CBRN events management and the use of the Hysplit model: an integrative literature review

Gestão de eventos QBRN e a utilização do modelo Hysplit: uma revisão integrativa de literatura

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ABSTRACT The potential risk of exposure of populations to Chemical, Biological, Radioactive and Nuclear agents (CBRN), either by intentional causes or not, is a matter of national security and demands a constant improvement in its management. The models of atmospheric dispersion have been gaining prominence as a tool to support the management of risks to CBRN agents. The objective of this research was to identify and evaluate studies that used the Hysplit model in the context of CBRN events. For this purpose, an integrative literature review of published articles was conducted between 2014 and 2018, from the PubMed, Scopus, Web of Science and Lilacs databases. The analysis of the selected articles revealed the potential of the Hysplit model, as a mathematical model, to understand the transport, dispersion and deposition of CBRN threats released into the atmosphere. The data produced by the simulations generated by this code can reveal which areas will be potentially impacted in a given event or the region of origin of elements dispersed in the air. In addition, Hysplit can be aggregated as a decisions support tool in the different phases of CBRN event management.

KEYWORDS Pollutants dispersion. Scattering radiation. Chemical accidents and events. Radioactive hazard release. Risk management.

RESUMO *O potencial risco de exposição das populações aos agentes Químicos, Biológicos, Radioativos e Nucleares (QBRN), seja por causas intencionais ou não, configura-se como questão de segurança nacional e demanda um constante aprimoramento do seu gerenciamento. Os modelos de dispersão atmosférica vêm ganhando destaque como ferramenta de apoio à gestão dos riscos aos agentes QBRN. O objetivo desta pesquisa foi identificar e avaliar estudos que utilizaram o modelo Hysplit no contexto de eventos QBRN. Para tanto, foi realizada uma revisão integrativa de literatura de artigos publicados entre 2014 e 2018, nas bases de dados PubMed, Scopus, Web of Science e Lilacs. A análise dos artigos selecionados permitiu verificar o potencial do uso do modelo Hysplit, enquanto modelo matemático, para compreender o transporte, a dispersão e a deposição de ameaças QBRN liberadas na atmosfera. Os dados produzidos pelas simulações geradas por esse código podem revelar quais áreas serão potencialmente impactadas em um determinado evento ou a região de origem de elementos dispersos no ar. Ademais, o Hysplit pode ser agregado como uma ferramenta de suporte às decisões perante as distintas fases da gestão de eventos QBRN.*

PALAVRAS-CHAVE *Dispersão de poluentes. Espalhamento de radiação. Acidentes e eventos químicos. Liberação nociva de radioativos. Gestão de riscos.*

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Introduction

The evolution of society and the advance of technological and industrial processes demand the manufacturing or manipulation of a relevant quantity of chemical substances, biological agents and radioactive elements[1]. Rapid advances in scientific and technological knowledge, coupled with the development of industry, the expansion of power generation capacity, increased agricultural productivity, food engineering, among others, were accompanied by increased exposure to the risks posed by Chemical, Biological, Radioactive and Nuclear agents (CBRN). However, there was, also, the improvement of strategies for occupational health care and the improvement of diagnoses and care of human and animal health[2].

The use of agents of physical, chemical and biological risks in environments and in concentrations capable of causing harm to human health or causing death transcends the labor dimension. Historically, the use of these agents in territorial, religious, social and cultural disputes has been registered. Such uses are listed from Antiquity to World War I and II, pervading the most contemporary terrorist attacks, such as: the dispersal of anthrax and ricin in letters addressed to American politicians (2001, 2003, 2004, 2013 and 2018); the detonation of improvised explosive devices during the Boston Marathon in the United States (2013), on the outskirts of the Stade de France, in the city of Saint-Denis, in France (2015), and inside Brussels Airport, in Belgium (2016); the sarin gas attacks on the Tokyo subway, in Japan (1995), and with chemical containing reactive chlorine in Douma, Syria (2018).

In a different context, there are thefts of sources or radiological materials, such as the accident occurred in Goiania, in 1987, with cesium-137, which is still considered one of the largest radiological disasters in the world.

Under other circumstances, there is, also, the possibility of disasters, such as floods, earthquakes, landslides, explosions triggering events by CBRN agents *a posteriori*, such as the one at Fukushima Nuclear Power Plant, on March 11, 2011, when it was hit by a tsunami originated from an earthquake that occurred on the coast of Japan.

All these aspects demonstrate how populations are exposed to the risks of accidents, incidents and disasters involving chemicals, biological agents, radiological and nuclear elements (CBRN). Furthermore, the impacts of these events may result in human, environmental, economic and social losses, which translate into an emergency public health situation and may take decades to be remedied[3]. Thus, the ability and technical skills to rapidly detect an attack with CBRN agents is of paramount importance in response action, in order to protect individuals and the environment.

The events management of CBRN nature has gained prominence in the international and national scenarios, as it serves as a framework for the design of public policies, which guides the creation and maintenance of sustainable capacities, as well as the investment, funding and planning of operational response plans, improving control, supervision, information exchange and decision making[4]. It is configured itself as a matter of national security and governance, which involves a variety of sectors, including, especially, defense, science and technology, health and the environment[5].

The management of these events is understood as a cyclical process, consisting of stages: (a) planning – related to the evaluation of the environment, vulnerabilities, capabilities and risks. Evaluation should be implemented before and after events, as it determines readiness and facilitates response and recovery; (b) preparation – stage of implementation of the plan and readiness mechanisms through training, exercises and certification. The planning and preparation stages are aimed at reducing vulnerabilities, which will support prevention and mitigation; (c) response – it acts against the direct, immediate effects of a

CBRN event, including health and safety preservation actions, safeguarding lives; prevention of human suffering; property protection and establishing control measures, in order to prevent or reduce the spread of contamination, human injury or deaths, environmental damage and material damage; (d) recovery – only initiated after containment or control of immediate risks. Recovery aims to restore essential services and complete immediate risk mitigation[6].

Components such as command, control, communications, computers, intelligence, surveillance and reconnaissance are considered to be fundamental requirements for a CBRN threat response force, and the use of information systems can make the entire operation more agile, efficient, intelligent and secure[1].

Therefore, for the management of CBRN threats, especially the impacts of airborne dispersal agents, atmospheric dispersion studies are critical in supporting decision making, relating to scenario evaluation and modeling of the consequences for teams responsible for first response action to CBRN emergencies and the population by and large. Dispersion models can help in understanding the mechanisms of agent dissemination capable of causing damage on a local, regional and global scale; and, thereby, make predictions of the impacts of emissions on the troposphere, whether that impact is from stationary sources or from mobile sources. These models use mathematical equations to describe the atmosphere, dispersion and physical and chemical processes that occur with a plume emitted by a particular source.

Among the most established methodologies, are the physicochemical and biological analyzes of air samples, as well as the evaluation of the deposition of these samples in water bodies or soil and its possible effects[7,8]. However, with the advancement of data science and the potential for processing large volumes of information, the use of computational models capable of analyzing the various dimensions of numerous substances in the face of different situations has been gaining prominence, mainly because it can incorporate notions of scenarios real and hypothetical[9].

Models of Atmospheric Transport, Dispersion and Atmospheric Deposition (MTADD) describe the transport, in space and time, of gases and particles carried in air masses in the atmosphere, including chemical pollutants, radioactive matter, particulate matter such as dust and bioaerosols. The modeling with the use of logic tools offers different data output models, from Gaussian plume models to very complex models, based on Computational Fluid Dynamics (CFD, in english). Thus, the choice of a particular model depends on the purpose of the study, the substances involved and the extent and complexity of the area to be evaluated[7,10].

Among the most well-known MTADD, are: Atmospheric Dispersion Modeling System (ADMS), American Meteorological Society/United States Environmental Protection Agency Regulatory Model (Aermod), Areal Locations of Hazardous Atmospheres (Aloha), Californian Puff Model (Calpuff), Hybrid Single-Particle Lagrangian Integrated Trajectory Model (Hysplit), Numerical Atmospheric-dispersion Modeling Environment (Name), Risø Mesoscale PUFF Model (Rimpuff).

Among these models, Hysplit has stood out for being a public domain platform, effective for different classes of atmospheric scales, with easy to use graphical user interface, fast processing and that has an online module[11]. Weather data may come from *in situ* measurements, from (local) weather stations or from the Global Data Assimilation System (GDAS)[9].

GDAS is a worldwide weather observation database that records observations in a space modeled on a three-dimensional grid. It presents the purpose of starting or initializing weather forecasts with verified observations. It adds observations such as surface data, balloon data, wind profile data, aircraft reports, buoy observations, radar observations and satellite observations[9,12].

According to the National Oceanic and Atmospheric Administration (NOAA)[9], the Hysplit model is a complete system for computing simple air mass trajectories, as well as complex transport, dispersion, chemical transformation and deposition simulations. One of the most common applications is posterior trajectory analysis to determine the origin of air masses and to establish thermo-source and receptor relationships. It adopts a hybrid method of calculation using lagrangean approach and the eulerian methodology or *puff* and particle models. It is also capable of employing CFD models, useful in complex lands, such as urban environments, where spatial scales of interest are close to characteristic scales of the landscape.

According to Silva[13], lagrangian models describe the trajectory of each particle from a moving reference frame, and eulerian models describe the dispersion processes through a fixed observer regarding plume movement.

Leelössy et al.[14] state that the *puff* models treat the scattered materials as a superposition of several clouds, with a certain volume, and calculate the trajectories of these *'puffs'*.

International and national studies reveal that Hysplit has been used in a variety of simulations to describe atmospheric transport, dispersion and deposition of pollutants and hazardous materials[9-13]. Thus, this model presents itself as a potential tool to assist in outlining the various phases of CBRN event management.

This article aims to identify and evaluate studies that used the Hysplit model in the context of CBRN events.

Methodology

In the present study, one of the resources of evidence-based practice was selected as the method, that is, the integrative literature review, which enables the synthesis and analysis of the scientific knowledge already produced on the subject, interconnecting isolated elements of studies already existing[15].

The study was designed in the following stages: (1) hypothesis establishment; (2) choice of eligibility criteria, that is, inclusion and exclusion; (3) identification of pre-selected studies; (4) full reading of articles, data extraction and categorization of selected studies; (5) analysis, interpretation and discussion of results; and (6) presentation of the review/synthesis of knowledge.

To guide the integrative review, the following question was asked: How has the Hysplit model been used in the context of CBRN event management?

For data collection, the following databases were used: National Library of Medicine (PubMed), SciVerse Scopus (Scopus), Web of Science and Latin American and Caribbean Health Sciences Literature (Lilacs).

The search strategy used in these databases was: ['Hybrid Single Particle Lagrangian Integrated Trajectory Model' OR Hysplit]. The search and selection of articles were performed in titles, abstracts and keywords, based on the inclusion and exclusion criteria, by two independent evaluators.

In addition, the bibliographic survey restricted the search for publication languages (English, Spanish and Portuguese), for the year of publication (2014 to 2018), as for the type of published material (scientific articles and/or review articles) and studies that directly addressed the use of the Hysplit model in CBRN event scenarios.

Exclusion criteria were defined as: articles of general content, that is, that dealt with the dispersion of atmospheric pollutants, articles that did not directly portray CBRN accidents and articles not fully available.

Endnote® software was used for the management of bibliographic references, easy application and availability in most databases and journals. It assisted in the importation and direct transfer of selected studies from the researched databases to a specific research archive.

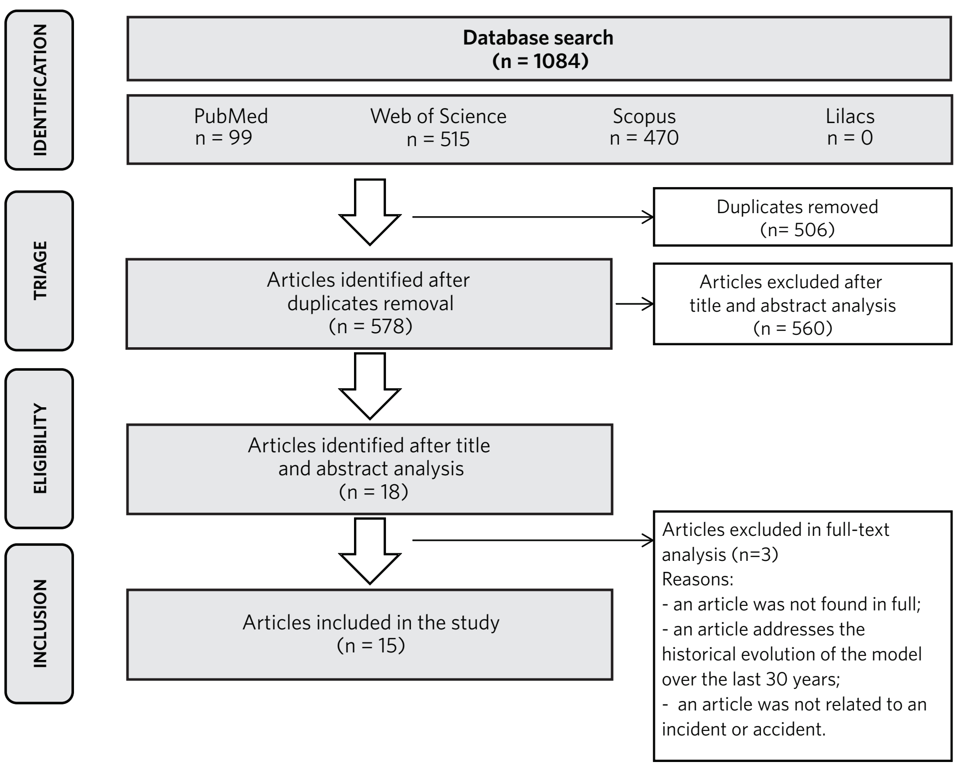
The articles were read in their entirety, and, for the analysis, synthesis tables specially built for this purpose were used, contemplating the following aspects, considered pertinent: data related to authorship; year of publication; study area; general purpose of the work; purpose of using the Hysplit model; and methodological characteristics.

Consensus meetings were held with other researchers when there were questions about including studies in the review. Studies whose summaries were dubious were read in full.

Results and discussion

A total of 1084 records were identified in the databases consulted, and 506 duplicates were removed, resulting in 578 studies submitted to title, abstract and keyword screening. This initial screening removed 560 articles that did not meet the eligibility criteria. Subsequently, after reading the full text of the 18 elected articles, 3 were excluded (one article because it was not found in its entirety; one because it was a historical article; and another because it was not related to an incidental or accidental scenario), totaling 15 articles selected for this study (*figure 1*).

Figure 1. Study selection flowchart



The description of the studies included in the review is presented in *chart 1*, as well as the purpose of using Hysplit. The main sites for these studies were North America (United States and Canada), Europe (France and Germany), and Asia (Japan, China, South Korea, Iran). Only one study was carried out in Brazil, a fact that may be related to the higher occurrence of CBRN events in the mentioned sites and for being at the forefront of scientific and technological development.

Chart 1. Description of articles included in the research

Reference (year)	Study site	Objectives	Hysplit use purpose
An et al. (2016)	South Korea	Evaluate the atmospheric dispersion of radioactive material (cesium-137) according to local climatic conditions and emission conditions.	Analyze the characteristics of radioactive dispersion in the atmosphere.
Auxier, Auxier e Hall (2017)	United States	Review and compare the different codes that were developed to predict the consequences of chemical weapons.	Hysplit presents prediction capability of nuclear precipitation.
Chai, Draxler e Stein (2015)	United States; Canada and Europe	Determine if global monitoring networks can be used to quantify temporal variations of emissions from a known source site.	Assist in the creation of a transfer coefficient matrix (TCM) to test an inverse emission estimation system.
Felsberg et al. (2018)	Germany and France	Evaluate the ability to simulate kriptton-85 dispersion emitted by a nuclear fuel reprocessing power plant in northwestern France.	Simulate Kr-85 transport in Europe over three periods of time.
GeYang e Ou (2018)	China	Design a set of dynamic surveillance systems against chemical accidents structured from the internet of things, embracing the principles of speed, simplicity and reliability.	Quantitatively simulate the diffusion model of a particular type of air pollution from a chemical accident.
Katata et al. (2015)	Japan	Estimate detailed atmospheric releases during the Fukushima Daiichi Nuclear Power Plant accident using a reverse estimation method that calculates radionuclide release rates by comparing air concentration measurements of a radionuclide or its ambient dose rate with those calculated by atmospheric and oceanic transport, dispersion and deposition models.	Compare the numerical simulations of three atmospheric dispersion models (Hysplit, MLDP0 and Name) with the observations using new source term estimates.
Leelossy et al. (2017)	Europe	To evaluate the performance of the online WRF-Chem Eulerian, Hysplit and Raptor Lagrangian models and to indicate uncertainties in a complex climate situation in Central Europe, on November 4, 2011.	Hysplit has been adopted as a reference model against the online WRF-Chem Eulerian and Raptor Lagrangian models for simulating radioactive plume dispersion and spatial distribution of I-131 in Central Europe.
Pirouzmand, Kowsar e Dehghani (2018)	Iran	Simulate the consequences of a blackout at the cooling station of the Bushehr-1 Nuclear Power Plant and the subsequent loss of large amounts of liquid used in this process.	Evaluate radionuclide dispersion and transport to a limited number of fission products released under a hypothetical accident.
Ramana, Nayyar e Schoeppner (2016)	India	Describe different chemical explosions and examine how such explosions could occur at the Kalpakkam Reprocessing Plant and discuss the results of a simulation of atmospheric dispersion, including a calculation of the potential radiation dose for the exposed population.	Calculate the radioactivity atmospheric dispersion of an explosion in a reprocessing waste tank.
Rolph, Ngan e Draxler (2014)	United States	Model the dispersal, deposition, decay of nuclear debris and calculate the radioactive dose rates following the detonation of six relatively small nuclear devices in the 1950s, in Nevada.	Configure the model with various particle size and activity distributions obtained from various published sources, and calculate dose rate contours for various nuclear tests at the site studied.

Chart 1. (cont.)

Silva et al. (2018)	Brazil	Simulate the air mass trajectories of two case studies: a natural event (volcano eruption) and a chemical accident that generated fire in the port region of Guarujá, São Paulo.	Simulate the air mass trajectories of the analyzed events.
Simsek et al. (2014)	Europe; Turkey	Simulate the transport and disposal of Cs-137 over Europe that occurred after the Chernobyl Nuclear Power Plant accident.	Calculate the total Cs-137 deposition (wet and dry) and surface air concentrations that occurred in Europe and Turkey after the Chernobyl nuclear reactor accident.
Vali et al. (2018)	Iran	Evaluate radiation doses for residents of Tehran province following a hypothetical accident in the Tehran Research Reactor (TRR), including determining any protective actions that may be necessary for the benefit of human health.	Calculate the concentration of radionuclides in the air and the one deposited on the soil surface as a result of a hypothetical release of radionuclides from the TRR following a hypothetical accident scenario.
Wu et al. (2015)	China	Detect the arrival of radionuclides through atmospheric transport after the Fukushima Daiichi nuclear power plant accident in Lanzhou, China.	Simulate the path of the air masses of the Fukushima crash that arrived in Lanzhou, China.
Zhang et al. (2015)	Hungary	Investigate the temporal variations of radionuclides discharged from the Fukushima Daiichi nuclear power plant accident, from aerosol sample collections in Osaka, Japan.	Verify the direct air mass transportation from Fukushima area to Osaka city.

Most of the studies expressed as main objective the analysis of transport, dispersion and deposition of CBRN material in the atmosphere, adopting Hysplit as a tool to predict hypothetical scenarios and/or confirm the potentially impacted route, extent and locations in case of accidents. It is emphasized, furthermore, that this model can be used in a wide range of simulations outside the CBRN context, such as volcanic eruptions, burns, and sandstorms[11].

In this review, twelve articles adopted as a methodology the simulation from real scenarios, and four addressed hypothetical scenarios. Among the real scenarios, Katata et al., Wu et al. and Zhang et al.[16-18] presented simulation results related to the Fukushima accident, where they demonstrated that the Hysplit model was able to represent the phenomenon of atmospheric transport and dispersion, as well as the deposition of radioactive substances released during the nuclear power plant accident impacted by the tsunami.

Katata et al.[16] estimated the variations in atmospheric releases of radionuclides during the event. According to the simulations, during March 15 and 16, the highest rates of radioactive contamination were created in the areas around the power plant. The authors related this increase to the complicated interactions between precipitation, plume movement and temporal variation of iodine-131 and cesium-137 release rates.

Wu et al.[17], besides simulating the direct transfer of the air masses released from Fukushima to China, crossing the Pacific Ocean, North America and Europe, at a height close to 9.000 meters above the ground, presented data from the radioactivity monitoring program in atmospheric particles of the chinese city of Lanzhou, which detected and measured aerosol samples from March 26 to May 2, 2011. The authors assume that contamination was still monitored for a long time, but that no evidence of large air fluctuations was found, except in March 2013, where a significant increase in Cs-137 concentration was detected in aerosol samples during a sandstorm period.

Zhang et al.[18] evaluated the daily variation in activity concentrations of iodine-131, cesium-134 and cesium-137 in the atmosphere in the city of Osaka, Japan, between March 15 and May 11, 2011. The authors observed an increase in activity concentration between April 6 and April 17 and correlated it with the direct transport of the Fukushima area, as demonstrated by the Hysplit model path simulations.

In another context, but also using information about the accident of Fukushima, Chai, Draxler, and Stein[23] conducted a survey of airborne cesium-137 concentration data, deriving from monitoring stations in the USA, Canada and Europe, to determine whether global monitoring could be used to quantify temporal variations in emissions from a known source site. The researchers developed an inverse emission estimation system based on a transfer coefficient matrix, using the Hysplit model, and a functional cost that measures the differences between model predictions and actual air concentration measurements. Compared to other studies, research has shown that the system created was able to successfully capture major temporal variations and identify most major events in the temporal profile of the release.

In addition to the work involving the Fukushima accident, a study related to the Chernobyl Nuclear Power Plant accident, in 1986, was found. Simsek et al.[19] used Hysplit to simulate cesium-137 deposition on Turkey from data of the Atlas Caesium in Europe (published in 1998), which contains the accident information, but does not cover the territory of Turkey. The authors also estimated the effective radiological doses of simulated air concentrations and deposition, which reached 0,15 millisievert (mSv)/year in northeastern Turkey, which revealed contamination within the allowable limits proposed by the International Atomic Energy Agency, which is 1 mSv/year for individuals in general (not occupationally exposed).

Felsberg et al.[20] evaluated Hysplit's ability to simulate the dispersion of radiokryton-85 released by a nuclear fuel reprocessing power plant in northwestern France. Researchers show that this material is an important marker for testing the performance of atmospheric dispersion models due to their half-life, chemical inertia and low water solubility. Although the results have demonstrated a slight tendency to underestimate the concentrations found, there is a significant correlation and moderate dispersion between observations and simulations.

Other research addressed a real accident scenario by investigating the leakage and subsequent fire of a chemical load containing sodium dichloroisocyanurate dihydrate, potassium nitrate, herbicides, insecticides, resins and insulating oil, in a business cargo area of the Port of Guarujá in São Paulo, on January 14, 2016. Silva et al.[21] simulated the spread of pollutants emitted during the event and were able to verify that, although it had a small range, on a regional scale, it could have serious consequences for the public and environmental health of the region around Porto, as several toxic gases were released.

Regarding the hypothetical scenarios, An et al.[22] used data from the Chernobyl and Fukushima nuclear disasters, from the Atmospheric Transport Model Evaluation Study and the Tokyo Electric Power Company, as a basis for assessing the climate conditions of surrounding areas and the conditions of emission of radioactive materials in the event of accidents at the Kori Nuclear Power Plant in South Korea. The study showed that, even within a radius next to the plant, cesium distribution and concentration levels may vary with changing conditions, with the topography of the region and the number of particles emitted. The authors point out that the main results could be used to formulate efficient and systematic prevention measures for nuclear disasters and to obtain emergency responses against radiation accidents.

Ramana, Nayyar and Schoeppner[24] demonstrated the results of a possible explosion at the Kalpakkam Atomic Reprocessing Plant, in India. The simulated scenarios of a radioactive release, assumed to be 10% of the inventory of only one of the plant's tanks, show that such an accident could have serious public health consequences, with nearly 47.000 cancer-related deaths, an increase in the incidence of this pathology in about 97.000 cases and contamination of large areas for decades.

Pirouzmand, Kowsar and Dehghani[25] present a case study of the Bushehr-1 Nuclear Power Plant, in Iran, where they evaluated the atmospheric concentration of 23 released radioactive material types and the effective external doses received by populations within 30 km of the facility. The researchers found that the highest doses would be expected 3 km north and 4 km northwest of the reactor location, in addition, the maximum effective doses for all emission scenarios have alarmingly exceeded (at least more than 40 times).

Also in Iran, Vali et al.[26] evaluated the effects of a hypothetical accident following an earthquake in the area near the Tehran Research Reactor, simulating the dispersion of radioactive elements and calculating the annual total of the effective equivalent dose that could be received by city residents of Tehran and parts of its neighboring provinces. However, it was found that the maximum doses were lower than the dose limits adopted by regulatory agencies, and, thus, there would be no need for protective action if this type of accident occurred.

The Hysplit model was also confronted with other dispersion models[14,16,27]. Auxier, Auxier and Hall[27] compared Defense Land Fallout Interpretative Code (Delfic), Hazard Prediction and Assessment Capability (HPAC), Hysplit and Fallout Dispersion Code (FDC) codes to predict the consequences of chemical and nuclear weapons in order to reduce time response for the government to deal with the event. The authors stated that, even with some differences in the results, most of the codes analyzed proved to be reliable, however, the best models to be used in evaluating a post-detention scenario were FDC or Delfic.

Katata et al.[16] compared the numerical simulations of the Hysplit, Zeroth Order Lagrangian Dispersion Model (MLDP0) and Numerical Atmospheric-dispersion Modeling Environment (Name) models during the accident at the Fukushima Daiichi Nuclear Power Plant, in 2011. The results obtained demonstrated agreement with radionuclide airborne concentration and cesium-137 surface deposition in eastern Japan.

Leelössy et al.[14] adopted Hysplit as a reference model against the online WRF-Chem Eulerian and Raptor Lagrangian models to simulate radioactive plume dispersion and iodine-131 distribution in Central Europe. In the aforementioned study it was possible to verify that the continental scale dispersion is largely dominated by atmospheric characteristics and wind uncertainty. Furthermore, the authors cite that Hysplit has been extensively applied for research and decision support in the case of the Fukushima accident.

Rolph, Ngan, and Draxler[28] analyzed the Hysplit model against nuclear precipitation measurements from six nuclear tests conducted between 1951 and 1957 in Nevada, United States. According to the authors, the model was able to reproduce general patterns of direction and deposition, however, plume simulations using Weather Research and Forecasting (WRF) weather data performed more consistently than plume simulations using data from National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis Project (NNRP).

GeYang and Ou[29] used Hysplit as a component of a surveillance system structured from the Internet of Things principle, a technological concept in which everyday objects and conditions are connected to the internet. This system acts intelligently and sensorially, from the interaction between 'real world' and 'digital world'. These same authors indicate that this integration has positive effects on environmental risks, as it has strong access to information, delivery and solution capacity.

All evaluated articles demonstrated the applicability and multifunctionality of Hysplit, mainly because of its main characteristics: working with smaller calculation volume and taking less time to obtain results, compared to other atmospheric dispersion models. The use of the model in both hypothetical and real scenarios also revealed the competence of this code.

Chart 2 presents the main characteristics of the selected studies, such as: type of event analyzed; CBRN management phase; spatial scale adopted; simulated path type; and origin of weather data.

Chart 2. Characterization of the studies included in the research. Global Data Assimilation System (GDAS)

Characteristics		**Reference (year)**
Type of event	Chemical	Auxier, Auxier and Hall (2017); Ramana, Nayyar and Schoeppner (2016); Silva et al. (2018); GeYang and Ou (2018).
	Biological	-
	Radiological/Nuclear	An et al. (2016); Auxier, Auxier and Hall (2017); Chai, Draxler and Stein (2015); Felsberg et al. (2018); Katata et al. (2015); Leelossy et al. (2017); Pirouzmand, Kowsar and Dehghani (2018); Ramana, Nayyar and Schoeppner (2016); Rolph, Ngan and Draxler (2014); Simsek et al. (2014); Vali et al. (2018); Wu et al. (2015); Zhang et al. (2015).
Management stage	Planning	An et al. (2016); Auxier, Auxier and Hall (2017); Chai, Draxler and Stein (2015); Felsberg et al. (2018); Katata et al. (2015); Leelossy et al. (2017); Pirouzmand, Kowsar and Dehghani (2018); Ramana, Nayyar and Schoeppner (2016); Rolph, Ngan, Draxler (2014); Simsek et al. (2014); Vali et al. (2018).
	Preparation	Auxier, Auxier and Hall (2017); Leelossy et al. (2017); Pirouzmand, Kowsar and Dehghani (2018); Vali et al. (2018).
	Response	GeYang and Ou (2018); Silva et al. (2018); Wu et al. (2015); Zhang et al. (2015).
	Recovery	GeYang and Ou (2018); Wu et al. (2015).
Spatial scale	Microscale	-
	Medium scale	-
	Local	-
	Urban	An et al. (2016); Auxier, Auxier and Hall (2017); GeYang and Ou (2018); Felsberg et al. (2018); Pirouzmand, Kowsar and Dehghani (2018); Ramana, Nayyar and Schoeppner (2016); Rolph, Ngan and Draxler (2014); Silva et al. (2018); Vali et al. (2018).
	Continental	Katata et al. (2015); Zhang et al. (2015).
	Global	Chai, Draxler and Stein (2015); Katata et al. (2015); Leelossy et al. (2017); Rolph, Ngan and Draxler (2014); Simsek et al. (2014); Wu et al. (2015).
Trajectory	*Backward*	Katata et al. (2015); Wu et al. (2015).
	Forward	An et al. (2016); Auxier, Auxier and Hall (2017); Chai, Draxler and Stein (2015); Felsberg et al. (2018); GeYang and Ou (2018); Leelossy et al. (2017); Pirouzmand, Kowsar and Dehghani (2018); Ramana, Nayyar and Schoeppner (2016); Rolph, Ngan and Draxler (2014); Silva et al. (2018); Simsek et al. (2014); Vali et al. (2018); Zhang et al. (2015).

Chart 2. (cont.)

Meteorological data	*In situ*	An et al. (2016); Vali et al. (2018).
	Local databases	Auxier, Auxier and Hall (2017); Felsberg et al. (2018); GeYang and Ou (2018); Katata et al. (2015); Rolph, Ngan and Draxler (2014); Simsek et al. (2014).
	GDAS	Chai, Draxler and Stein (2015); Leelossy et al. (2017); Pirouzmand, Kowsar and Dehghani (2018); Ramana, Nayyar and Schoeppner (2016); Silva et al. (2018); Wu et al. (2015); Zhang et al. (2015).

Only articles referring to the transportation, dispersion and deposition of radioactive or chemical materials were identified, such as the events mentioned above (Fukushima, Chernobyl, fire in the Port of Guarujá, in São Paulo). No article addressed the context of biological agents. However, it is noteworthy that, despite this result, there are already research groups demonstrating such application[10,12,30].

Van Leuken et al.[10] performed a review on the use of computer modeling and bioaerosol dispersion; Jamolin et al.[12] adopted Hysplit to simulate the release of anthrax spores in the metropolitan area of Washington. Prinslow[30] simulated the release of the ebola virus in different areas of the United States. All of these studies have demonstrated the capabilities and potentialities of the Hysplit model against bioaerosol simulation, however, do not take a deep read between its results and CBRN event management.

Eleven articles presented simulation characteristics more related to the planning phase. Of these, four studies are potentially linked to the prevention phase. Another four studies demonstrated the applicability of the model, being more focused on the response phase, and two were also associated with the recovery phase. Given the characteristics of the model and the information presented by the articles evaluated, it is considered that Hysplit can be used throughout the CBRN event management cycle, as a support tool in the management of scenarios involving CBRN threats.

The variable related to spatial scales was subdivided, according to Oken's classification (1998), into the following categories: microscale (10 to 100 m); medium scale (100 m to 500 m); local (50 m to 4 km); urban (4 to 100 km); regional (100 km to 1000 km); continental (1000 km to 10000 km); > 10000 km)[31]. The most widely used spatial scales were urban and global *(chart 2)*.

To simulate the transport and dispersion processes, the most adopted trajectory type was forward. This type of trajectory has the purpose of describing air mass transport processes and was adopted in 13 of the 15 selected articles. The backward trajectory, whose main function is to determine the origin of air masses, was used in 2 studies. These functions demonstrate the multifunctionality of Hysplit.

Regarding the use of meteorological data, two groups of researchers collected the data on the same place, six used local databases and seven articles used the GDAS database, which demonstrates the versatility of the model with respect to the type of data users can adopt.

All articles reviewed cited the relevance of the information generated by Hysplit to the preparation and response to distinct CBRN threats, which indicates that this model can be a useful tool in CBRN event management.

Conclusions

This review allowed us to understand the potential of using the Hysplit code as a mathematical model to understand the transport, dispersion and deposition of CBRN threats released into the atmosphere, which can have serious consequences for human health and impact various environmental matrices.

The articles retrieved in this review demonstrated the peculiarities, capabilities, limitations, robustness and accuracy of Hysplit in different contexts. In addition, Hysplit has proved to be a worldwide technological resource, especially in research related to the atmospheric sciences.

The data produced by the simulations generated by this code can reveal which areas are potentially impacted by a given event or the source region of elements dispersed into the atmosphere. In addition, Hysplit generates information that can corroborate other risk assessment tools, such as, for example, dose-response evaluation in a given exposed population. It has also been shown to be an interesting component of accident surveillance systems based on internet of things.

Furthermore, Hysplit can be added as a decision support tool to the different phases of CBRN event management, assisting in activities such as: identification of emitting sources; delimitation of safety zones (hot, warm and cold); definition of escape routes in evacuation processes. However, this study reveals the need to broaden the theoretical and practical knowledge of this model, particularly at the national level.

Collaborators

Pereira APMF (0000-0002-7041-4255)* contributed to the conception, planning, analysis and interpretation of data, as well as the writing and approval of the final version of the manuscript. Rodrigues LAC (0000-0003-0025-4177)* contributed to the conception, planning, analysis and interpretation of data, as well as to the elaboration of the draft and critical revision of the content. Santos EA (0000-0001-9620-9498)* contributed to the analysis and interpretation of data, critical review of the content and approval of the final version of the manuscript. Cardoso TAO (0000-0002-5430-7273)* contributed to the conception, planning, analysis and interpretation of the data, as well as critical review of the content and approval of the final version of the manuscript. Cohen SC (0000-0001-6228-6583)* contributed to the conception, analysis, interpretation of data, critical review of the content and approval of the final version of the manuscript. ■

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