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The characteristics of the vertical distribution of radionuclide in free troposphere from simplified release scenarios: a case study

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Abstract: Dose estimation in the upper air is not studied as much as on ground level or in boundary layer. However, there is a need from stakeholders in aviation industry for a reasonable estimation of the radioactive plume impact at cruising levels. This study aims to provide a quantitative estimation of the dose and how reliable it is for dispersion processes up to seven days. A Lagrangian atmospheric dispersion model is used to estimate quantitatively the vertical extension of radionuclides from simplified hypothetical radionuclide release scenarios. Sources at different latitudes are selected for simulation in a boreal winter case. Three meteorological data are examined to test the sensitivity of vertical plume distribution to driving meteorological data. The vertical distribution of air concentration of radionuclides is investigated and the associated uncertainties are analysed. It is found that the vertical extension of plumes is sensitive to meteorological data being used where vertical turbulent velocities play an important role. It is therefore necessary to address the uncertainties of air concentration or dose in the free troposphere and caution must be taken when providing the results to stakeholders.

Keywords: *atmospheric dispersion; turbulent mixing; ERA5; GFS; HYSPLIT.*

I. INTRODUCTION

Consequences of radioactive contamination from nuclear power plant (NPP) accidents can extend to thousands of kilometres horizontally due to the fast processes of transport of radionuclides in the atmosphere [1]. The vertical extension of plume, on the other hand, is largely limited in the troposphere where convections are confined within. There are many literatures on horizontal transport, dispersion, deposition processes and uncertainty analysis [2-5], but only in a handful of model development papers can one find details describing modelling approaches on turbulent mixing [6-9] regarding the vertical extension of radioactive plume in the free troposphere. The vertical extension of plume, however, is closely related to the vertical mass distribution of pollutants and thus affects the concentration level in lower atmosphere as well as horizontal distribution. A better understanding of the vertical distribution of radioactive pollutants not only provides reliable information of radiation dose in aviation industry, but also helps improve the estimation of pollutant

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concentration in lower atmosphere or on ground level. Draxler et al. [6] found that the horizontal transport of plume is sensitive to vertical atmospheric structure and this is more evident in long-range dispersion simulations. One can also find from the control equations of the dispersion processes [6-10] that meteorological data is the most crucial factor for plume dispersion apart from the model itself. It is not difficult to obtain quantitative results of radioactive pollutant concentration or dose using community dispersion models [6-8]. However, the question follows immediately is how sensitive these results are to the driving meteorological data.

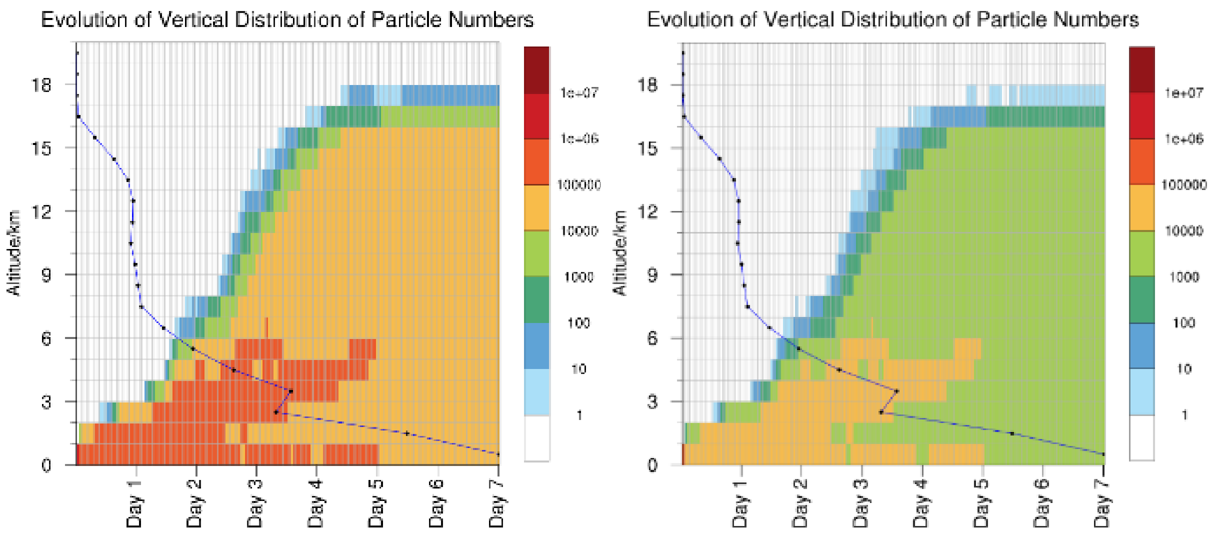
This study aims to address this question through a Lagrangian dispersion model driven by different meteorological data sets. The following paragraphs are organised as such: Section II introduces the methodology, experiment design as well as the simulation results and discussion followed by the major findings and conclusions summarised in Section III.

II. CONTENT

A. Methodology

Firstly, the study aims to estimate the air concentration and dose of radionuclides in the free atmosphere (above 1 km) up to airplane cruising levels (around 12 km). Secondly, the study analyses how sensitive the results are to meteorological data. The first goal is achieved through running a Lagrangian atmospheric dispersion model for point-source release scenario. The second one is accomplished by in-depth analysis of the two critical processes for plume elevation, namely, the vertical grid-resolvable wind advection process, and the vertical sub-grid turbulent mixing process.

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) is employed to simulate the vertical distribution of radionuclide concentrations. The HYSPLIT model [6,7] is one of the state-of-the-art community dispersion models suitable for single source long-range dispersion simulations, which is exactly of our interest. Another reason for choosing this model is because of its flexibility in ingesting commonly used meteorological data, such as the ERA5 re-analysis data [11] from the European Centre of Medium-range Weather Forecast, and the GFS data [12] from the National Centers for Environmental Prediction, etc. In order to investigate the model behaviour across different latitudes, three source locations are selected and they are Singapore, Changjiang, China, and Zaporizhzhia, Ukraine with latitudes of 1.25 ºN, 19.46 ºN, and 47.51 ºN respectively. A simple release scenario is adopted by releasing Cs-137 non-stop at the rate of 7×10^{13} Bq/h from the aforementioned three locations at the height of 100 m. The release rate is based on the 2011 Fukushima Dai-ichi NPP accident release [13]. To determine a proper particle number for the simulations, a simple experiment is set up to look at the vertical plume extension using one million particles in one simulation and 100,000 in another. The results from these two simulations demonstrate good agreement of the vertical distribution of the particles (see Fig. 1). Therefore, in the study a total of 168,000 particles (1000 released per hour) are used to save unnecessary computation while keeping the results as reliable. However, when it comes to analysing turbulent velocities, 100 particles are used instead as otherwise because the diagnosing information on timestep level would be otherwise too large to process.



(a) (b)

Fig. 1. Comparison of the vertical particle extension for 7-day period simulations using (a) 1 million particles and (b) 100,000 particles. The dot-line curves are normalised particle number at each level

Three different meteorological data are employed as the driving data for the dispersion simulations. They are namely the real-time GFS forecast, the mixed GFS short-term forecasts, and the ECMWF ERA5 re-analysis (hereafter referred as GFSr, GFSm, and ERA5 respectively). All three data sets contain 7-day meteorological fields starting from 15 January 2023 1200 UTC till 22 January 2023 1200 UTC at 3-hour intervals. The horizontal resolutions of the three data sets are same, which is 0.25 degrees, or roughly 28 km in tropical area. For vertical resolution, the ERA5 has a higher one for the layer from 1 km to 3.2 km comparing with that of the GFSr or the GFSm. Since the GFSr are real-time forecasts, the data quality decreases over time due to the unavailability of observations in future times. The ERA5, as a retrospectively analysed data set, is able to incorporates observations throughout the entire course. The GFSm are constructed from a series of 3-hour and 6-hour GFS forecasts such that the validity times of the meteorological fields are identical with the other two data sets. By doing this, new observations can be incorporated every three hours in the data set, making the GFSm comparable to the ERA5 in quality while having the grid structure as the GFSr (see Fig. 2). In this sense, the data quality of the GFSm and the ERA5 are better than the GFSr. The reason we still keep the GFSr is because it is still one of the best meteorological data sets when it comes to real-time applications.

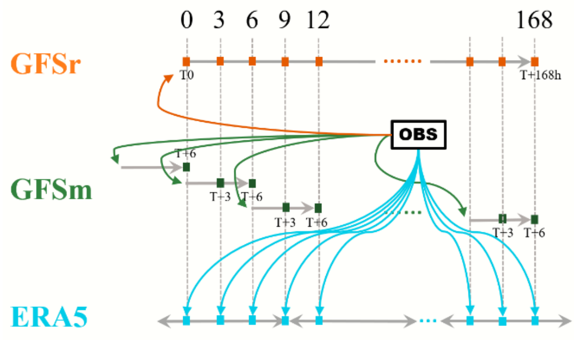
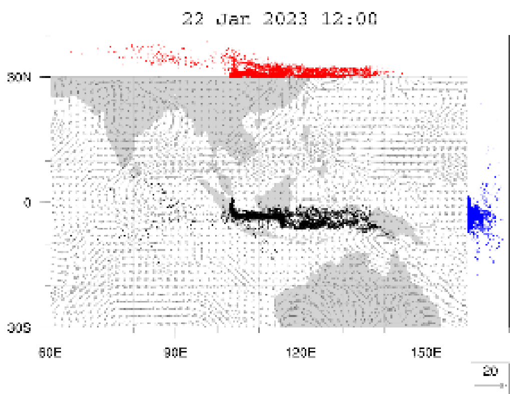


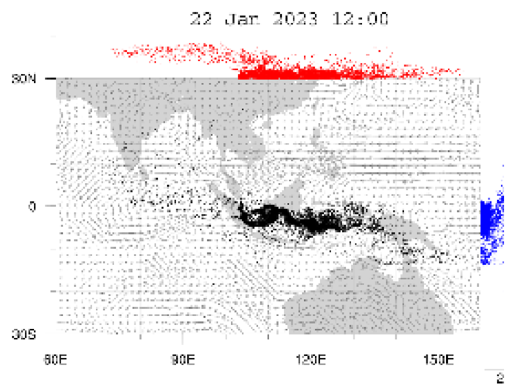
Fig. 2. Demonstration of the three data sets (GFSr, GFSm, and ERA5 from top down) used as the driving meteorological data for the dispersion model

For the turbulent mixing scheme in the HYSPLIT model, the default Kantha-Clayson method is used. According to Fong et al. [14], there is no clean winner among all the turbulent mixing options. Besides, as our focus in on the differences between meteorological data, no efforts are taken in testing different turbulent mixing methods. In the simulations, however, experiments of switching on and off of the turbulent mixing are conducted.

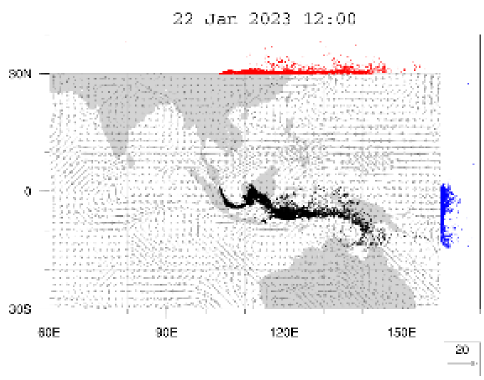
B. Results



(a)



(b)



(c)

Fig. 3. The horizontal distribution of Cs-137 particles on day 7 of top view (black dots), vertical distribution of south view (red dots) and east view (blue dots) from using (a) the GFSr, (b) the GFSm, and (c) the ERA5

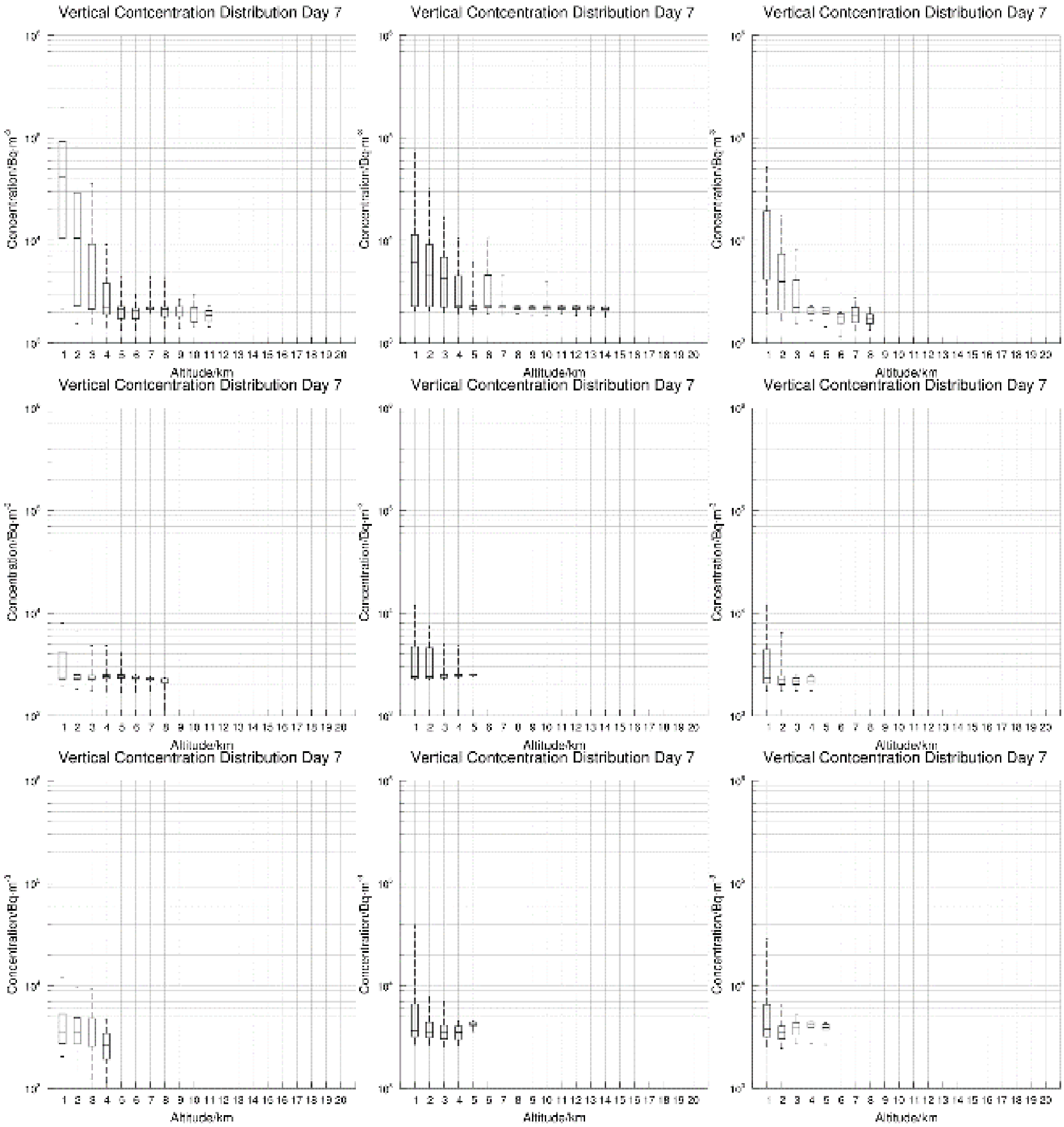


Fig. 4. The simulated concentration spread of Cs-137 over different altitudes (x-axis) on day 7 from using the three different meteorological data (left, centre, right columns for GFSr, GFSm, and ERA5 respectively) from simulations with different source locations (top, middle, bottom rows for Singapore, Changjiang, and Zaporizhzhia respectively)

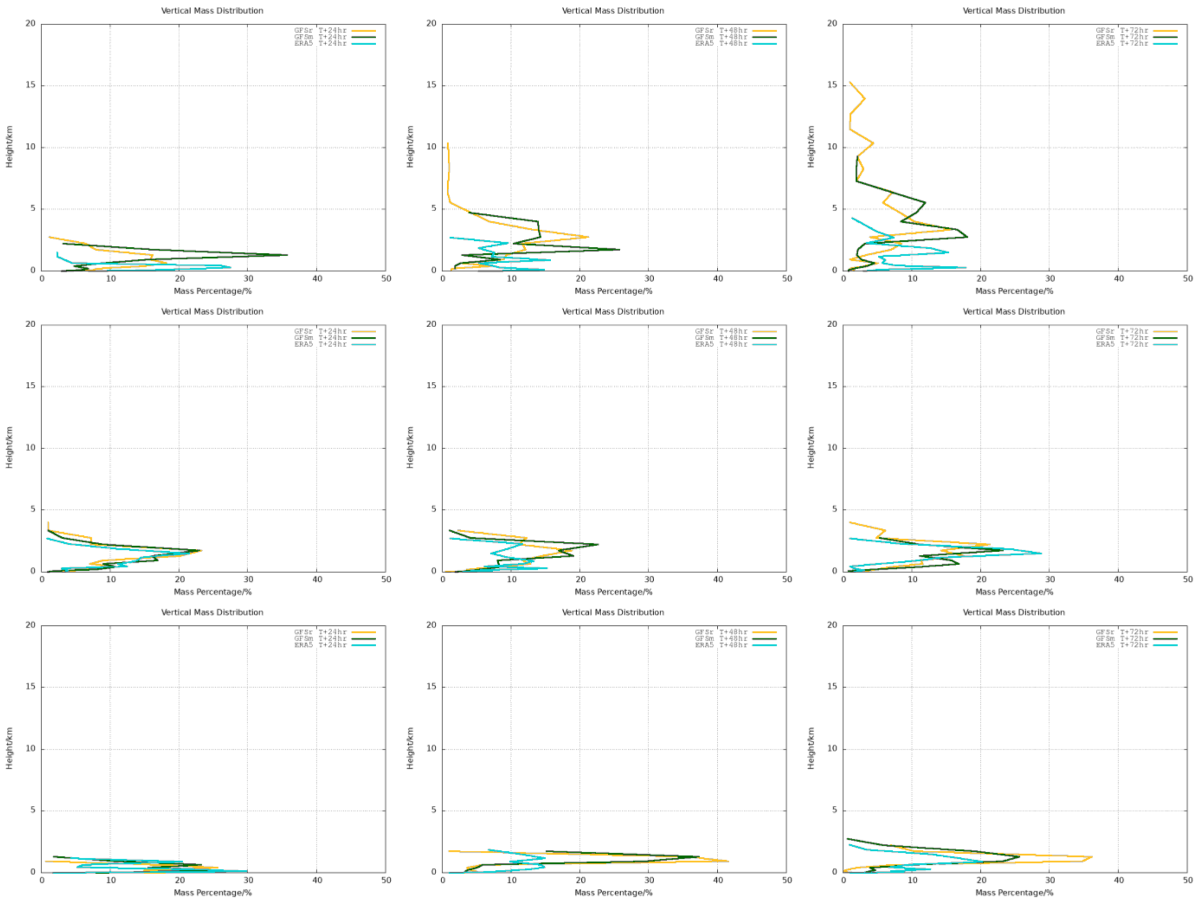


Fig. 5. Vertical mass distribution of Cs-137 evolution over the first three days (left, middle, right columns are for day 1 , day 2 and day3 respectively) using the three different driving meteorological data (orange, green, blue lines respectively for GFSr, GFSm, and ERA5) from simulations with different source locations (top, middle, bottom rows for Singapore, Changjiang, and Zaporizhzhia respectively)

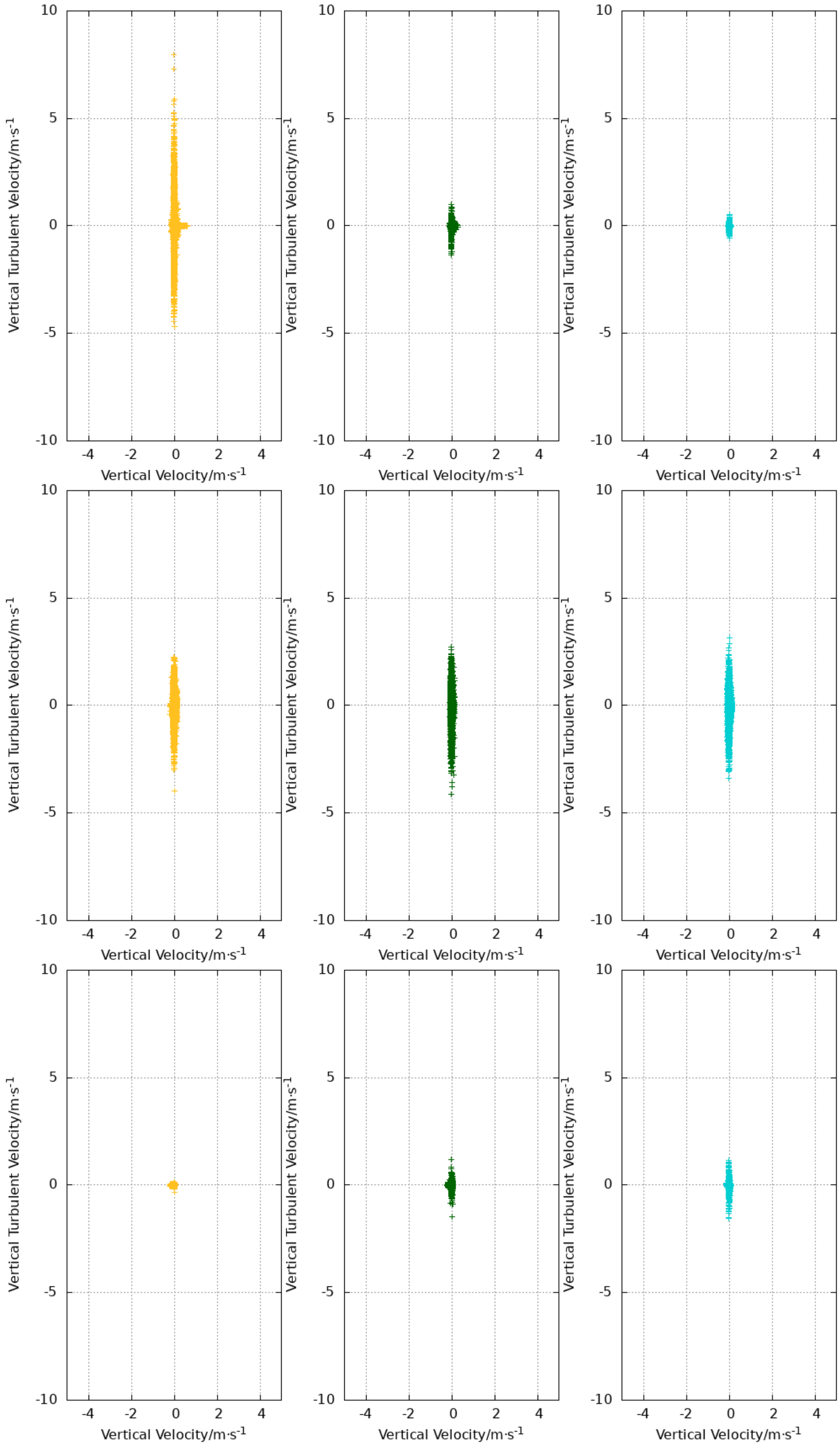


Fig. 6. Scatter plot of vertical grid-resolvable wind (x axis) and vertical turbulent velocity (y axis) using the GFSr (left column in orange), the GFSm (centre column in dark-green), and the ERA5 (right column in light-blue) from simulations with different source locations (top, middle, bottom rows for Singapore, Changjiang, and Zaporizhzhia respectively)

C. Discussion

Figure 3 demonstrates the horizontal and vertical spatial distribution of Cs-137 particles for the Singapore run. It is evident that both the horizontal distribution and vertical extension of the particles are sensitive to meteorological data, especially between the ERA5 and the other two in the vertical direction. This is consistent with the conclusion by Draxler et al. [6]. Although the GFSm and the ERA5 are closer to the true state of the atmosphere, the vertical extension of plume in the GFSm run is comparable to the GFSr, indicating the growing forecast errors inherent in the GFSr is not a factor for the vertical extension differences between the ERA5 and the GFS families. The systematic turbulence and stability differences between the GFS model and ECMWF model are instead the main reasons. By switching off the vertical turbulent mixing, the plume height for all experiments are confined within the 1 km above the ground, indicating that the vertical turbulent mixing is the key for the plume to be able to shoot up to aircraft cruising level of 12 km or higher. It can be seen from Fig. 4 that the GFSr and the GFSm results for Singapore have higher plumes than the ERA5, but less pronounced in the Changjiang or Zaporizhzhia case. This is mainly due to the vertical turbulent velocity differences. Figure 4 also illustrates that the plumes are generally higher in the tropical area than higher latitude cases, which is expected as the heating and convection are stronger in lower-latitude regions.

The Cs-137 concentrations in the free atmosphere are largely smaller than 10000 Bq/m^3. In the case where plume rises to cruising levels (top centre chart in Fig. 4, the GFSm Singapore simulation), the majority concentrations of Cs-137 are around 2200 Bq/m^3. Based on the International Commission on Radiological Protection Publication 60 (ICRP 60) [15], the air submersion effective dose rate is 0.734 μSv/h, or 0.2 mSv/h if considering its decay product Ba-137m. Since the horizontal scale of the plume at that level is very limited, which is 100 km in our case, the effective dose received for typical aircraft flying through the plume is 22.2 μSv at a speed of 900 km/h, similar to that of cosmic ray radiation one may receive during a long-haul flight [16].

Further analysis on the turbulent vertical velocity supports the conclusion that the turbulent mixing is the key to plume vertical extension. Figure 5 shows the vertical mass distribution profiles in the 100-particle release simulations. The two GFS simulations for Singapore exhibit significant higher plumes development than the ERA5 (top row) but not for the rest. Figure 6 illustrates the relative magnitude comparison of vertical grid-resolvable velocity (x axis) and vertical turbulent velocity (y axis) by pairing them up in scatter plots. The figure demonstrates that the vertical turbulent velocities are in many cases much larger than the vertical grid-resolvable velocities. Comparison across driving meteorological models shows that the magnitude of vertical turbulent velocities from the two GFS simulations are very different from the ERA5 in the Singapore runs (top row), but arguably comparable in the results of Changjiang (middle row) and Zaporizhzhia (bottom row). This is largely consistent with the pattern differences of vertical mass distribution in Fig. 5. This tells us that the differences of vertical turbulent velocities between different driving meteorological data are latitude dependent.

It should be noted that there are a few ways to improve the study of the vertical plume distribution in free atmosphere. Firstly, it is desirable to include boreal summer cases to investigate if there are any seasonal differences. Our team would also like to carry out in the future using higher-resolution (~ 1 km) regional meteorological data instead to further study the sensitivity of the vertical extension of plume to the horizontal resolutions of the driving meteorological data. Additionally, based on recommendations by Zhuang et al. [17], the vertical resolution of meteorological data also play a role in diagnosing vertical turbulent velocity, experimenting different vertical resolutions is another direction to attempt in the future.

III. CONCLUSIONS

The Lagrangian atmospheric dispersion model HYSPLIT is used to investigate the vertical extension of radionuclides in hypothetical release scenarios of Cs-137 using different meteorological data and for different source locations. Through a boreal winter case study, the concentration and dose rate of the radionuclide plumes in the upper air are calculated. With similar release rate of Cs-137 in the Fukushima Dai-ichi NPP accident, the total upper air dose simulated in one of the worst results at cruising level is 22.2 μSv, about the same order that one may receive from cosmic rays during a long-haul flight. It is found that the key factor to determine how high the plume can reach is the vertical turbulent velocity, which is in most cases much larger than corresponding vertical grid-resolvable velocity at the same position. The vertical turbulent velocity obtained from different meteorological data differ and such differences are latitude dependent. In our case study, significant differences are found in the tropical region. Considering the sensitivity to meteorological data and the dependency on the latitudes of simulation domains, the uncertainties of air concentration or dose in free troposphere need to be addressed and caution must be taken when providing the results to stakeholders.

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REFERENCES

[1]. Á. Leelőssya, I. Lagzib, A. Kovácsa, et al., “A review of numerical models to predict the atmospheric dispersion of radionuclides”, *J. Environ. Radioact.*, 182, pp. 20-33 (2018). https://doi.org/10.1016/j.jenvrad.2017.11.009.

[2]. I. Korsakissok, A. Mathieu, D. Didier, “Atmospheric dispersion and ground deposition induced by the Fukushima Nuclear Power Plant accident: A local-scale simulation and sensitivity study”, *Atmos. Environ.*, 70, pp. 267-279 (2013). http://dx.doi.org/10.1016/j.atmosenv.2013.01.002.

[3]. G.-S. Choi, J.-M. Lim, K.-S. Lim, et al., “Characteristics of regional scale atmospheric dispersion around Ki-Jang research reactor using the Lagrangian Gaussian puff dispersion model”, *Nucl. Eng. Technol.*, 50, pp. 68-79 (2018). https://doi.org/10.1016/j.net.2017.10.002.

[4]. K. Silva, P. Krisanungkura, N. Khunsrimek, et al., “Inter-comparison of transboundary atmospheric dispersion calculations: A summary of outputs from the ASEAN NPSR benchmark exercise”, *Prog. Nucl. Energy*, 135, pp. 1-12, (2021). https://doi.org/10.1016/j.pnucene.2021.103718.

[5]. M. Ulimoen, E. Berge, H. Klein, et al., “Comparing model skills for deterministic versus ensemble dispersion modelling: The Fukushima Daiichi NPP accident as a case study”, *Sci. Total Environ.*, 806, pp. 1-17 (2022).

https://doi.org/10.1016/j.scitotenv.2021.150128.

[6]. R. R. Draxler and G. D. Hess, "An Overview of the HYSPLIT_4 Modelling System for Trajectories, Dispersion, and Deposition", *Aust. Meteorol. Mag.*, 47, pp. 295-308 (1998).

[7]. A. F. Stein, R. R. Draxler, G. D. Rolph, et al., "NOAA's HYSPLIT atmospheric transport and dispersion modeling system", *Bull. Amer. Meteor. Soc.*, 96, pp. 2059-2077 (2015). https://doi.org/10.1175/BAMS-D-14-00110.1.

[8]. J. Brioude, D. Arnold, A. Stohl, et al., "The Lagrangian particle dispersion model FLEXPART-WRF", *Geosci. Model Dev.*, 6, pp. 1889-1904 (2013). https://doi.org/10.5194/gmd-6-1889-2013.

[9]. I. Pisso, E. Sollum, H. Grythe, N. I. Kristiansen, et al., "The Lagrangian particle dispersion model FLEXPART version 10.4", *Geosci. Model Dev.*, ***12***, pp 4955-4997 (2019). https://doi.org/10.5194/gmd-12-4955-2019.

[10]. A. Bátkai, P. Csomós, I. Faragó, et al., "Chapter 5 Eulerian and Lagrangian Approaches for Modelling of Air Quality" in *Mathematical* Problems *in Meteorological Modelling* (Springer, Switzerland, 2016), pp. 73-74.

[11]. H. Hersbach, B. Bell, P. Berrisford, et al., "The ERA5 global reanalysis", Q. *J. R. Meteorol. Soc.*, 146, pp. 1999-2049 (2020). https://doi.org/10.1002/qj.3803.

[12]. National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (2015): "NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive". Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D65D8PWK. Accessed 01 Feb 2023.

[13]. K. Takuya, N. Haruyasu, M. Chino, et al., "Source term estimation of atmospheric release due to the Fukushima Dai-ichi Nuclear Power Plant accident by atmospheric and oceanic dispersion simulations", *J. Nucl. Sci. Technol.*, 50 (3), pp. 255-264 (2013).

https://doi.org/10.1080/00223131.2013.772449.

[14]. N. Fong, C. P. Loughner, A. Stein, "The evaluation of mixing methods in HYSPLIT using measurements from controlled tracer experiments", *Atmos. Environ.*, 219, pp. 1-15 (2019).

https://doi.org/10.1016/j.atmosenv.2019.117043.

[15]. ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1-3).

[16]. J.-F. Bottollier-Depois, Q. Chau, P. Bouisset, et al., "Assessing exposure to cosmic radiation during long-haul flights", *Radiat. Res.*, 153, pp. 526-532 (2000).

[17]. J. Zhuang, D. J. Jacob, and S. D. Eastham, "The importance of vertical resolution in the free troposphere for modeling intercontinental plumes", *Atmos. Chem. Phys.*, 18, pp. 6039-6055 (2018). https://doi.org/10.5194/acp-18-6039-2018.