushima 1 NPP between 01/January/2000 and 31/December/2010.

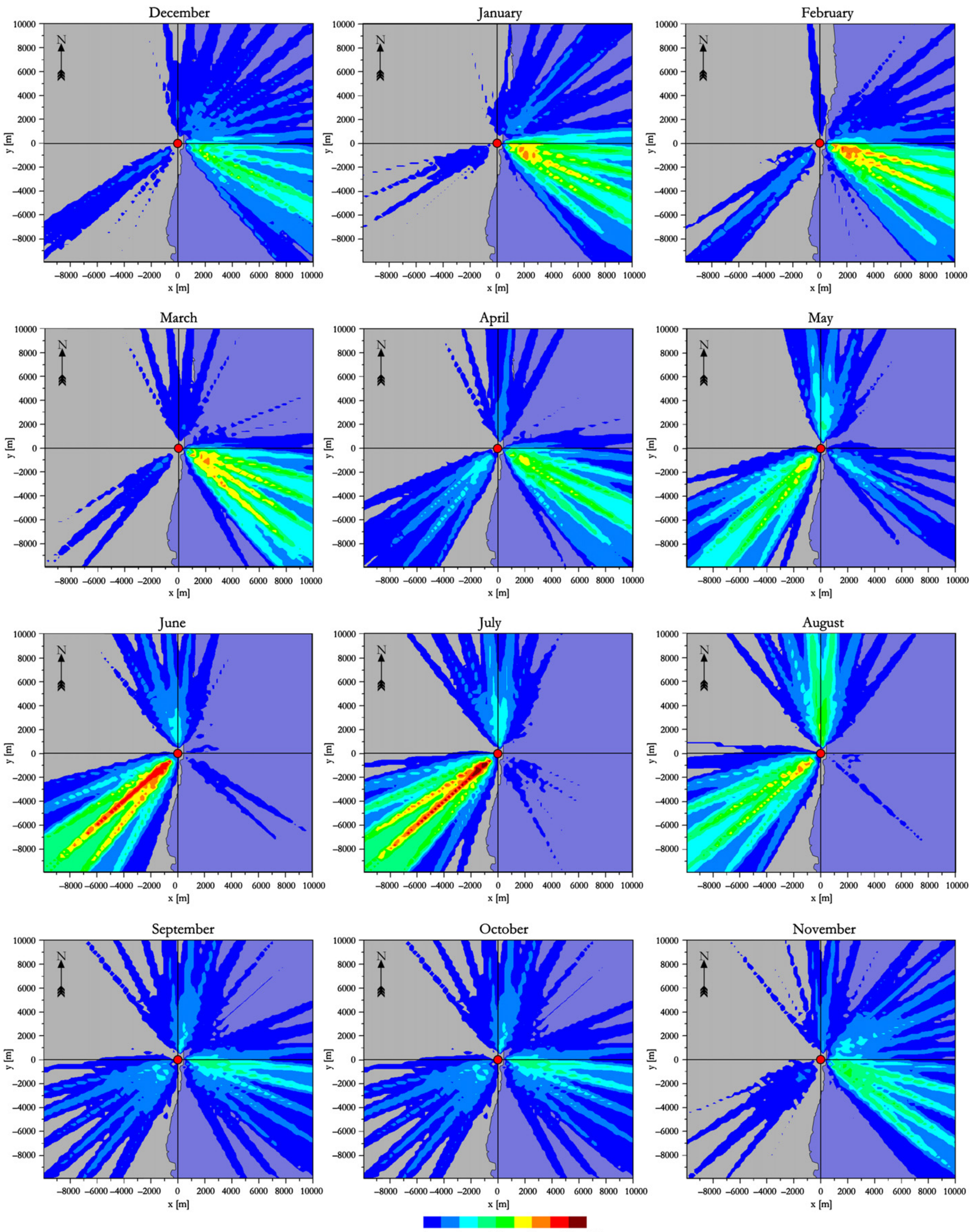

Fig. 3. Average monthly relative distribution of the plume of a passive tracer released from the Fukushima 1 NPP between 01/January/2000 and 31/December/2010.

ALOHA Gaussian model for 1 h during a short time period covering a month after the accident (12 March 2011–15 April 2011) and an 11 years period (01 January 2000–31 December 2010) to obtain the most probable dispersion (plume) patterns based on surface meteorological data. Weather reports of the nearest weather station operated by the Japanese Weather Service (in Fukushima, about 60 km from the NPP) were used as an input dataset for the model. These meteorological reports were processed automatically to filter and convert data into the required input format. ALOHA model was continuously provided with meteorological data using a SendKey method (Jakala, 2007). One hour after each release, the size and location of the area polluted over the 10^{-4} ppm user pre-defined concentration threshold were estimated, averaged and analysed. As the amount of released material during the accident is not known, a low threshold concentration with fairly high emission rate was chosen to locate areas where pollution occurred. It should be noted that the Gaussian approximation has some limitations in case of low wind speed due to its uncertain direction and weak effect on the dispersion. Moreover, ALOHA cannot handle wet deposition. According to the User's Manual (NOAA and EPA, 2007), all observations that reported either wind speed lower than 2 m/s or presence of fog or precipitation (SYNOP code vv $\geq$ 30 in the meteorological dataset) were excluded in this study. We performed 101 and 10,192 individual simulations after filtering field measurement meteorological data according to these guidelines in case of the short and longer time statistics, respectively. Results were processed automatically to estimate the maximum distance from the source and the total area where ground concentration level reached the threshold concentration. We also summarized the frequency of plume occurrence on a 50 m $\times$ 50 m resolution rectangular grid. There was no significant difference between the numbers of filtered data for all seasons. This means that such a high number of data and model runs allow a statistical study to obtain the most probable plume directions and structures occurring at Fukushima 1 NPP in pre-defined periods.

Fig. 1 shows a cumulated "infected" area during the short period study after the accident at the Fukushima 1 NPP. It can be clearly seen that the most polluted area is located at south-east direction from the NPP and practically does not spread over the mainland. This statistical observation is in a good accordance with other sources and simulations, where it has been reported that the contaminated air travelled from the NPP towards the ocean, and elevated activity could be detected afterwards in the west cost of US, Europe and Asia (Bowyer et al., 2011; Manolopoulou et al., 2011; Pittauerová et al., 2011; Diaz Leon et al., 2011; Sinclair et al., 2011; Bolsunovsky and Dementyev, 2011). This local scale model obviously cannot predict the long range dispersion of radioactive species, however, it can capture the most important behaviour, namely, polluted air masses practically did not spread to the mainland of Japan.

After this short period study, we investigated the dispersion patterns based on an 11 years long 6-hourly meteorological database. Fig. 2 depicts the plume direction statistics and structure for the whole 11 year period. It can be seen that there are three pronounced directions: north, south-west and south east. This also determines the most probable dispersion directions after an accident at the Fukushima 1 NPP. Additionally, we analyzed seasonal and monthly variation of the typical dispersion plumes, which contains sensitive and probably the most important information about a possible consequence of any further release (Fig. 3). During the winter the prevailing wind direction is west-northwest causing dispersion of radionuclides from the mainland of Japan to the Pacific Ocean. This trend does not change till late spring. However, a significant change in the atmospheric circulation can be experienced with a dominant north-east wind direction during summer. This relatively fast change in predominant wind direction can be attributed to the fact that the circulation pattern changes rapidly because of the coastal circulation at the east coast of Japan. Therefore, at the end of the spring and during summer after a possible accident, the most polluted area would probably be the mainland of Japan. In summertime the north-east direction is more dominant than in other seasons of the year. It should be noted that parallel with this phenomenon a new direction (from south) gets stronger, and even in September this northerly dispersion path is as probable and pronounced as south-westerly ones. In autumn the dispersion structure of the plume is turning from south-west and north direction to east, south-east direction caused by the prevailing west-northwesterly wind. We note that the easterly-westerly periodic wind direction shift is a consequence of the coastal circulation, while secondarily dominant north-south wind direction can be explained as an effect of the terrain.

4. Conclusion

This detailed investigation provides two important findings, first of all, during the accidental release at the Fukushima 1 NPP in March, 2011, the contaminated air masses spread towards the ocean, thus reducing dramatically the human dimension of possible consequence of this disaster. Secondly, more serious consequences could have been observed in other period of the year (especially between May and October), when the dispersion from the NPP would be more dominant towards the mainland because of the dominant atmospheric circulation pattern. Moreover, intense rainfall in June and July can cause additional impact on local scales due to wet deposition of radionuclides (not addressed here due to model limitations).

After an accidental release, the prediction of the expected plume dispersion must be as fast and accurate as possible. Here, we presented a short and a long term statistical studies for the Fukushima 1 NPP to estimate the most probable dispersion directions and plume structures. This analysis can provide a "first-guess" distribution pattern on local scale, and that can be available immediately after or even before an accidental release, using an appropriate inventory built by adequately high number of simulations. The main goal of our investigation was to determine statistically the most probable dispersion direction of toxic substances originated from the Fukushima 1 NPP in case of an accidental release. The atmospheric conditions can be represented by different macro-circulation patterns corresponding to the related area. Results show that there are significant differences among plume directions and structures in each month and season of the year. Using this statistical-climatological method, a "first-guess" approximation of the dispersion of toxic substances can be provided to support decision makers before results of detailed dynamic model simulations are available. These estimations are not as reliable as the results of other numerical models (e.g., Eulerian, Lagrangian models) using current predicted meteorological data due to their statistical nature, but this approach has undisputedly several advantages like easy-to-use for decision making strategy and pollution statistics for an arbitrarily chosen point or region, which can be available at the moment of a potential accident. This approach could be an additional and powerful extension for decision makers in the near future.

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