

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**MATHEMATICAL MODELING OF
ATMOSPHERIC DISPERSION AND RISK
ASSESSMENT OF RADIONUCLIDES RELEASED
FROM REAL OR HYPOTHETICAL NUCLEAR
POWER PLANT ACCIDENTS UNDER NORMAL
OR EXTREME METEOROLOGICAL
CONDITIONS**

by
Efem BİLGİÇ

September, 2022
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CONDITIONS**

**A Thesis Submitted to the
Graduate School of Natural and Applied Science of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Doctor of
Philosophy in Environmental Engineering**

**by
Efem BİLGİÇ**

**September, 2022
İZMİR**

Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**MATHEMATICAL MODELING OF ATMOSPHERIC DISPERSION AND RISK ASSESSMENT OF RADIONUCLIDES RELEASED FROM REAL OR HYPOTHETICAL NUCLEAR POWER PLANT ACCIDENTS UNDER NORMAL OR EXTREME METEOROLOGICAL CONDITIONS**” completed by **EFEM BİLGİÇ** under supervision of **PROF.DR. ORHAN GÜNDÜZ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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MATHEMATICAL MODELING OF ATMOSPHERIC DISPERSION AND RISK ASSESSMENT OF RADIONUCLIDES RELEASED FROM REAL OR HYPOTHETICAL NUCLEAR POWER PLANT ACCIDENTS UNDER NORMAL OR EXTREME METEOROLOGICAL CONDITIONS

ABSTRACT

The impact of extreme weather events on the atmospheric dispersion of radioactive materials released from nuclear accidents has not been investigated. Therefore, this study presented a new comprehensive risk assessment methodology for nuclear accidents under normal and extreme weather conditions. With this methodology, many simulations were performed under all extreme meteorological conditions and one full year that represented year-round normal conditions. The WTEM (Weather Types and Extreme Meteorology) analysis tool developed in this study was used to analyze extreme conditions. The WTEM tool detected periods of extreme temperature, heavy rainfall, and low wind speeds between 1979-2021. Simulations were performed for Akkuyu Nuclear Power Plant (NPP) using FLEXPART dispersion model, and the source term was generated with the RARE (Radioactive Release) tool developed in this study. The results were used to calculate the 1-year total effective dose equivalent (TEDE) for adults and infants. In addition, more comprehensive TEDE calculations were applied for five worst-case scenarios, considering twenty radionuclides. All TEDE values were calculated with the SDEP (Simple Dose Estimation and Plotting) tool developed in this study. In simulations conducted throughout 1986, ground-level radio-caesium depositions were higher in the North and East of the Akkuyu NPP. On the other hand, radio-iodine concentrations were higher in the South of the source. With the effect of precipitation and transport direction, the highest depositions and TEDE were detected in the North and West of Turkey in extreme rainy periods. In extreme warm and stagnant periods, radionuclides were transported mainly to eastern Mediterranean, and the highest depositions and TEDE were determined in this region.

Keywords: Extreme weather events, nuclear power plant accidents, atmospheric dispersion modelling, radiological risk assessment, Akkuyu

GERÇEK VEYA HİPOTETİK NÜKLEER GÜÇ SANTRALİ KAZALARINDAN SALINAN RADYONÜKLİDLERİN NORMAL VEYA UÇ METEOROLOJİK KOŞULLAR ALTINDAKİ ATMOSFERİK DAĞILIMI VE RİSK DEĞERLENDİRMESİNİN MATEMATİKSEL MODELLENMESİ

ÖZ

Aşırı hava olaylarının nükleer kazalardan salınan radyoaktif maddelerin atmosferik dağılımı üzerindeki etkisi daha önce araştırılmamıştır. Bu nedenle, bu çalışma, normal ve aşırı hava olayları altındaki nükleer kazalar için yeni bir kapsamlı risk değerlendirme metodolojisi sunmaktadır. Bu metodoloji ile, normal koşulları temsil eden bir tam yıl ve uç meteorolojik koşulları temsil eden dönemler için çok sayıda simülasyon gerçekleştirilmiştir. Bu çalışmada geliştirilen WTEM aracı, uç koşulları analiz etmek için kullanılmıştır. WTEM aracı, 1979-2021 yılları arasındaki aşırı sıcak, yoğun yağışlı ve düşük rüzgârlı dönemlerini tespit etmiştir. Akkuyu Nükleer Santrali (NGS) için FLEXPART kullanılarak simülasyonlar yapılmış ve bu çalışmada geliştirilen RARE aracı ile kaynak terim üretilmiştir. Tüm simülasyonlardan elde edilen sonuçlarla, yetişkinler ve bebekler için 1 yıllık toplam etkin doz eşdeğerini (TEDE) hesaplanmıştır. Ayrıca, yirmi farklı radyonüklit dikkate alınarak beş en kötü durum senaryosu için daha kapsamlı TEDE hesaplamaları yapılmıştır. Tüm TEDE değerleri bu çalışmada geliştirilen SDEP aracı ile hesaplanmıştır. 1986 yılı boyunca yürütülen simülasyonlarda, yer seviyesindeki radyo-sezyum birikimlerinin, Akkuyu NGS'nin kuzey ve doğusunda daha yüksek olduğu tespit edildi. Öte yandan, radyo-iyot konsantrasyonları ise kaynağın güneyinde daha yüksek hesaplanmıştır. Yağışların ve taşınım yönünün de etkisiyle, aşırı yağışlı dönemlerde en yüksek birikimler ve TEDE, Türkiye'nin kuzey ve batı bölgelerinde tespit edilmiştir. Aşırı sıcak ve durgun dönemlerde ise radyonüklidler ağırlıklı olarak doğu Akdeniz'e taşınmış ve en yüksek birikimler ve TEDE bu bölgede tespit edilmiştir.

Anahtar kelimeler: Uç hava olayları, nükleer güç santrali kazaları, atmosferik dispersiyon modelleme, radyolojik risk değerlendirmesi, Akkuyu

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LIST OF SYMBOLS

He	:	Helium
CO ₂	:	Carbon Dioxide
UO ₂	:	Uranium dioxide
mSv	:	MilliSievert
ha	:	Hectares
PBq	:	Peta Becquerel, 1 PBq = 1 x 10 ¹⁵ Bq



ABBREVIATIONS

USEPA	: The United States Environmental Protection Agency
IAEA	: The International Atomic Energy Agency
USA	: The United States of America
CTBTO	: The Comprehensive Nuclear-Test-Ban Treaty Organization
WNA	: World Nuclear Association
USNRC	: The United States Nuclear Regulatory Commission
UK	: The United Kingdom
UNSCEAR	: The United Nations Scientific Committee on the Effects of Atomic Radiation
IPCC	: The Intergovernmental Panel on Climate Change
USAEC	: United States Atomic Energy Commission
NOAA	: The National Oceanic and Atmospheric Administration
EMEP	: European Monitoring and Evaluation Program
CMAQ	: The Community Multiscale Air Quality Modeling System
WRF	: The Weather Research and Forecasting
MM5	: The Fifth-Generation Penn State University/NCAR Mesoscale Model
NCAR	: The US National Center for Atmospheric Research
CPU	: Central Processing Unit
SCUAE	: USSR State Committee on the Utilization of Atomic Energy
USSR	: The Union of Soviet Socialist Republics
ICRP	: The International Commission on Radiological Protection
VVER	: The water-water energetic reactor
WHO	: The World Health Organization

CHAPTER 1

INTRODUCTION

This chapter presents the discovery of radioactivity and basic information about nuclear energy. The development of nuclear reactors for electricity production and the changes in using these reactors in time are analyzed together with severe nuclear reactor accidents and their environmental effects. Later, the importance of meteorology for accidental transport is emphasized, and the study's primary motivation, purpose, scope, and original value are presented.

1.1 Discovery of Radioactivity

In the early 1900s, some discoveries caused great excitement in the scientific community. On November 8, 1895, Wilhelm Conrad Röntgen discovered X-rays. About two months later, Antoine Henri Becquerel detected X-ray-like radiation from uranium salts and named them Becquerel rays. Marie and Pierre Curie noticed that Polonium and Radium also emit Becquerel rays, and they generalized this phenomenon, calling it radioactivity (Radvanyi & Villain, 2017).

Radiation is energy in wave or particle form (Figure 1.1) grouped in different ways. Its effect on the matter is divided into two groups: ionizing and non-ionizing radiation. High wavelength rays such as radio waves, microwaves and infrared waves are grouped as non-ionizing radiation because they do not have an ionizing effect on matter. Ultraviolet rays, gamma and X rays, short waves, and particles such as alpha and beta have an ionizing effect on matter. Therefore, such waves and particles are defined as ionizing radiation. Due to their environmental and health effects, ionizing radiation is the main scope of this study.

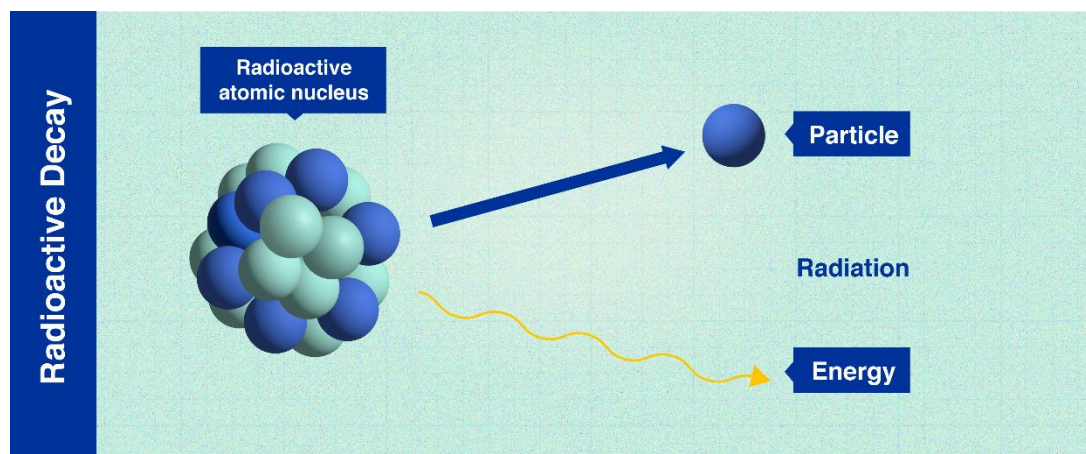


Figure 1.1 Radiation emits from the nucleus in particle or wave form (Vargas, 2022)

Radioactive elements exist in unstable forms and emit particles such as alpha, beta, and positron as well as gamma rays to become stable. The alpha particle is equivalent to a Helium atom, and because of its high mass, it loses energy very quickly by Coulomb interactions. Therefore, it can be absorbed even by thin materials such as paper and leather. On the other hand, the beta particle is an electron equivalent and has less interaction with substances since its mass is less than Helium. For this reason, thicker and more absorbent materials such as aluminum plates are required for complete absorption. On the other hand, Gamma rays are electromagnetic radiation with very low wavelengths and high energy. That is why materials like lead plates and thick concrete are necessary to stop gamma radiation (USEPA, n.d.).

Radiation activity was initially defined in Curie (Ci) units. 1 Ci is accepted as equivalent to the amount of decay (3.7×10^{10}) made by 1 gram of radium in 1 second. Today, the Becquerel (Bq) unit, which directly corresponds to the amount of decay in 1 second, is used to define the activity (Table 1.1).

The interaction of radiation with matter is examined with the concept of absorbed dose. The radiation energy absorbed by a substance in a unit mass is defined as the absorbed dose. Today, the Gray (Gy) unit expresses the absorbed dose, and 1 Gy is equivalent to 1 joule absorbed in 1 kg of substance. The erg/g and rad units were previously used for the absorbed dose. The concepts of equivalent and effective dose are used to show the biological effect of radiation. The Röntgen equivalent man (rem)

unit was initially used for these dose types, which will be explained in detail in the following sections. The Sievert (Sv) unit is used today, where 1 Sv equals 100 rem (Table 1).

Table 1.1 The units for radioactivity

Type	Unit		Conversion
	Conventional	SI Unit	
Activity	Curie, Ci	Becquerel, Bq	1 Ci = 3.7×10^{10} Bq
			1 Ci = 37 GBq
Radiation Absorbed Dose	Rad	Gray, Gy	1 Gy = 100 Rad
			1 rad = 0.01 Gy
Dose equivalent	Röntgen equivalent man, rem	Sievert, Sv	1 Sv = 100 rem

1.2 Nuclear Energy

With the discovery of radioactivity, research in physics and chemistry revved up. During this period, many new elements and subatomic particles were discovered, and the fundamental theories of modern physics were developed. The milestone for nuclear energy was the discovery of fission. Hahn and Strassmann bombarded uranium with neutrons in 1938 and obtained the elements Barium and Krypton. Later, Lise Meitner noticed that a significant amount of energy was released after this reaction, and new neutrons were formed. Thanks to these new neutrons, it was realized that more fission could be made with fissile radioelements in the environment, and more energy and neutrons could be obtained. This event is called a fission chain reaction as shown in Figure 1.2 (IAEA, 2017).

Unfortunately, these developments, which took place on the eve of the Second World War, caused the research on nuclear energy to shift to war technologies. Enrico Fermi performed the first self-contained chain fission reaction in a controlled environment in 1942. Subsequently, the USA developed a nuclear weapon with the Manhattan Project research. The nuclear weapon, called the "atomic bomb", was detonated on 6 and 9 August 1945 in the Japanese towns of Hiroshima and Nagasaki, respectively. This event revealed the destructive power of nuclear energy (CTBTO, n.d.).

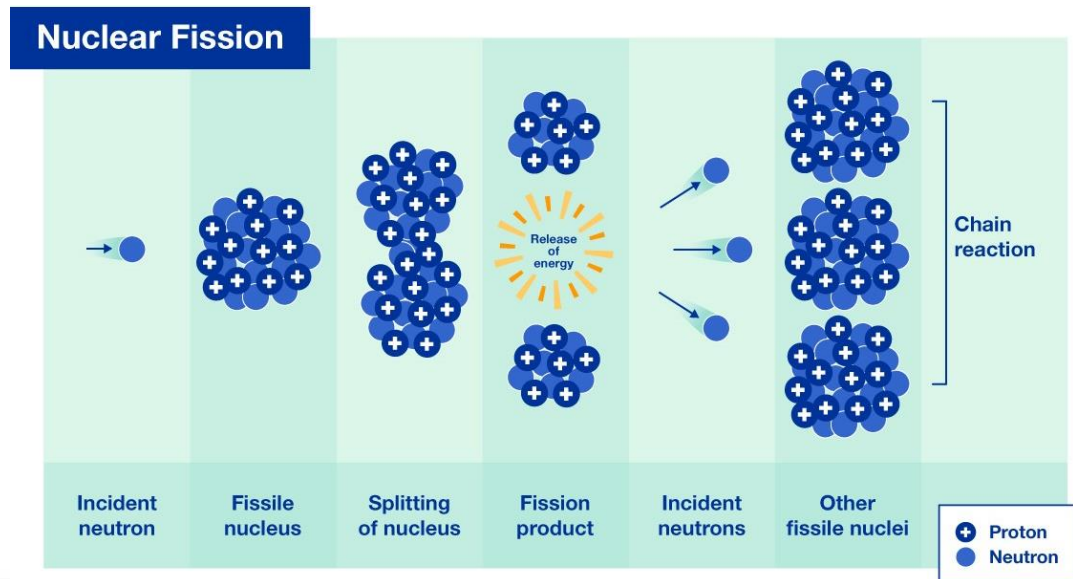


Figure 1.2 Chart of chain fission reaction (Vargas, 2021)

After the War, nuclear energy began to be used for civilian purposes and military fields. In the 1950s, some countries produced first-generation nuclear reactors used in electricity generation. In 1954, the world's first nuclear reactor, Obninsk NPP, was commissioned in the Soviet Union and had a gross capacity of only 6 MW. Calder Hall NPP in the UK with a gross capacity of 60 MW in 1956 and Shippingport NPP in the USA with 68 MW were connected to the grid. Different countries such as France, Canada, and Germany also commissioned early prototype reactors (WNA, n.d.-b).

1.3 Nuclear Reactors

Numerous fission reactions occur in nuclear reactors under controlled conditions to produce energy. It is used in steam production with the heat energy generated in many thermal power plants. The turbines are fed with the resulting steam, and electricity is produced. A nuclear reactor consists of the following parts: fuel, moderator, control rods, coolant, pressure vessel/tubes, steam generator and containment as shown in Figure 1.3 (WNA, n.d.-a).

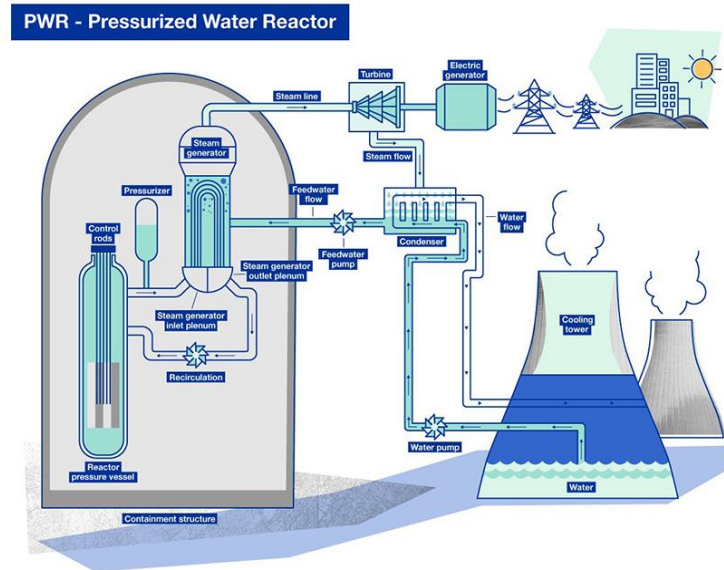


Figure 1.3 Flow chart of a pressurized water reactor (Vargas, 2021)

Fuel rods consist of fissile materials, usually containing uranium. The fuel that is typically stored in a full steel vessel is bombarded with neutrons, and a fission chain reaction begins. Moderator is used to slow down the emitted neutrons. Water, heavy water and graphite are commonly used as moderators. Control rods are the components that serve to control the neutron flow. The heat generated in the reactor core is usually removed by the coolant water and gas (e.g. He, CO₂). The cooling water is also used as a steam generator in pressure reactors. The system that houses all these processes is contained in a reinforced concrete structure with an average thickness of 1 m against possible accident situations (WNA, n.d.-a).

With the commissioning of second-generation commercial nuclear reactors, the number of nuclear plants increased and nuclear energy use became widespread. Starting from 82 in operation in 1970, the number of active nuclear reactors increased to 420 after 20 years. The Chernobyl NPP and Fukushima NPP accidents in 1986 increased safety concerns and paved the way for third and third+ generation reactors. Reasons such as the Chernobyl NPP accident, reaching the end of the economic life of many power plants as well as numerous political issues decreased the rate of increase in the total number of reactors after the 1990s. As of May 2022 , the total number of reactors in operation reached 441 as shown in Figure 1.4 (IAEA, 2021).

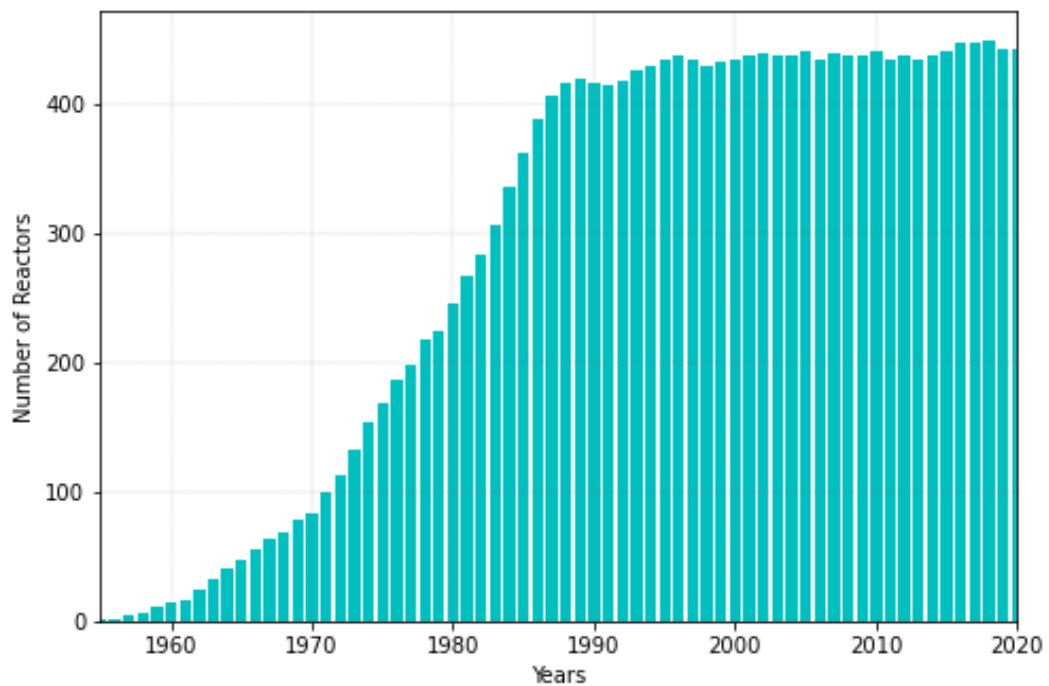


Figure 1.4 Total number of nuclear reactors worldwide by years (IAEA, 2021)

Different countries' development of nuclear reactors for electricity generation and the widespread use of reactors resulted in different reactor types. Today, these differences are taken into account to classify the types of reactors. Reactor types were determined by fuel, moderator, and coolant properties. The most common reactor types are Pressurized Water Reactor (PWR), Boiling Light-Water Cooled and Moderated Reactor (BWR), Gas Cooled and Graphite Moderated Reactor (GCR), Light-Water Cooled and Graphite Moderated Reactor (LWGR), and Fast Breeder Reactor (FBR) (WNA, n.d.-a).

As of May 2022, there are 307 PWR type nuclear reactors and 61 BWR type nuclear reactors worldwide. Both reactors use enriched UO_2 as fuel and light water as coolant and moderator. In addition, there are 48 pressurized water reactors (PHWR) in operation that use heavy water. PHWR uses natural uranium as fuel. GCR and LWGR use graphite as moderators. As of 2022, 10 GCRs are operating worldwide, which as gas (CO_2)-cooled reactors using natural uranium and enriched UO_2 together as fuel. Similarly, there are 12 LWGR type nuclear reactors in operation today. Finally, due to economic reasons, only a few (3) FBR type reactors operate with fast neutrons.

These reactors use PuO_2 and UO_2 as fuel and do not use moderators. It is thought that FBR will be the reactor type of the future. In addition, one of the latest technologies, the High-Temperature Gas-Cooled Reactor, was commissioned in China at the end of 2021 (IAEA, n.d.-c). The distribution of NPPs according to reactor types is given in Figure 1.5.

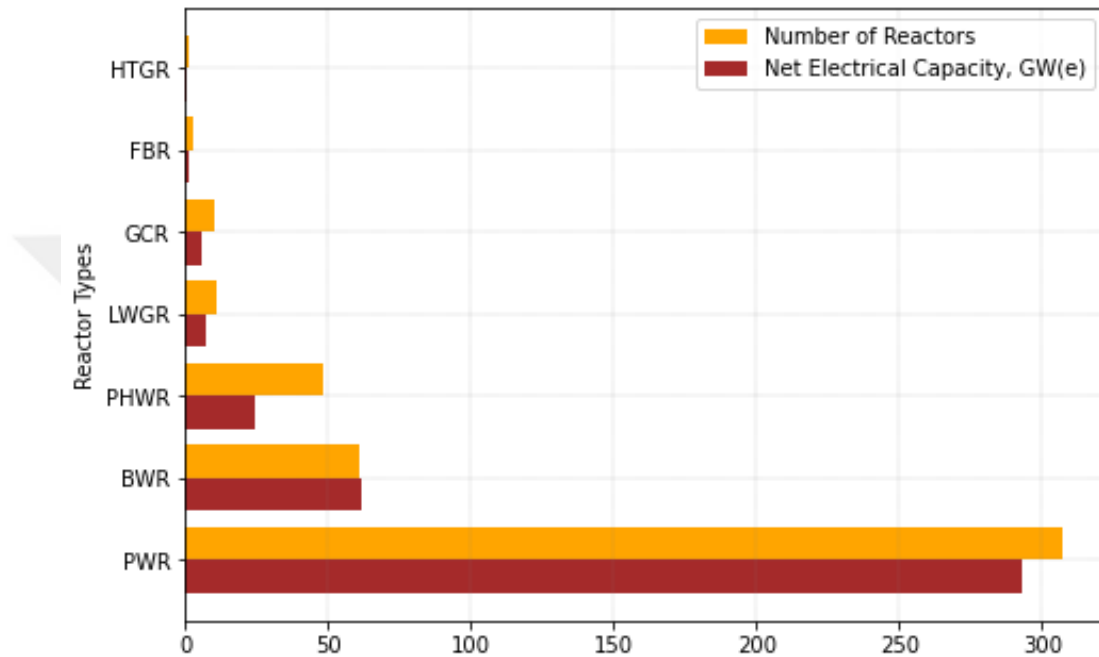
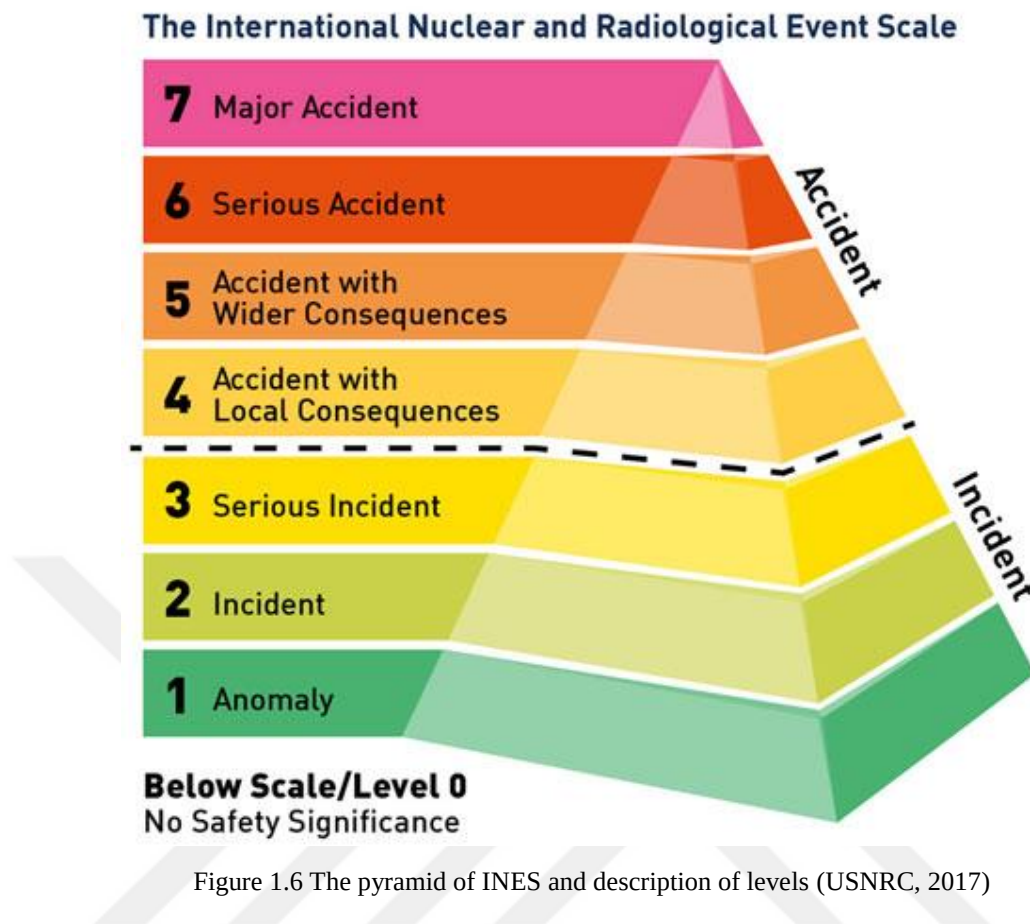


Figure 1.5 Distribution of reactor numbers and net electrical capacities by reactor type (IAEA, n.d.-c)

1.4 Nuclear Reactor Accidents

The International Atomic Energy Agency (IAEA) and Organization for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) consider events that significantly affect people, the environment and facilities as nuclear accidents. In 1990, the International Nuclear and Radiological Event Scale (INES) was developed by the IAEA and OECD/NEA to classify accidents (Figure 1.6). This scale classifies three categories as an incident and four categories as an accident. The INES rate increases as the severity of the accident increases (IAEA, 2013).



The first known significant reactor accident occurred in Canada in 1952. On December 12, 1952, an accident happened in the experimental NRX CHALK RIVER reactor core, which used heavy water as the moderator and light water as the coolant. Partial melting occurred in the reactor core, but no radioactivity was released into the environment (Lewis, 1953). The accident was rated as category five on the INES.

In 1957, one of the most significant nuclear reactor accidents occurred in the UK. On October 8, 1957, a fire broke out in the graphite blocks and melted most of the reactor core in the Windscale No-1. Significant amounts of radioactive pollutants were released into the environment. In London, 500 km from the reactor, 20 times higher than the average level of radiation was measured, and the pollutants reached as far as Denmark. No deaths were reported due to the accident (Loutit et al., 1960). This accident was also rated as a category five event on the INES, like the NRX Chalk River accident.

On March 28, 1979, a severe nuclear reactor accident occurred in the USA. In the PWR type Three Mile Island (TMI-2) reactor, the reactor overheated due to the reactor core's loss of coolant and partial melting occurred. High amounts of radiation were released into the environment after the accident, and high dose rates were measured in surrounding settlements. However, no deaths and no physical injuries were reported. The maximum whole-body dose was calculated as approximately 0.83 mSv around the accident region (USNRC, 1980). The accident was also rated as a category five event with regards to the INES. After this event, substantial impact of the accident was felt on the nuclear industry. TMI-2 accident is considered as the first severe commercial nuclear power plant accident. With the negative image created against nuclear power, the anti-nuclear social movement gained strength after this accident (IAEA, n.d.-a).

The most significant nuclear power plant accident occurred at Chernobyl NPP in the former Soviet Union. This accident was defined as a category seven event on the INES. Vast amount of radionuclides were released into the atmosphere in an accident during a test on April 26, 1986. As a result of the continued release for ten days, 12 - 15 EBq radionuclides were released (Table 1.2). About 400,000 people living in the highly contaminated zone were forced to evacuate the area (UNSCEAR, 2000). The effects of the accident were observed in almost the entire Northern hemisphere. Average effective doses for those most affected by accident were estimated to be approximately 120 mSv for 530,000 rescue workers, 30 mSv for 115,000 evacuees, and 9 mSv for those who continued to reside in contaminated areas two decades after the accident. In less contaminated regions, first-year dose values remained below 1 mSv (UNSCEAR, n.d.). When the Chernobyl forum modeled the radiation doses received by workers and residents, the results revealed that about 4000 deaths were likely to be caused by the Chernobyl NPP accident (IAEA, 2008).

The impact of the Chernobyl nuclear power plant accident has been continuing for many years. After the accident, approximately 2600 km² area around the reactor and a similar area in Belarus was abandoned, and the Chernobyl Exclusive Zone (CEZ) was formed. Contamination levels in the CEZ vary significantly (Beresford et al., 2021;

Kashparov et al., 2018, 2020), but the area is probably the most radioactive terrestrial ecosystem globally. Many forest fires occurred in the region before 2020, the most extensive of which burnt over 10,000 ha in the CEZ region (Beresford et al., 2021; Goldammer et al., 2014; Kashparov et al., 2017). In a recent wildfire that occurred in the Ukrainian CEZ in 2020, Protsak et al. (2020) calculated that 87,000 ha were burned (Beresford et al., 2021). Radionuclides were emitted into the atmosphere from the contaminated trees due to this fire. Beresford et al. (2021) evaluated the effect of radionuclides released from fire radiologically. They calculated that the external or inhalation dose values were low in the centre of Kyiv and that the dose was not dangerous for firefighters.

Table 1.2 Released radionuclides and their amounts after the Chernobyl NPP accident (UNSCEAR, 2000)

Radionuclides	Activities released (PBq)
Noble Gases	⁸⁵ Kr
	33
	¹³³ Xe
	6500
Volatile elements	^{129m} Te
	240
	¹³² Te
	1000 - 1150
	¹³¹ I
	1200 - 1800
	¹³³ I
	2500
	¹³⁴ Cs
	44 - 54
	¹³⁶ Cs
	36
	¹³⁷ Cs
	74 - 86
Intermediate	⁸⁹ Sr
	80 - 115
	⁹⁰ Sr
	8 - 10
	¹⁰³ Ru
Refractory (including fuel particles)	120 - 170
	¹⁰⁶ Ru
	25 - 73
	¹⁴⁰ Ba
	160 - 240
	⁹⁵ Zr
	140 - 196
	⁹⁹ Mo
	168 - 210
	¹⁴¹ Ce
	120 - 200
	¹⁴⁴ Ce
	90 - 140
	²³⁹ Np
	945 - 1700
	²³⁸ Pu
	0.03 - 0.035
	²³⁹ Pu
	0.03 - 0.0334
	²⁴⁰ Pu
	0.042 - 0.053
	²⁴¹ Pu
	5.9 - 6.3
	²⁴² Pu
	0.00009
	²⁴² Cm
	0.9 - 1.1

After the Russian armies' occupation of the Chernobyl nuclear power plant region in the Russia-Ukraine War in 2022, dose rates were increased. According to the

assessment made by the IAEA, it was calculated as 6.5 mSv/year for excavations and 1.6 mSv/year for the roads nearby (WNA, n.d.-c).

More recently in 2011, a magnitude nine earthquake struck the ocean off the coast of Japan. After the earthquake, the tsunamis flooded the Fukushima Daiichi Nuclear Power Plant and caused the second most significant nuclear power plant accident. This accident was also rated category seven on the INES. As a result of the accident, radionuclides were released into the atmosphere and the ocean. 21,135 workers involved in remediation at the Fukushima NPP site were exposed to an average effective dose of approximately 13 mSv. 0.8% of workers were exposed to doses higher than 100 mSv. Children were affected more than adults in the accident and doses up to 5.1 mSv were observed in children aged 1 year in Fukushima Prefecture in the first year after the accident. Adults in the same area were exposed to doses up to 3.8 mSv, while in neighboring settlements and the rest of Japan, they were exposed to doses less than 1 mSv (UNSCEAR, 2022). Even one decade after the accident, the problems and effects of the nuclear power plant continue. Large amounts of water are still used to cool reactors today, and contaminated water is stored in tanks after cooling. However, as the tank capacities will be complete soon, lower levels of contaminated water from existing tanks will be discharged into the ocean (IAEA, n.d.-b).

1.5 Novelty of the Study

Nuclear accidents such as Chernobyl and Fukushima Daiichi NPPs demonstrated that atmospheric transport of released radioactive material is the most crucial threat to the environment and human health. Radionuclides released into the atmosphere from an accident may travel long distances and affect large areas. For instance, radiation from Chernobyl NPP was detected in distant countries such as the USA and Japan (De Cort et al., 1998; Gudiksen et al., 1989). The radionuclides that travel long distances cause not only temporary air pollution but also cause contaminations that will be effective for many years due to factors such as gravity and precipitation. For example, higher depositions were observed in the UK after the Chernobyl NPP accident (De Cort et al., 1998).

The primary factor in atmospheric transport is meteorological conditions. Many meteorological parameters, such as wind, precipitation, and mixing height, affect the direction and deposition of the radioactive cloud. Therefore, analyzing meteorological conditions is a critical topic in nuclear risk studies. However, the chaotic nature of the atmosphere makes these analyses difficult today. In addition, the increase in extreme meteorological events due to climate change will cause atmospheric risk studies to become more complicated. Seasonal normals will change, and outliers in meteorological parameters will more likely influence atmospheric transport and deposition.

IPCC (2012) indicated that global temperature increased before the industrial revolution and is predicted to increase by about 6°C in 2100 if no efforts are taken. Global temperature rise has many global catastrophic consequences. One of the most critical results will be the increased frequency of extreme meteorological events. IPCC (2012) demonstrated that heat waves, extreme precipitation, and storms are likely to increase.

Many studies have considered meteorological conditions in nuclear risk assessment applications. Some studies in the literature consider only rainy periods with high wet deposition or analyze periods with particular wind directions and patterns. Others focus more on seasonal effects and seasonal and climatological normals. These studies are discussed in detail in chapter two. However, none of these studies considered the effect of extreme weather events, the frequency of which is increasing with the effect of climate change. Therefore, this study was designed by considering this deficiency in the literature. For this purpose, a new nuclear risk approach was developed in this thesis, and scenarios that could produce the worst cases were produced with preliminary analysis. In the definition of these scenarios, extreme meteorological parameters were chosen as the most critical parameter. Thus, researchers and practitioners can find the worst meteorological condition in their study area and implement the methodology developed herein to make their own assessments for their particular cases. In addition to meteorological conditions and parameters, the

parameters affecting the source term were also discussed in detail in this thesis. Thus, researchers can define their own worst-case conditions for the accident using this methodology. Finally, a dose calculation method has also been developed using recent ICRP (The International Commission on Radiological Protection) guidelines. In this way, researchers and practitioners can perform a comprehensive radiological analysis using this method.

1.6 Aim and Scope of the Study

Based on the premise discussed above, the main objective of this study is to propose a new and comprehensive risk assessment methodology for nuclear accidents/incidents, which can serve as a guide for practitioners and researchers working in the field. This method is analyzed in terms of setting up an atmospheric transport model, determining source terms, assessing meteorological conditions, and calculating dose values.

Under this primary objective, several tools were developed for formulating accident source terms, analyzing meteorological fields, and estimating and plotting dose results in a nuclear risk assessment study. Furthermore, extreme conditions emphasizing climate change effects were analyzed to define the worst possible settings for the dispersion of radionuclides that originate from real/hypothetical nuclear power plant accidents. Finally, a risk analysis study for a potential nuclear power plant accident in and around Turkey was presented using this methodology via the tools developed in this thesis.

CHAPTER 2

LITERATURE REVIEW

This section presents previous research published in the literature from the background of this study. These studies are divided into five groups. First, the development of the Atmospheric Dispersion Model (ADM) is presented. Then, nuclear risk studies using ADMs are reviewed. In the third group, studies focusing on the source term are compiled. Later, studies indicating the influence of meteorological conditions on radioactive release from nuclear accidents are examined. Finally, studies related to the history of risk assessments and health consequences are presented.

2.1 Atmospheric Dispersion Modeling

Aerosols and gases containing toxic and harmful substances are emitted into the atmosphere in various ways. Materials released from point and area sources can travel thousands of kilometers and affect human and environmental health. This type of accidental release can have severe economic costs. For example, air transport was severely affected by the Eyjafjallajökull volcano eruption in Iceland in 2010. It is estimated that the cost of the eruption on airlines is about 1.7 billion US\$ (Anonymous, 2010; Leelössy et al., 2014).

Atmospheric transport models have long been widely used to analyze the environmental, health, and economic risks of pollutants transported through the atmosphere. Field experiments by Richardson & Walker (1926), Taylor (1922), and Roberts & Simpson (1923) in the 1920s form the basis of atmospheric dispersion models (Hanna, 2010; Leelössy et al., 2018). Created by the Cold War's tensions, some numerical models were developed for security purposes to assess the potential risks associated with nuclear and chemical attacks. With Clean Air Acts in the UK (1956) and US (1963), the concept of regulatory modeling emerged. USAEC (1955) created a directive that suggested using simple Gaussian dispersion models for small-scale investigations and simple trajectory analyses for large-scale assessment of nuclear and chemical attacks. Gaussian dispersion models were mainly used as a regulatory and

nuclear emergency tool to scrutinize the fate and transport of nuclear and chemical contamination (Hanna, 1982; Leelőssy et al., 2018). Significant industrial accidents such as Seveso in 1978 and Bhopal in 1984 revealed that an accidental release is a vital topic to be studied thoroughly besides continuous emissions. Moreover, events such as severe acid rains caused the spatial extent of studies to be expanded from the local to the continental scales (Fraenkel, 1989; Leelőssy et al., 2018). In this way, the Eulerian and Lagrange models became widespread (Arnold, Gufler, et al., 2012; Leelőssy et al., 2018).

The Chernobyl NPP accident in 1986 increased the importance of long-range atmospheric transport models. Numerous studies were conducted immediately after the accident (Albergel et al., 1988; Gudiksen et al., 1989; Hass et al., 1990; Kimura & Yoshikawa, 1988; Lange et al., 1988; Persson et al., 1987). These studies modelled the transport of radioactive materials released from the accident and calculated their radiological effects. The impact of the Chernobyl NPP accident and the developing computational technology led to developing more complex and comprehensive dispersion models and new nuclear risk studies.

The period from the Chernobyl NPP accident to 2000 was called by Leelőssy et al. (2018) as a “development era” for dispersion models. Many significant Lagrangian and Eulerian dispersion models were developed in this period. The UK Meteorological Office developed the Numerical Atmospheric-dispersion Modelling Environment (NAME) to estimate the impact of the Chernobyl NPP accident (A. Jones et al., 2007; Maryon et al., 1991). Besides nuclear applications, NAME can be used for mesoscale applications such as volcanic ash transport (Leadbetter & Hort, 2011) and accidental petroleum evaporation (Welch et al., 1999). Danish National Environmental Research Institute developed a three-dimensional tracer model that combines a Lagrangian mesoscale model and an Eulerian long-range transport model (Brandt et al., 1996, 1999, 2000). The Danish RIMPUFF (the Risø Meso-scale PUFF model) and Eulerian Accidental release Model (DREAM) were used for atmospheric dispersion and ground-level deposition of the radionuclides released from the Chernobyl NPP accident (Brandt et al., 2002). US National Oceanic and Atmospheric Administration

(NOAA) developed a hybrid Lagrangian dispersion model named The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler & Hess, 1998; Stein et al., 2015). HYSPLIT was used in many applications such as volcanic ash dispersion (Hurst & Davis, 2017), radioactive material release (Pirouzmand et al., 2018), and dust transport (Salvador et al., 2014; Stein et al., 2011). Another Lagrangian particle dispersion model, FLEXPART (FLEXible PARTicle dispersion model), was also developed in this period (Pisso et al., 2019; Stohl et al., 1998, 2005; Stohl & Thomson, 1999). Similar to HYSPLIT, FLEXPART is also used in many fields, such as nuclear accidents (Evangelou et al., 2017; Stohl et al., 2012), volcanic eruptions (Perrone et al., 2012), dust transport (Ansmann et al., 2005; Williams et al., 2007) and wildfires (Wotawa & Trainer, 2000).

United States Environmental Protection Agency (US EPA) developed an advanced Gaussian dispersion model, AERMOD, in this period (Cimorelli et al., 2005). Many countries accepted AERMOD as the standard regulatory model (Leelössy et al., 2018). Further, large-scale Eulerian models such as EMEP and CMAQ were also developed to analyze photochemical pollutants (Byun & Schere, 2006; Leelössy et al., 2018; Tørseth et al., 2012). Recently, some online coupling models, such as FLEXPART-WRF (Brioude et al., 2013) and HYSPLIT-WRF (Ngan et al., 2015), were developed. Further, data assimilation and inverse modelling applications (Bocquet et al., 2015; Chai et al., 2015; Davoine & Bocquet, 2007; Evangelou et al., 2017; Quélo et al., 2005) and assessment of uncertainties in model results (Galmarini et al., 2004; Katata et al., 2015) were also considered in modelling studies (Leelössy et al., 2018).

2.2 Risk Assessment Studies

Nuclear risk studies based on Atmospheric Dispersion Models in the literature can be divided into two groups:

- Simulation of entire meteorological conditions: In this approach, the simulations are conducted at the exact location, using the same accident scenario, within a certain period (e.g., one year) with equal frequency (e.g.,

once a week). All meteorological features of the region are tried to be represented. The longer the period and the higher the applying frequency, the more representative the meteorological features of the region. Thus, more realistic risk analyzes can be examined in this group. However, an increased number of simulations over a long period creates long simulation times and extra computational costs. Thus, either significant infrastructural support is needed in these studies, or adjustments should be made to reduce the simulation load.

- Simulation of selected meteorological conditions: In this approach, various meteorological periods are selected according to the purpose of the study, and targeted analyzes are applied with less number of simulations in this selected time period.

The literature demonstrated that many studies based on entire meteorological condition use a Lagrangian particle dispersion model, FLEXPART, to calculate atmospheric transport and surface deposition (Andreev et al., 1998; Arnold, Gufler, et al., 2012; Min & Kim, 2018; Seibert et al., 2013, 2014). The RISKMAP project conducted in Austria is an important example of this approach. In the RISKMAP project, Andreev et al. (1998) presented a nuclear risk method to prepare a tool to determine which nuclear power plants pose the most significant risk to a given area. The FLEXPART model was used to conduct the simulations, and risk analysis was performed for all nuclear power plants in Europe. For this purpose, 88 simulations were made within one year, and risk values for Europe were calculated based on the ^{137}Cs deposition results. The analysis of synoptic air patterns between 1977 and 1996 indicated that 1995 was a representative year, and simulations were conducted for this year.

Similar to the RISKMAP project, the FLEXRISK project carried out in Austria (Arnold et al., 2012; Seibert et al., 2013) demonstrates another example for the first approach. Entire meteorological conditions were simulated to investigate the impacts of particular hypothetical accidents in numerous nuclear power plants in Europe. FLEXRISK is a more comprehensive project than RISKMAP with the help of

developing technology. FLEXRISK project also used the FLEXPART model. In this study, Seibert et al. (2013) simulated numerous NPP accidents under various release conditions and meteorological periods over 11 years (2000-2009 and 1995). Moreover, atmospheric transport and deposition were modeled for 20 different radionuclides. The results obtained from these models were post-processed, and short and long-term total effective dose equivalents and thyroid doses were calculated for different age groups. The radiological effects of each power plant and the risks that European countries face are available online at <http://flexrisk.boku.ac.at/> with maps and graphics. A similar project was also conducted for only one nuclear site in Poland (Seibert et al., 2014). Unlike the original FLEXRISK project, this study defined six release scenarios, and simulations were applied for 88 meteorological conditions in 1995. The dispersion, deposition, and dose results for all scenarios and meteorological periods are available at https://www.univie.ac.at/theoret-met/flexrisk_pl/.

Min & Kim (2018) also conducted a study based on the analysis of entire meteorological conditions using FLEXPART. They investigated the effects of a possible accident in the Haiyang NPP in China on the Korean peninsula. Simulations were launched for each day in 2015. Analyses were performed on ^{137}Cs deposition of 365 simulations, and the effects were evaluated. The highest three ^{137}Cs scenarios were discussed, and the worst case was selected, which was taken to be the scenario that gave the highest spatial distribution. A dose calculation was also made using the worst-case scenario.

There are also studies using models other than FLEXPART for simulations conducted for analyzing entire meteorological conditions. Pirouzmand et al. (2018) investigated the radiological impact of a hypothetical accident at Bushehr NPP with HYSPLIT. For this purpose, 23 radionuclides were assumed to be released after a blackout accident, and dose estimation was conducted in an area within 30 km from the accident site. The simulations were conducted for each day of 2014. In this study, the release duration was accepted to be the most sensitive parameter, and four different release durations were used as 4h, 12 h, 24 h, and 48 h. Simulation duration was taken

to be 48 hours in all four scenarios. The results showed the significant effect of wind and atmospheric conditions on the effective dose calculation in different directions.

Park et al. (2017) developed an emergency response system including a Lagrangian particle dispersion model and an Eulerian dispersion model. This system modeled the accidental ^{137}Cs released from the Uljin NPP in Korea. With the 2013 meteorological data, the model was run for 72 different conditions. The scenario that gave the highest ^{137}Cs deposition (September 16 - 20, 2013) was assumed to be the worst case. The synoptic conditions of the period in which the worst-case occurred were examined in detail. In addition, dose calculation was carried out to evaluate the radiological effect.

The second group of typical nuclear risk analyses in the literature consists of studies conducted for selected meteorological periods. This approach requires less number of stimulations than the studies simulating entire year meteorological conditions. Baklanov & Mahura (2001, 2004) and Mahura & Baklanov (2002) presented a comprehensive probabilistic risk analysis method defining meteorological conditions. Baklanov & Mahura (2004) suggested several research tools for this approach, including

- i) long-term trajectory modeling,
- ii) a set of statistical methods to analyze trajectory modeling results,
- iii) and constructing and mapping probabilistic fields of different nuclear plants' possible impact indicators due to atmospheric transport.

Further, several useful indicators and methods were suggested, such as atmospheric transport pathways, airflow fields, fast transport probability fields, specific transport time fields, maximum reaching distance, maximum possible impact zone, and removal or precipitation factor.

Although some studies were determined by extensive preliminary analyzes using trajectory modeling (e.g., Mazur, 2019), many studies for selected meteorological conditions were determined by more straightforward approaches. FLEXPART is also widely used in studies that analyze selected meteorological periods (Bilgiç & Gündüz,

2020; Srinivas & Venkatesan, 2005; Zhu et al., 2014). Srinivas & Venkatesan (2005) investigated the possible consequences of an accidental release in the FBR reactor planned in India. For this purpose, they estimated the transport and deposition of radionuclides with FLEXPART. The simulation was conducted on May 24, 2003, a typical summer sea breeze day. Before atmospheric dispersion modeling was conducted, the MM5 model was first carried out to provide some meteorological parameters such as winds, vertical temperature, stability structure, mixing depths, and some additional parameters for FLEXPART. Further, results were post-processed and effective doses were calculated to reveal the radiological consequences.

Zhu et al. (2014) investigated the possible consequences of an accident in Sanmen NPP in China. Atmospheric dispersion and deposition of various radionuclides released from the reactor were simulated with FLEXPART. The simulation period was determined considering wind directions. The period when the wind blows from the East, between August 25 and September 4, 2011, was chosen to be the simulation period. Furthermore, dose values and health risks were estimated from the model output through external and inhalation pathways. The results indicated that the highest radiological effect occurred near the plant, and dose values higher than 20 mSv were calculated in approximately 140,000 km².

In a study published from this thesis, it was also conducted a radiological risk analysis for Akkuyu NPP in Turkey using the FLEXPART model (Bilgiç & Gündüz, 2020). The simulations were carried out in December 2009 and August 2010, representing the rainy and dry periods. Chernobyl NPP accident's release was used as the source term, and one-year and lifetime effective dose values from ¹³⁷Cs were calculated. In addition, the 7-day thyroid dose was also calculated from the ¹³¹I results. The results revealed higher values near the power plant, but transport of contaminants to far countries has been simulated.

Another Lagrangian particle dispersion model widely used in studies conducted for selected meteorological periods is HYSPLIT (Mitrakos et al., 2016). Mitrakos et al. (2016) examined the case of an accident similar to Fukushima in Europe (Greece) with

the HYSPLIT model, where they estimated radionuclide transport and made dose calculations. In order to determine the meteorological periods, a trajectory analysis was conducted for 2013. Later, an evaluation was conducted based on the number of trajectories reaching the country of interest. From this analysis, July 20 and July 25 were chosen for simulation start dates. A 2-hour duration constant rate release pattern was defined for both periods. This release was unrealistic because it was very short, but it was a logical scenario regarding the impact of meteorological conditions. In their simulations, case 3 was considered a more realistic risk analysis where a release identical to that of 10-day Fukushima NPP accident was defined and launched on July 20, similar to case 1. The results revealed that not only was the distance the determining factor in the impact of the accident, but the most critical parameter in long distances was the adverse meteorological conditions.

As an alternative to Lagrangian particle dispersion models, methods that consider the Eulerian approach is also widely used in the literature. Mészáros et al. (2010) simulated hypothetical accidents in Paks NPP to demonstrate the new atmospheric dispersion approach they developed. An Eulerian dispersion model TREX was used with a new algorithm to reduce CPU time. The user defines a threshold concentration value in this algorithm to decrease the active cells. Numerical simulations are carried out only in these active cells. Two periods (December 2, 2005, and March 24, 2006) were simulated, and ^{131}I was released in this study to demonstrate the efficiency of the new approach. Mészáros et al. (2010) revealed that the semi-adaptive method could be an appropriate tool for accelerating the simulations.

Mazur (2019) conducted an atmospheric dispersion study investigating the release from a hypothetical accident in Zarnowiec NPP in Poland. The accident was assumed to be similar to Chernobyl and Three Mile Island accidents. An Eulerian dispersion model was used, and meteorological conditions representing the worst cases were determined from trajectory analysis. Eleven determined cases by trajectory analysis were simulated, and results were compared. The worst-case scenario showed that the time needed to prepare and react would be very short in case of an accident.

Puff models also have a considerable place in nuclear risk analysis. Gering et al. (2013) presented a study of two nuclear sites in North and South Germany under hypothetical accidents with more prolonged releases like Fukushima. Atmospheric dispersion and radiological effect were performed with RODOS's decision support system. RODOS is a widely used approach in Europe, which includes a segmented puff model for atmospheric transport and a deposition model. Regarding source terms, two release scenarios were defined by Gering et al. (2013). The first one was precisely equal to the Fukushima NPP accident release, whereas the second one was a scenario where similar amounts of radionuclides were released constantly. The simulations were carried out in two different periods, in June and December 2010, for Unterweser and, in October and December 2010, in Philippsburg. Effective and thyroid doses were calculated and compared with Germany's dose levels needed to initiate preventive action.

2.3 Source Term Analysis

The "Source term", a crucial input for atmospheric transport models, is a significant factor influencing both the design of safety equipment and risk and safety assessments (Mehboob et al., 2012; Rosen & Jankowski, 1985). The source term for nuclear power plants came to the fore in the early 1960s. Technical document TID 14844 (DiNunno et al., 1962) indicates that 100% of the noble gases, 50% of the iodine, and 1% of the solid fission products in the inventory are released. Moreover, fractions for the coolant loss accident in guidelines 1.3 (USAEC, 1974a) and 1.4 (USAEC, 1974b) are derived from this report. WASH-1400 for nuclear risk management was published in the USA in 1975 (USNRC, 1975). This report explained many vital accidents, and the release rates and probabilities for various radionuclide groups in different accident types were presented.

The TMI-2 accident in 1979 marked a turning point for source term analysis and severe accident management. After the accident, numerous technical reports were published, and codes providing the source term were developed (Mehboob et al., 2012). Then, WASH-1400 was peer-reviewed and summarized in a report (USNRC,

1981). Later, various applications were published using the codes that generated the source term. In 1983, the source term was generated for five nuclear power plants in the USA (Gieseke et al., 1983). These source terms were then evaluated (Silberberg et al., 1985) and analysed as a risk method (Denning et al., 1986). Later, a new source term generation and risk management method from these studies were documented (USNRC, 1990), and the document was revised in 1995 (Soffer et al., 1995).

Source term models and technical documents have been widely used in nuclear risk studies. Slaper et al. (1994) conducted a nuclear risk study for Europe and obtained the source terms from Eendebak et al. (1992), which is the study based on the technical document NUREG 1150 (USNRC, 1987, 1990). Srinivas & Venkatesan (2005) used data from a source term study for a prototype FBR (Keshavamurthy et al., 2003) as input in the risk study conducted for Kalpakkam NPP. Seibert et al. (2013) conducted a risk study for all nuclear reactors in Europe. Necessary source term data was obtained from the reports in the literature according to the type of all reactors. Zhu et al. (2014) performed a risk analysis for an AP1000 model PWR-type reactor. In this study, the source term was derived from the reactor manufacturer Westinghouse's document (Westinghouse Electric Company, 2011) and an NRC report (USNRC, 2000). Min & Kim (2018) used a document published by Westinghouse in 2004 (Winters et al., 2004) in their risk study for another AP1000 reactor.

These models and approaches are not only used in hypothetical risk analysis. They have also been used in past accidents, such as the Chernobyl NPP accident (Devell et al., 1995; Gudiksen et al., 1989). The Chernobyl NPP accident revealed that only the release amount was insufficient to define the source term. In addition, the source term includes injection height (effective stack height), temporal variation, and characteristics of released species (e.g., aerodynamic diameter, particle density, wet scavenging constant, half-life time). SCUA's (1986) measurements showed that emissions exceeded 1200 meters on the first day of the Chernobyl NPP accident. Persson et al. (1987) revealed that the initial release is above 2000 m by applying an atmospheric modeling study. Measurements by Jaworowski & Kownacka (1986) and model applications by Lange et al. (1988) and Gudiksen et al. (1989) demonstrated

that this height might be higher. Hass et al. (1990) assumed that the emission increased to 2225 m and divided it into 6 different layers. Brandt et al. (2002) conducted an atmospheric dispersion model study and achieved good agreements with ground depositions measurements using the vertical profile of Hass et al. (1990).

Many modeling studies have investigated the release amount, vertical profile, and temporal change of both the Chernobyl and Fukushima Daiichi NPP accidents (Chino et al., 2011; Davoine & Bocquet, 2007; Evangeliou et al., 2013, 2017; Katata et al., 2015; Stohl et al., 2012; Talerko, 2005a, 2005b). All these studies revealed that the release height could rise to the upper levels of the atmosphere and was not distributed homogeneously. On the other hand, in hypothetical studies, temporal resolution is usually kept constant or changed similar to that of a past accident, and vertical release is generally assumed homogeneous. A study published from this thesis produced various release pattern functions for the vertical release distribution evaluating the Chernobyl NPP accident (Bilgiç & Gündüz, 2021). The results of their study showed that different patterns produced different worst cases. Accordingly, their study presented an alternative source term methodology for risk assessment of hypothetical accidents.

2.4 Meteorology

One of the most essential components of an atmospheric dispersion modeling study is the data defining the meteorological conditions. Many meteorological factors such as precipitation (snow, rain, dry), humidity, stability (stable, neutral, unstable) and wind speed and direction of the simulation period directly affect atmospheric dispersion and surface deposition. There have been many studies investigating the post-nuclear accident effects of these individual parameters, directly or indirectly.

Baklanov et al. (2002) studied radionuclides' possible effects and consequences on the Arctic and European regions from a hypothetical accident at the Kola Nuclear Reactors (KNR) in Russia. Firstly, a trajectory analysis was applied between 1991 and 1995. After the analysis, five worst-case scenarios were determined considering some

factors such as the direction of transport of the accidental release, precipitation Atmospheric Boundary Layer (ABL) height, travel time, and impacted area:

- i) rapid transport to Finland and Scandinavia,
- ii) significant pollution in Scandinavia and Finland,
- iii) major pollution in Scandinavia and Western Europe,
- iv) transport to Scandinavia and the Baltic countries,
- v) transport to Northern Scandinavia, Norway, and the Baltic Seas.

Transport time results for these five worst cases showed that the longest transport time to Sweden and the Nordic countries occurred in stable and stratified conditions. The highest total area of contamination was seen in the case called “Large contaminated areas”. The maximum deposition for the study area was determined in the “rapid transport and stable stratification to Finland and Scandinavia” scenarios. Maximum deposition in Sweden was found in the case “transport to Scandinavia and Baltic countries”.

Srinivas & Venkatesan (2005) studied the transport of radionuclides that would be released during a hypothetical nuclear accident in the prototype FBR in a coastal city. The effect of different conditions at different times was examined in the simulation for a typical summer day. The results revealed that the maximum dose was at the thermal internal boundary layer (TIBL) fumigation conditions during the sea breeze. The maximum dose also occurred in stable conditions at night. The highest concentrations were found to occur during periods of TIBL fumigation rather than under stable atmospheric conditions.

Mészáros et al. (2010) estimated the atmospheric transport of radionuclides emitted from a hypothetical accident in Paks NPP. Simulations were conducted for two different meteorological periods. December 2005 simulation results demonstrated that wind components are the determining meteorological factor. During this simulation period, a Mediterranean cyclone and a warm front affected the study area and caused precipitation. The variable wind direction caused the radionuclides to affect large

areas. This scenario detected a significant amount of wet deposition with precipitation. In the 24-25 March 2006 simulation, the anticyclone in central Europe caused sunny, dry weather. Therefore, dry deposition dominated in this simulation.

Gering et al. (2013) conducted a radiological risk study for two nuclear power plant sites in Northern and Southern Germany. Atmospheric dispersion calculations were conducted for two meteorological periods to examine possible seasonal impacts. Gering et al. (2013) revealed that the determining meteorological factors were the effective wind direction and the homogeneity of the wind directions.

An et al. (2015) investigated the influence of local meteorological conditions around 50 km of Kori NPP on the atmospheric dispersion after the possible accident, using the WRF/HYSPLIT model. First, eight meteorological patterns frequently occurring around Kori NPP were determined. A consistent wind system was observed under relatively strong synoptic weather conditions in three patterns, while weak and variable winds were observed in five. The highest average deposition occurred during the period affected by a narrow range of ^{137}Cs distribution and precipitation. This study revealed that the distribution and levels of ^{137}Cs concentration differed according to the variation of weather conditions in time and space (height of the atmospheric boundary layer, the height of the atmospheric boundary layer, horizontal and vertical distribution of local winds, and precipitation levels).

Mitrakos et al. (2016) studied the long-range transport of radionuclides after a nuclear accident. For this purpose, three scenarios were defined regarding trajectory analysis, precipitation, wind direction, and source terms. The simulations showed that the distance and adverse meteorological conditions, especially precipitation, were the determining parameters in severe nuclear reactor accident.

Ahangari & Noori-Kalkhoran (2019) conducted hypothetical accident simulations at the Bushehr NPP under different meteorological conditions. Six scenarios were determined according to the stability classes. There was no precipitation in stability A, B, and F scenarios, and 200 mm/year precipitation was considered in stability C, D,

and E cases. Class A and F scenarios were defined as calm weather (1.8 m/s wind speed), and Class B scenario was defined as windy weather (6.75 m/s wind speed). Wind speed was accepted as 3.6 m/s in scenarios with C, D, and E stability classes with rainy weather. The results revealed that the prevailing metrological conditions significantly influenced the atmospheric dispersion and the corresponding doses. They revealed that the worst case for TEDE and thyroid dose was in the F-class scenario.

Studies on past nuclear power plant accidents have also demonstrated the effect of meteorological factors on atmospheric transport. In the Chernobyl NPP accident, wind speed and directions in different layers of the atmosphere, vertical convection, and precipitation were effective on atmospheric dispersion and surface deposition. On the night of the accident, there was a high-pressure center in Northeast Russia and a weak low-pressure trough between Western and Northern Europe. Ground-level winds were weak and had variable directions, and Southeasterly winds prevailed at 1500 m altitude with a speed of 8-10 m/s. Due to the stability and cloudlessness around Chernobyl, a temperature inversion occurred 400-500 m above the surface. Since the release reached 1500-3000 m after the accident, meteorological conditions in the upper atmosphere were found to be significant. Thus, the radionuclide from initial release was towards Scandinavian countries. The next day, the direction of atmospheric movement changed due to an anticyclone over Northern Central Europe. Europe was contaminated as the wind direction was variable during a total of 10 days of release. Except for the plant vicinity, the most significant contamination occurred in Western parts during rainy periods due to wet deposition (De Cort et al., 1998; Devell et al., 1986; Persson et al., 1987; UNSCEAR, 1988).

Meteorological conditions were also crucial concerning contamination and radiology in the Fukushima Daiichi NPP accident. Srinivas et al. (2012) simulated the atmospheric dispersion of radionuclides released from the Fukushima Daiichi Power Plant with FLEXPART-WRF. The model results revealed that air flows over Japan during the accident period were determined by large-scale extra-tropical West waves and associated low-pressure systems. Radioactive materials were generally dispersed towards the ocean surface as Westerly winds prevailed. Due to the effective easterly

winds on 15-17 and 19-21 March 2011, landward transports were detected for a few days. Extensive radionuclide deposition occurred over the land region during this period, as precipitation was also observed in the Northwestern parts of Fukushima from March 16-to 21.

2.5 Health Effects Studies

When X-rays were discovered, there was no information about ionizing radiation's effects. Therefore, no precautions were initially taken in many studies and activities where radioactive materials were researched or used. The first case of human dermatitis was reported immediately after discovering X-rays in January 1896 (Grubbé, 1949). After many cases, the International X-ray and Radium Protection Committee (IXRPC) published the first recommendations to avoid the dangers of overexposure in 1928 (Hamada & Fujimichi, 2014; Norstedt & Söner, 1929). In addition to unconscious contact with similar radioactive materials experienced in the first period, the nuclear bombs dropped on Japan in the second world war presented a bitter opportunity to investigate the health effects of ionizing radiation (Hollingsworth et al., 1960; Nefzger et al., 1969; Preston et al., 2003). Twenty years after the atomic bombs, the ICRP (1966) presented a radiation risk assessment report. Numerous dose calculation codes were developed during this period, including atmospheric dispersion models (Binford et al., 1968; Bonzon & Rivard, 1970; Spangler et al., 1967; Trubey & Kaye, 1973).

After the Three Mile Island and Chernobyl NPP accidents, there was a significant increase in dose modeling studies for accidental release (Cotter et al., 1980; Fabrikant, 1980; Gudiksen et al., 1989; Lange et al., 1988; Pasciak et al., 1981; UNSCEAR, 1988). Especially the substantial radiological impact of the Chernobyl NPP accident paved the way for hypothetical risk studies. First, Slaper et al. (1994) conducted a risk study for several nuclear reactors in Europe and calculated possible effective dose values. A comprehensive study calculated effective and thyroid dose values for different age groups. In the FLEXRISK project completed in 2012, a comprehensive risk assessment was carried out on all nuclear reactors in Europe. Total effective and

thyroid doses were calculated and analyzed from model data for many meteorological conditions (Arnold, Gufler, et al., 2012; Seibert et al., 2013). Seibert et al. (2014) also conducted another risk study for a planned nuclear reactor in Poland. A similar radiological risk approach to FLEXRISK was also used in this study, in which fewer simulations were made than FLEXRISK. Radiological dose calculations have also been part of many academic studies. Srinivas & Venkatesan (2005) conducted a risk study for an FBR planned in India and calculated the effective dose. Zhu et al. (2014) performed a hypothetical dose analysis for Sanmen NPP in China. Min & Kim (2018) calculated the effective dose for the worst-case conditions among 365 different meteorological conditions in Haiyang NPP in China. Bilgiç & Gündüz (2020) calculated the thyroid dose from ^{131}I and the effective dose from ^{137}Cs in their risk analysis for Akkuyu NPP.

CHAPTER 3

METHODOLOGY

This section presents the methodology utilized and developed in the studies performed within the scope of the thesis. First, the risk analysis algorithm produced within the scope of this thesis is presented. Then, the mathematical background of ADM used in risk analysis is explained. Later, the tool developed for resource term calculation within the scope of this thesis is explained. In the next section, the details related to meteorological analyses are presented. In the following section, the dose calculation method and the background of the tool are presented. The last section summarizes the simulation applications conducted in this study.

3.1 Nuclear Risk Methodology

A comprehensive nuclear risk methodology is presented in this thesis. For this purpose, pertinent approaches in the literature were examined, and a new methodology was developed. At the same time, source terms, meteorological analysis and dose calculation tools have been developed to strengthen this approach. The literature review in Chapter 2 has shown that nuclear risk studies are applied in two groups: i) studies of a large number of simulations for ordinary meteorological conditions over a regular period and ii) studies carried out in pre-defined specific meteorological periods. In order to minimize seasonal differences in the first group of studies, simulation periods should cover all year-round conditions, and all simulations should be distributed over at least one particular year. Simulation start dates should be defined on equally spaced intervals, and all other factors (e.g., source term, simulation duration) should be kept constant to represent all possible meteorological conditions under standardized auxiliary data. In the second group of studies, special simulation periods are selected. This method makes a preliminary meteorological analysis for the simulation periods, and the selection is made accordingly.

The flow chart for nuclear risk management presented in this thesis is shown in Figure 3.1. As mentioned above, the first step involves selecting the analysis approach.

In the second step, the appropriate ADM is determined. The method related to ADM is explained in detail in section 3.2. In the next step, the release source, domain, and receptors are identified. In the fourth step, the radionuclides to be released and their amounts are determined, and then the release's vertical profile and temporal variation are set. These steps are explained in detail in sections 3.3 and 3.4. In the next step, the simulation periods are determined. The reference year or years should be determined if the risk study is conducted to cover entire meteorological conditions. If simulations are made for a selected period, simulation periods should be determined by considering the local/regional meteorological conditions. The meteorological data is determined according to the ADM and risk analysis method. A detailed explanation is specified in section 3.5. Then simulations are performed. In the last step, the results are used in dose and risk calculations. Dose and risk calculations are explained in section 3.6.

Two applications were conducted with the methodology presented in this thesis. In the first approach, where entire meteorological conditions were assessed, 72 simulations were carried out for the Akkuyu NPP during the meteorological conditions of the year 1986. The air activity concentration, deposition and TEDE results of these simulations were examined, and the effect of meteorological conditions throughout the year was revealed. In the second approach, simulations were made only for the Akkuyu NPP with the selected meteorological conditions. As the selection criteria, extreme meteorological conditions were determined for this approach. Relationships between air activity concentration, deposition and TEDE results and extreme meteorological conditions and synoptic weather types were investigated.

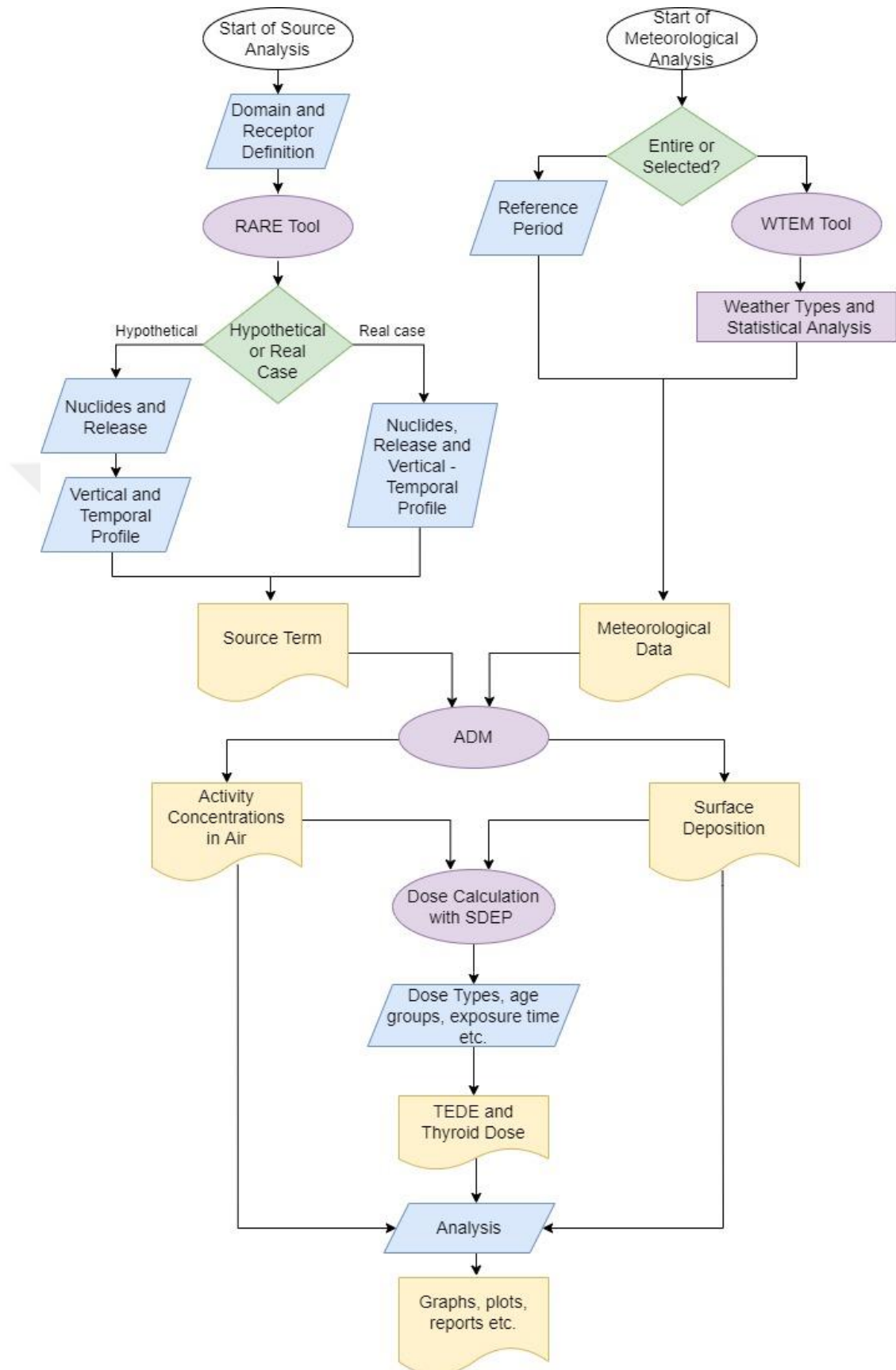


Figure 3.1 Representative algorithm of methodology developed in the thesis

3.2 Atmospheric Transport

ADM is the most crucial part of nuclear risk studies. Atmospheric transport is mainly driven by the wind advection of the radioactive cloud. All removal processes, such as chemical reactions, radioactive decay, physical transformations, and depositions, occur in the advective cloud. Further, vertical and horizontal mixing is produced by turbulent diffusion. The atmospheric transport mechanism is explained with the following formula (Leelőssy et al., 2018),

$$\frac{\partial c}{\partial t} = -v\nabla c + \nabla K \nabla c + E \pm R - D \quad (3.1)$$

where c is the concentration, v is the wind vector, K is the matrix of turbulent diffusion coefficients, E is emission from the source, R is chemical reactions, and D is deposition (Leelőssy et al., 2016). The first term on the right represents the advection, while the second describes the turbulent diffusion (Leelőssy et al., 2018).

With the analytical solution of Equation 3.1, the Gaussian dispersion equation is obtained. Gaussian dispersion models are widely used today, especially in regulatory applications. The primary advantages of Gaussian dispersion models are being fast and robust, and they can use locally measured meteorological data. However, Gaussian dispersion models are only suitable for short-range transports (Arnold, Seibert, et al., 2012). Therefore, they are out of the scope of this study.

Eulerian and Lagrangian Particle Dispersion Models with stochastic turbulence closure are developed based on Equation 3.1. The reference coordinate system is the main difference between the Eulerian and Lagrangian approaches (Figure 3.2). The coordinate system is fixed in the Eulerian approach. In contrast, the Lagrangian reference system follows the average atmospheric movement (Zannetti, 1993).

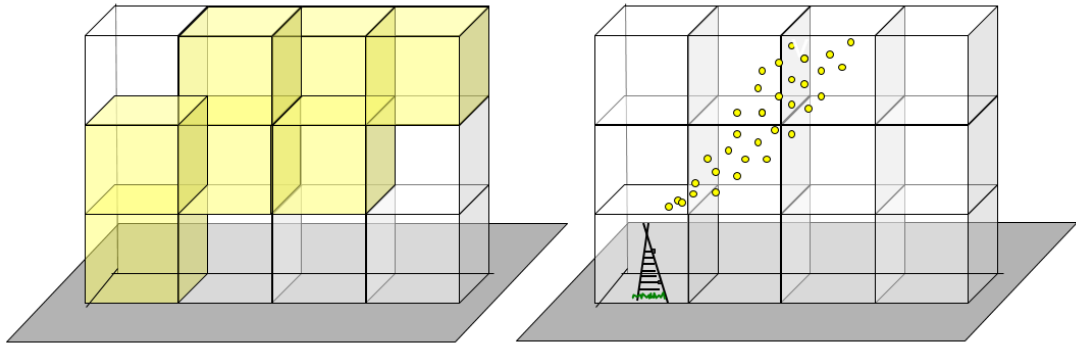


Figure 3.2 The difference in coordinate systems between the Eulerian (left-side) and Lagrangian (right-side) approaches (Arnold, 2019)

Eulerian models use submodels for defining plumes before the immediate dilution in the primary grid cell. However, these submodels mostly have simple approaches. Further, applying submodel approaches is quite complicated. LPDMs do not use submodels because estimation for grids is only conducted in output fields. In addition, point releases usually produce narrow plumes in various meteorological conditions. Eulerian models cannot be good at representing such plumes. Because Eulerian models have lower grid resolution and artificial diffusion from the advection, they produce smooth plumes (Arnold, Seibert, et al., 2012; Zannetti, 1993).

LPDMs use a more natural approach for turbulent processes than Eulerian models. In the close area, an accurate description of turbulent motion is critical. Although not all are equally qualified for this scale, this is exclusively attainable with LPDMs in the numerical models. Furthermore, one particle can represent several species simultaneously in LPDMs (Arnold, Seibert, et al., 2012; Zannetti, 1993).

Because of all these advantages, LPDMs are widely used in many nuclear risk assessment applications. The literature review in Chapter 2 supports this situation. In this study, FLEXPART, a LPDM developed for nuclear accident applications and used in mesoscale transports, is used as the ADM. FLEXPART was initially developed with ECMWF products and uses NCEP reanalysis datasets (Arnold, Gufler, et al., 2012; Pisso et al., 2019; Stohl et al., 1998, 2005; Stohl & Thomson, 1999).

FLEXPART calculates trajectories of so-called particles with 1st order zero acceleration equation (Stohl et al., 2005),

$$X(t + \Delta t) = X(t) + v(X, t)\Delta t \quad (3.2)$$

where X is the position vector, t is time, Δt is time increment and v is the wind vector that is comprised of grid-scale wind ($\bar{v}$), turbulent wind fluctuations (v_t) and mesoscale wind fluctuations (v_m) depicted as follows:

$$v = \bar{v} + v_t + v_m \quad (3.3)$$

FLEXPART considers physical processes separately as under and above Atmospheric Boundary Layer (ABL). Thus, ABL height calculation is a critical step. FLEXPART calculates the ABL height based on an approach that uses critical Richardson number (Vogelezang & Holtslag, 1996). The ABL height h_{mix} is set to the height of the first model level l , for which the Richardson number,

$$Ri_l = \frac{(g/\Theta_{v1})(\Theta_{vl} - \Theta_{v1})(z_l - z_1)}{(u_l - u_1)^2 + (v_l - v_1)^2 + 100 u_*^2} \quad (3.4)$$

exceeds the critical value of 0.25. In this equation, g is the gravity and u_* is the friction velocity, Θ_{v1} and Θ_{vl} are the virtual potential temperatures, z_1 and z_l are the heights of the 1st and l^{th} model level, and (u_1, v_1) , and (u_l, v_l) are the wind components at the 1st and l^{th} model level, respectively. The friction velocity is calculated as:

$$u_* = \sqrt{\tau/\rho} \quad (3.5)$$

where τ is total surface stress and ρ is the air density. Total surface stress is calculated by obtaining vectorial sums of surface stresses in East/West direction (τ_1) and surface stresses in North/South direction (τ_2) according to:

$$\tau = \sqrt{\tau_1^2 + \tau_2^2} \quad (3.6)$$

Equation 3.4 can be adapted for convective conditions by replacing Θ_{v1} with

$$\Theta'_{v1} = \Theta_{v1} + 8.5 \frac{(\overline{w'\Theta_v})_0}{w_* c_p} \quad (3.7)$$

where

$$w_* = \frac{(\overline{w'\Theta_v})_0 g h_{mix}}{\Theta_{v1} c_p} \quad (3.8)$$

is the convective velocity scale. The second term on the right-hand side of Equation 3.6 represents a temperature excess of rising thermals. As w_* is unknown beforehand, h_{mix} and w_* are calculated iteratively. After ABL height is determined, turbulence estimations are conducted. FLEXPART uses a Markov process based on Thomson (1987)'s Langevin equation to estimate the turbulent motions in the ABL:

$$dv_{t_i} = a_i(x, v_t, t) + b_j(x, v_t, t)dW_j \quad (3.9)$$

where i is the component of wind and, a and b represent drift and diffusion terms, respectively. Both terms are functions of position, turbulent velocity and time. dW_j are incremental components of a Wiener process. It is independent of time and mean value is zero with dt variance. FLEXPART assumes Gaussian turbulence (Stohl et al., 2005) and the Langevin equation for the vertical wind component w :

$$dw = -w \frac{dt}{\tau L_w} + \frac{\partial \sigma_w^2}{\partial z} dt + \frac{\sigma_w^2}{\rho} \frac{\partial \rho}{\partial z} dt + \left(\frac{2}{\tau L_w} \right)^{\frac{1}{2}} \sigma_w dW \quad (3.10)$$

where σ_w is the standard deviation of the turbulent vertical wind component and τL_w is the Lagrangian timescale for the vertical velocity autocorrelation. The second term

on the right side is the drift correction (McNider et al., 1988) that is used for preventing accumulation of particles in areas of low-turbulence. The third term on the right-hand side is the density correction (Stohl & Thomson, 1999) to account for the decrease of air density with height.

However, this approach is not well suited for unstable conditions. Because a larger area is occupied by downdrafts than by updrafts, turbulence is skewed (e.g., Luhar & Britter, 1989; Stull, 1988) in the convective ABL. The Gaussian turbulence model cannot reproduce the observed upward bending of plumes from near-ground sources or the rapid downward transport of plumes from elevated sources (Venkatram & Wyngaard, 1988). However, the Gaussian approximation has negligible impact on transport distances where particles are rather well mixed throughout the ABL (Pisso et al., 2019; Stohl et al., 2005). In the latest version of FLEXPART (10.4), an alternative Langevin equation developed by Cassiani et al. (2015) was implemented for better calculation of vertical turbulence in convective conditions (Pisso et al., 2019).

FLEXPART uses Hanna (1982) parameterization scheme based on the boundary layer parameters. This scheme comprises of ABL height h , Monin-Obukhov length L , convective velocity scale w_* , roughness length z_0 and friction velocity u_* . Parameterization of Hanna (1982) is applied for unstable, neutral and stable conditions (Stohl et al., 2005, 2010). According to Hanna (1982),

$$\frac{\sigma_u}{u_*} = \frac{\sigma_v}{u_*} = \left(12 + \frac{h}{2|L|}\right)^{1/3} \quad (3.11)$$

$$\tau L_u = \tau L_v = 0.15 \frac{h}{\sigma_u} \quad (3.12)$$

where σ_u , σ_v are the standard deviation of the u and v wind components and τL_u and τL_v are the Lagrangian timescale for the u and v velocity component

autocorrelation. The standard deviation of the turbulent vertical wind component σ_w for unstable conditions is calculated as:

$$\sigma_w = \left[1.2w_*^2 \left(1 - 0.9 \frac{z}{h} \right) \left(\frac{z}{h} \right)^{2/3} + \left(1.8 - 1.4 \frac{z}{h} \right) u_*^2 \right]^{1/2} \quad (3.13)$$

where z is the height of the model level. The Lagrangian timescale for the vertical velocity autocorrelation τL_w are calculated considering the relation between z , h and L . Accordingly,

- If $\frac{z}{h} < 0.1$ and $z - z_0 > -L$,

$$\tau L_w = 0.1 \frac{z}{\sigma_w [0.55 - 0.38(z - z_0)/L]} \quad (3.14)$$

- If $\frac{z}{h} < 0.1$ and $z - z_0 < -L$,

$$\tau L_w = 0.59 \frac{z}{\sigma_w} \quad (3.15)$$

- If $\frac{z}{h} > 0.1$,

$$\tau L_w = 0.15 \frac{h}{\sigma_w} \left[1 - \exp\left(\frac{-5z}{h}\right) \right] \quad (3.16)$$

Parameters are shaped as follows under neutral conditions:

$$\frac{\sigma_u}{u_*} = 2.0 \exp(-3fz/u_*) \quad (3.17)$$

$$\frac{\sigma_v}{u_*} = \frac{\sigma_w}{u_*} = 1.3 \exp(-2fz/u_*) \quad (3.18)$$

$$\tau L_u = \tau L_v = \tau L_w = \frac{0.5z/\sigma_w}{1 + 15fz/u_*} \quad (3.19)$$

where f is the Coriolis parameter in the equations. The same parameters under stable conditions are calculated with the following equations:

$$\frac{\sigma_u}{u_*} = 2.0 \left(1 - \frac{z}{h}\right) \quad (3.20)$$

$$\frac{\sigma_v}{u_*} = \frac{\sigma_w}{u_*} = 1.3 \left(1 - \frac{z}{h}\right) \quad (3.21)$$

$$\tau L_u = 0.15 \frac{h}{\sigma_u} \left(\frac{z}{h}\right)^{0.5} \quad (3.22)$$

$$\tau L_v = 0.07 \frac{h}{\sigma_v} \left(\frac{z}{h}\right)^{0.5} \quad (3.23)$$

$$\tau L_w = 0.1 \frac{h}{\sigma_w} \left(\frac{z}{h}\right)^{0.5} \quad (3.24)$$

The free atmosphere above ABL has turbulence due to gravity wave breaking and wind shear. However, no detailed scheme is available to estimate this turbulence. FLEXPART uses constant diffusivities for the free troposphere and stratosphere. The vertical diffusivity of the free troposphere D_h is $50 \text{ m}^2 \text{ s}^{-1}$, and the horizontal diffusivity of the stratosphere D_z is $0.1 \text{ m}^2 \text{ s}^{-1}$ (Legras et al., 2003). The distinction between troposphere and stratosphere is determined with a threshold value of 2 pvu (potential vorticity units) (Pisso et al., 2019; Stohl et al., 2005). These threshold values are very reasonable for mid-latitudes. However, it may differ from the thermal tropopause in the polar regions and near the equator. The latest version of FLEXPART (10.4) considers the thermal tropopause and calculates it using the lapse rate definition of (Hoinka, 1997) (Pisso et al., 2019).

Reanalysis datasets and turbulent parametrization do not include mesoscale fluctuations. Because mesoscale motions can significantly influence the growth of a dispersing plume, FLEXPART estimates it using an approximate way. FLEXPART

solves a Langevin equation using a similar method to Maryon (1998). It was assumed that the variance of the wind on the grid-scale provides sub-grid scale information in this method (Stohl et al., 2005).

Another significant transport mechanism is the updrafts in convective clouds. They occur with downdrafts within the clouds and compensate for subsidence in cloud-free surroundings. These convective transports are grid-scale on the vertical but subgrid-scale on the horizontal. Reanalysis datasets of vertical velocity do not include this convective transport. Particles should be redistributed in the entire vertical column to represent convective transport. FLEXPART uses a convective parameterization scheme developed by Emanuel & Živković-Rothman (1999). This scheme depends on the grid-scale temperature and humidity fields and calculates a displacement matrix providing the required mass flux information for particle redistribution (Stohl et al., 2005).

FLEXPART simulates removal mechanisms, such as decay and deposition, after applying physical processes (Stohl et al., 2005). Radioactive or chemical decay of mass is defined as,

$$m(t + \Delta t) = m(t) \exp\left(-\frac{\Delta t \ln(2)}{T_{1/2}}\right) \quad (3.25)$$

where m is the mass of particle and $T_{1/2}$ is the half lifetime of the released particle (Stohl et al., 2005). Applying radioactive decay is optional. Radioactive decay can also be involved in the post-processing step. In this way, less memory, CPU time, and disk space are used for multiple nuclides with similar physical properties.

FLEXPART considers wet and dry depositions and calculates wet scavenging in three stages. In the first stage, the form of scavenging is determined. In the latest version FLEXPART (v10.4), wet deposition occurs in the presence of a cloud or when precipitation occurs. For this purpose, total cloud water content (q_c , kg kg⁻¹) is determined and q_c values greater than zero are assumed to correspond to the finding

that the cell is cloudy (Pisso et al., 2009). In addition, the column cloud water (c_l ; kg m^{-2}), which is necessary for in-cloud scavenging, is estimated by integrating q_c over all vertical z levels:

$$c_l = \sum_z q_c(z) \rho_{air}(z) \Delta z \quad (3.26)$$

where $\rho_{air}(z)$ is the air density in the grid cell, and Δz is the vertical extent of the grid cell (Pisso et al., 2009).

Furthermore, precipitation is assumed non-uniform in a grid cell. FLEXPART calculates sub-grid area fraction and precipitation rate (I_s) using grid-scale precipitation (I_t) based on values presented by Hertel et al. (1995). No precipitation is assumed outside the sub-grid area (Pisso et al., 2019; Stohl et al., 2005). Further, the precipitation phase needed for the below-cloud scavenging scheme is simply based on ambient grid-scale temperature (Pisso et al., 2019).

Wet scavenging coefficients (Λ , s^{-1}) are determined in the second stage. The coefficient for gases for below cloud scavenging is estimated according to Asman (1995):

$$\Lambda = A I_s^B \quad (3.27)$$

where the scavenging parameters A and B depend on the chemical properties of the gas. For aerosols, the scheme considers aerosol sizes and precipitation types. Grythe et al. (2017) used to estimate below cloud scavenging coefficient as:

$$\log_{10} \left(\frac{\Lambda}{\Lambda_0} \right) = C_* \left(a + b D_p^{-4} + c D_p^{-3} + d D_p^{-2} + e D_p^{-1} + f \left(\frac{I_s}{I_0} \right)^{0.5} \right) \quad (3.28)$$

where $D_p = \log_{10} \left(\frac{d_p}{d_{p0}} \right)$ and d_p is the particle dry diameter. Here, $d_{p0} = 1 \text{ m}$, $\Lambda_0 = 1 \text{ s}^{-1}$ and $I_0 = 1 \text{ mm h}^{-1}$ is used. Coefficients for factors a through f are different for rain

and snow scavenging. If C_* represents rain, the coefficients given in Laakso et al. (2003) are used. If it represents snow, on the other hand, the coefficients given in Kyrö et al. (2009) are used.

In cloud scavenging, wet scavenging coefficients for both gases and aerosols are calculated with Grythe et al. (2017):

$$\Lambda = i_{cr} S_i I_s \quad (3.29)$$

where i_{cr} is cloud water replenishment factor and a constant value of 6.2 is used as empirically calculated by Grythe et al. (2017). S_i is proportional to the in-cloud scavenging ratio and it is estimated for gases and aerosols separately. For gases:

$$S_i = \frac{1}{\frac{1 - C_l}{HRT} + C_l} \quad (3.30)$$

where H is Henry's constant, R is the universal gas constant and T is temperature. For aerosols,

$$S_i = \frac{F_{nuc}}{C_l} \quad (3.31)$$

where F_{nuc} is nucleation efficiency and describes how efficiently aerosol particles are activated as cloud droplet condensation nuclei (CCN) or ice nuclei (IN):

$$F_{nuc} = \alpha_L CCN_{eff} + \alpha_I IN_{eff} \quad (3.32)$$

where α sets the abundance of ice (I) or liquid (L) phases.

At the last stage, mass removal of particles with precipitation is estimated using the exponential decay process of McMahon and Denison (1979):

$$m(t + \Delta t) = m(t) \exp(-\Lambda \Delta t) \quad (3.33)$$

FLEXPART estimates the dry deposition of gases and aerosols separately. The dry deposition velocity for gases is estimated using Wesely and Hicks (1977)'s resistance method:

$$|v_d(z)| = [r_a(z) + r_b + r_c]^{-1} \quad (3.34)$$

where r_a is the aerodynamic resistance between z and the surface, r_b is the quasi-laminar sublayer resistance, and r_c is the bulk surface resistance. The aerodynamic resistance is calculated with an approach presented in Stull (1988) based on the Monin-Obukhov similarity theory. The Quasi-laminar sublayer resistance is estimated with an approach from Erisman et al. (1994), and the bulk surface resistance is calculated using Wesely (1989) method. Similarly, the dry deposition of aerosols is estimated with:

$$v_d(z) = [r_a(z) + r_b + r_a(z)r_b v_g]^{-1} + v_g \quad (3.35)$$

where v_g is the gravitational settling velocity calculated by (Slinn, 1982):

$$v_g = \frac{g \rho_p d_p^2 C_{cun}}{18\mu} \quad (3.36)$$

where ρ_p and d_p are the particle density and diameter, μ is the dynamic viscosity of air ($0.000018 \text{ kg m}^{-1} \text{ s}^{-1}$) and C_{cun} is the Cunningham slip-flow correction. Settling and dry deposition velocities strongly depend on the particulate size, and FLEXPART assumes a logarithmic normal size distribution of the particulate mass. In the last step, FLEXPART counts particles by sampling the tracer mass fractions of all particles in a grid and estimates the concentration by dividing the mass with the grid volume:

$$C_{Ts} = \frac{1}{V} \sum_{i=1}^N (m_i, f_i) \quad (3.37)$$

where C_{T_s} is the concentration of samplings time, V is the volume of the grid cell, N is the total number of particles in the grid, m_i is particle mass and f_i is the fraction of the mass of particle i in the related grid cell. In FLEXPART, the sampling time is different from the output time. The sampling time is shorter than the output time and is exactly divisible by it. The output concentration corresponds to the average of the sample concentrations at the time of calculation.

$$C_{T_c} = \frac{1}{N} \sum_{i=1}^N C_{T_s} \quad (3.38)$$

where C_{T_c} represents output concentration, and N is the number of sample concentrations at the calculation time. Further information about the fundamental principles and background of FLEXPART is available in Stohl et al. (2005) and Pissot et al. (2019).

3.3 Source Term

Source term is an essential input in nuclear risk analysis and ADM studies. The source term covers the released radionuclides, their amounts and properties. Within the scope of this thesis, a tool named RARE (Radioactive Release Tool), the source term for hypothetical nuclear reactor accidents, has been developed. This section discusses the core inventory and releases fractions used in this tool and also presents the details of the algorithm implemented.

The literature indicated that the release could be determined with two approaches for the risk studies of hypothetical nuclear accidents. In the first approach, source terms of past accidents estimated based on measurements and models can be used (Bilgiç & Gündüz, 2020; Mitrakos et al., 2016). The most important advantages of this approach are that it is both a practical solution and comparable to the results of the relevant accident. However, it is often unrealistic as each reactor and accident has its own characteristics.

The other method used in the literature is a release generation approach depending on the reactor types and their thermal capacities (Arnold, Gufler, et al., 2012; Seibert et al., 2014; Slaper et al., 1994). In this approach, core inventory is determined by considering the type of reactor. Then, regarding the accident type for the reactor, a release fraction is determined, and the released radionuclides and amounts are calculated. This approach gives a more realistic release than the first one. However, finding the appropriate core inventory for each reactor type is rather challenging. For instance, there is no published core inventory for Rosatom's VVER-1200 model (Bilgiç & Gündüz, 2020), while reactor manufacturer Westinghouse's core inventories are available for AP 1000 model reactors (Min & Kim, 2018; Zhu et al., 2014). Slaper et al. (1994) presented core inventory related to different reactor types and thermal powers in their risk study. This core inventory was considered in the tool developed in this study. The radionuclide list for core inventory and the relevant radionuclide groups are presented in Table 3.1 (Soffer et al., 1995).

Table 3.1 Nuclides and relevant groups used in source term estimations (Soffer et al., 1995)

Group	Nuclides
Noble gases	Xe, Kr
Halogens	I, Br
Alkali Metals	Cs, Rb
Tellurium group	Te, Sb, Se
Barium, strontium	Ba, Sr
Noble Metals	Ru, Rh, Pd, Mo, Tc, Co
Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
Cerium group	Ce, Pu, Np

Slaper et al. (1994) described four accident scenarios regarding Eendebak et al. (1992): i) Early release, ii) Bypass of containment, iii) Late release, and iv) No containment failure. Similar five accident phases for severe nuclear accidents were also defined in the NUREG-1465 (Soffer et al., 1995) report: i) Coolant Activity, ii) Gap Activity, iii) Early In-Vessel, iv) Ex-Vessel, and v) Late In-Vessel. Release fractions change based on the reactor type and release phase. Release fractions in the RARE tool are obtained from the NUREG-1465 (Soffer et al., 1995) report (Table 3.2).

Table 3.2 Release fractions for BWRs and PWRs (Soffer et al., 1995)

	Gap Activity		Early In-Vessel		Ex-Vessel		Late In-Vessel	
	BWR	PWR	BWR	PWR	BWR	PWR	BWR	PWR
Duration (Hours)	0.5	0.5	1.5	1.3	3	2	10	10
Noble gases	0.05	0.05	0.95	0.95	0	0	0	0
Halogens	0.05	0.05	0.25	0.35	0.3	0.25	0.01	0.01
Alkali Metals	0.05	0.05	0.2	0.25	0.35	0.35	0.01	0.01
Tellurium group	0	0	0.05	0	0.25	0.25	0.005	0.005
Barium, strontium	0	0	0.02	0.02	0.1	0.1	0	0
Noble Metals	0	0	0.0025	0.0025	0.0025	0.0025	0	0
Lanthanides	0	0	0.0005	0.0005	0.005	0.005	0	0
Cerium group	0	0	0.0002	0.0002	0.005	0.005	0	0

The accident scenario is picked depending on the purpose of the study. For example, the phase that gives the highest fraction for the nuclear reactor studied can be selected as the worst case. However, the highest phase usually occurs with the lowest probability. Therefore, probability can also be considered to select more probable and realistic states. For example, in the FLEXRISK project (Seibert et al., 2013), low-probability scenarios with significant releases and scenarios with non-low reasonable probability releases were simulated. Since worst-case conditions are investigated in this thesis, scenarios with the highest release fraction are taken into consideration regardless of the probability of likelihood.

Within the scope of this thesis, simulations were carried out at two locations (Chernobyl and Akkuyu NPPs). Modeling studies in the literature that focus on Chernobyl accident were used to define the source terms of Chernobyl simulations performed in this thesis (Brandt et al., 2002; Evangeliou et al., 2017; Talerko, 2005b, 2005a). The releases of radionuclides used in the simulations are exhibited in Table 3.3. The release for Akkuyu NPP was determined with the RARE tool. The inputs used in the RARE tool are shown in Table 3.4.

Table 3.3 Source terms for Chernobyl NPP accident used in this study

Source	Release (Bq)		
	¹³¹ I	¹³⁴ Cs	¹³⁷ Cs
Brandt et al. (2002)	1760×10^{15}	54×10^{15}	85×10^{15}
Talerko (2005b, 2005a)	975×10^{15}	46×10^{15}	73×10^{15}
Evangeliou et al. (2017)	1365×10^{15}	80×10^{15}	86×10^{15}

Table 3.4 Defined inputs for Akkuyu NPP in release estimation in the RARE tool

Reactor Type	PWR
Reactor Installed Capacity (MW_e)	1114
Radionuclides	¹⁰³ Ru, ¹⁰⁵ Ru, ¹⁰⁶ Ru, ¹³¹ I, ^{131m} Te, ¹³² I, ¹³² Te, ¹³³ I, ¹³³ Xe, ¹³⁴ Cs, ¹³⁴ I, ¹³⁵ I, ¹³⁵ Xe, ¹³⁶ Cs, ¹³⁷ Cs, ⁸⁶ Rb, ⁸⁷ Kr, ⁸⁸ Kr, ⁸⁹ Sr, ⁹⁰ Sr, ⁹¹ Sr
Accident Phase	Early In-Vessel

3.4 Vertical Release Patterns

Accidental release, especially nuclear fallouts, cannot be defined only as the total amounts of emitted radionuclides into the atmosphere. Temporal variations and vertical distribution characteristics of the release become significant parameters for the source term. For example, radionuclide emission from the Chernobyl NPP accident took a total of 10 days, and the daily release of radionuclides demonstrated changing rates. Moreover, the duration of the release from the Fukushima NPP accident took even longer than the Chernobyl NPP accident. Moreover, literature demonstrated that radioactive release may reach more than 3000 meters in the atmosphere during the Chernobyl Accident (Davoine & Bocquet, 2007; Evangeliou et al., 2017). Further, this vertical line source had an inhomogeneous distribution. On the opposite extreme, the vertical release of the Fukushima NPP accident was limited to only a few hundred meters (Chino et al., 2011; Katata et al., 2012; Saunier et al., 2013; Stohl et al., 2012; Terada et al., 2012).

Consequently, the impact of the vertical distribution of release on atmospheric dispersion and deposition of radionuclides after an accidental radioactive fallout is essential and must be thoroughly investigated. In this thesis, some vertical release patterns were defined in the RARE tool considering some known statistical functions (e.g., Exponential, Gaussian, Triangular, etc.). In this approach, the vertical line source is split into several layers. Each layer has a release value determined by the defined function.

The RARE tool is developed to include eight vertical release patterns: Uniform, Dirac Delta, Exponential, Log Pearson Type III (LPT III (1)), Gaussian, Triangular,

Log Pearson Type III – Inverse (LPT III (2)), Cumulative Distribution Function (CDF). In all of these functions, a maximum release height (z_{max}) and layer thickness are defined. Further, some functions also require specific parameters such as shape and scale. The RARE tool creates a matrix that consists of release fractions (RF) for each layer regarding selected patterns. In the last step, the release matrix is calculated by multiplying the total release amount and the RF matrix. The characteristics of these release functions are presented in the following paragraphs.

Uniform release produces a homogeneous distribution along the entire vertical line. The RARE tool calculates equal RF for each layer, with a total of 1. The emission occurs in the Dirac Delta pattern on the lowest layer. The RARE assumes the RF value as 1 in the lowest layer. Release clusters near ground levels in Exponential and LPT III (1) patterns. The following equation calculates the RF in each l layer for exponential and LPTIII (1) pattern:

$$RF(l) = \frac{RC_l}{\sum_{l=0}^n RC_l} \quad (3.39)$$

where, n represents the number of layers estimated by dividing z_{max} by layer thickness. RC_l in equation 3.39 is the release coefficient in layer l that is estimated for exponential release,

$$RC_l = e^{-a \cdot l} \quad (3.40)$$

where a is a coefficient computed by solving the following equation with the bisection method:

$$e^{a^{n+1}} - 2e^a + 1 = 0 \quad (3.41)$$

The following equation is used to calculate the RC_l for LPT III (1) pattern:

$$RC_l = \frac{1}{\alpha! * \theta^\alpha} * l^{(\alpha-1)} * e^{-\frac{l}{\theta}} \quad (3.42)$$

where α and θ are shape and scale parameters with default values of 2.0 and 4.0, respectively.

The release is more intense in Gaussian and Triangular patterns at medium altitudes. The Triangular release produces a linearly increasing and decreasing pattern regarding z_{max} . The number of layers determines the vertex of the triangle. If the number of layers is odd, there will be one; if the number of layers is even, there will be two peaks. The RARE calculates the RF for Triangular distribution:

$$RF(l) = \frac{2}{n+1} * \left(1 - \left| -1 + l * \frac{2}{n} \right| \right) \quad (3.43)$$

The Gaussian release pattern considers a normal distribution model evenly distributed along a mean value. The RF value for Gaussian distribution is estimated with:

$$RF = \frac{e^{-0.5 * \left(\frac{l - \frac{n+1}{2}}{\sigma} \right)^2}}{\sigma * \sqrt{2 * \pi}} \quad (3.44)$$

where σ is a shape parameter with a default value of 2.5.

Vertical release patterns where emission occurs predominantly at higher levels are simulated with the LPT III (2) and the CDF functions. The LPT III (2) is the mirror function of the LPT III (1). RARE calculates the RF matrix using equations 3.39 and 3.42 for the LPT III (2). The RF matrix elements for the LPT III (2) are ordered in the opposite direction from the matrix elements calculated for the LPT III (1). In addition, the cumulative version of equations 3.39 and 3.42 gave the RF matrix for the CDF pattern. The algorithm of the RARE tool is illustrated in Figure 3.3.

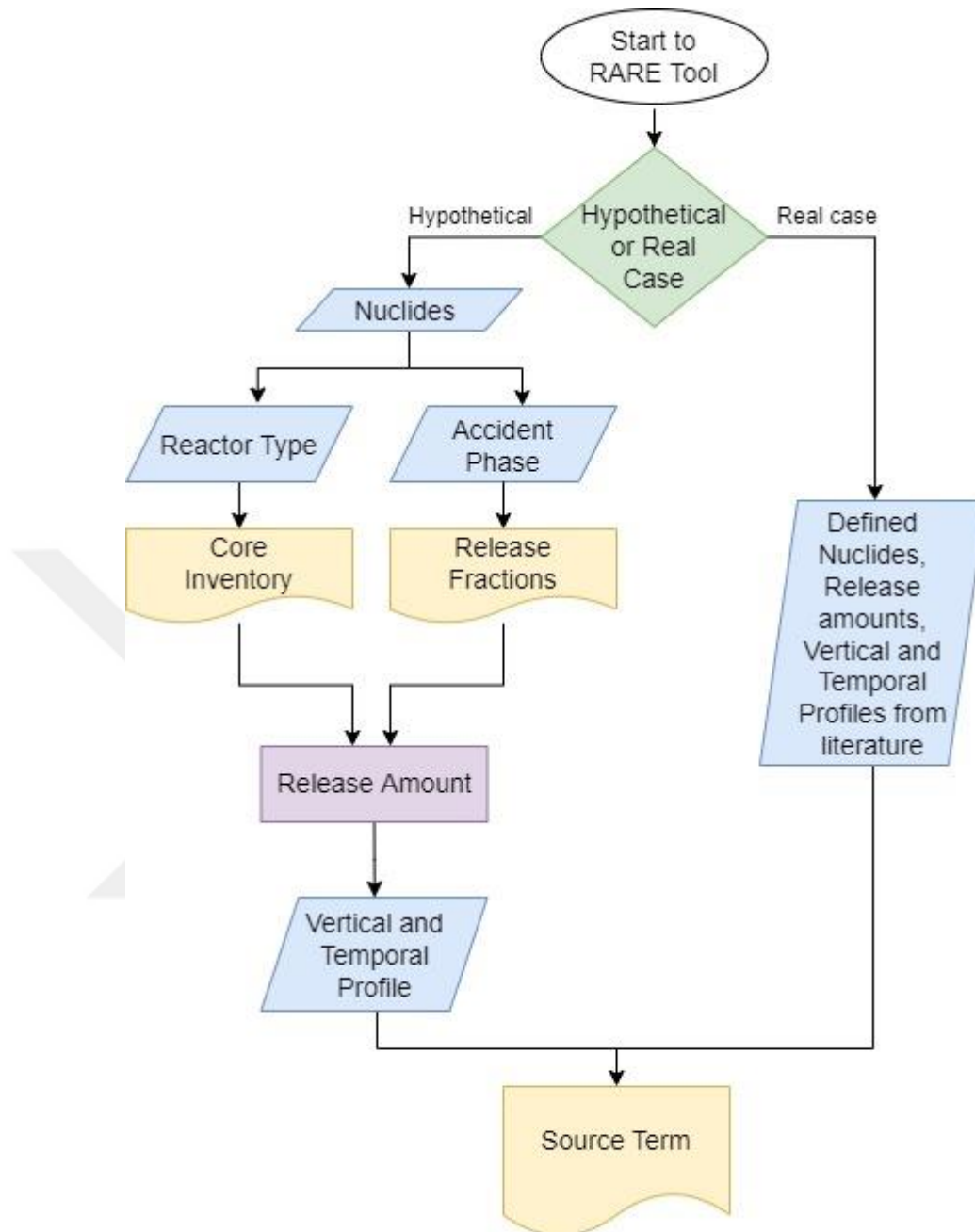


Figure 3.3 Flowchart of the RARE tool algorithm

In this thesis, the effects of release height and vertical release patterns are also examined. For this purpose, the Chernobyl NPP accident was simulated with ^{137}Cs radionuclide. Release amount and temporal variation of release are obtained from Brandt et al. (2002). Each vertical release pattern is defined for z_{max} as 2000, 3000 and 4000 meters. The results determined a vertical release pattern for hypothetical accident scenarios conducted in this thesis.

Furthermore, the RARE tool can optionally define temporal variation using the same patterns. The time step number is specified instead of the layer number used in the above functions. The number of time steps is the total release duration divided by the temporal resolution.

The RARE tool was developed as open source with PYTHON programming language. The tool can be accessed from https://bitbucket.org/efem_bilgi/rare/.

3.5 Analysis of Meteorological Conditions

Meteorological conditions directly influence the atmospheric transport and ground-level deposition of the pollutants. Pollutants can reach different locations in windy and unstable conditions or can influence only limited areas near the accident site under stable conditions. Precipitation is a crucial factor in depositions, that's why this mechanism can cause worst cases for some regions. Thus, analyzing the meteorological conditions is a crucial step for ADM and nuclear risk studies.

Reanalysis products are mostly used in long-range ADMs. Reanalysis data are formed by processing the meteorological parameters measured in the past regarding various approaches. These data are presented in large scale (e.g., global, continental, regional) in regular temporal resolution (e.g., 1h, 3h, 6h) and gridded format (e.g., 0.25 x 0.25, 0.50 x 0.50, 0.75 x 0.75). ECMWF and NOAA reanalysis datasets are the most widely used products in nuclear risk studies. Some of the different reanalysis products used in ADM studies are presented in Table 3.5.

Since FLEXPART was developed with ECMWF products, ECMWF reanalysis datasets were used in the applications conducted in this thesis. Lower resolution ERA-Interim reanalysis data were used in the applications that simulated the entire meteorological conditions of the analyzed cases. In applications conducted for selected meteorological conditions, high-resolution ERA-5 datasets were used. In the applications that simulated the entire meteorological conditions, the ERA-Interim data for the year 1986 were retrieved, as the reference year was assumed as the year of the

Chernobyl NPP accident. ERA-5 data, on the other hand, were downloaded separately for all periods determined after the meteorological analysis made in the selection of the simulation period.

Table 3.5 Some commonly used reanalysis products

Product	Source	Domain	Temporal Resolution	Horizontal Resolution	Number of Vertical Level
ASR	Bromwich et al. (2018)	Arctic	3-hourly	15 km x 15 km	71
JRA-55	Japanese Meteorological Agency	Global	6-hourly	1.25° x 1.25°	37
CFSR	NCEP	Global	6-hourly	0.5° x 0.5°	64
NARR	NCEP	North America	3-hourly	0.3° x 0.3°	29
ERA-40	ECMWF	Global	6-hourly	0.5° x 0.5°	60
ERA-Interim	ECMWF	Global	3-hourly	0.75° x 0.75°	60
ERA-5	ECMWF	Global	1-hourly	0.25° x 0.25°	137

A tool was developed for period selection analysis within the scope of this thesis: The weather Types and Extreme Meteorology (WTEM) analysis tool. WTEM analysis takes two parallel approaches (Figure 3.4). The first is synoptic-scale analysis, and the second is extreme period analysis. Since nuclear accidents cause long-range atmospheric transport, it is not sufficient to examine local meteorology only. Therefore, analyses at the synoptic scale are also required. Weather types of the study area are determined by synoptic-scale analysis in the WTEM analysis tool. For this purpose, the Lamb Weather Types method is implemented. Circulation weather type methods are commonly used to define synoptic weather conditions (P. D. Jones et al., 2013; Mészáros et al., 2012). Initially, these methods were subjective and needed evaluations by experts. With the development of computer technology, algorithms that can automatically define weather types were developed (Hess & Brezowsky, 1952; Lamb, 1972). One of the most commonly used methods is Lamb Weather Type (LWT) method developed by Lamb (1972) for the British Isles (Fernandez-Raga et al., 2017). The method was based on sea-level atmospheric pressures initially and was fairly subjective. Subsequently, Jenkinson and Collison (1977) produced an objective version of the method, and Jones et al. (1993) and Jones et al. (2013) refined it.

Many studies used LWT in circulation weather condition examination, such as the relation between weather types and rainfall (Akkoyunlu et al., 2019; Baltacı et al., 2015, 2017; Fernandez-Raga et al., 2017; Putniković & Tošić, 2018; Trigo & DaCamara, 2000), snowstorm (Baltaci et al., 2021), temperature (Peña-Angulo et al., 2016), or air pollution (Baltaci et al., 2019; Giaccone et al., 2019; Liao et al., 2017; Russo et al., 2014; Tso et al., 2022).

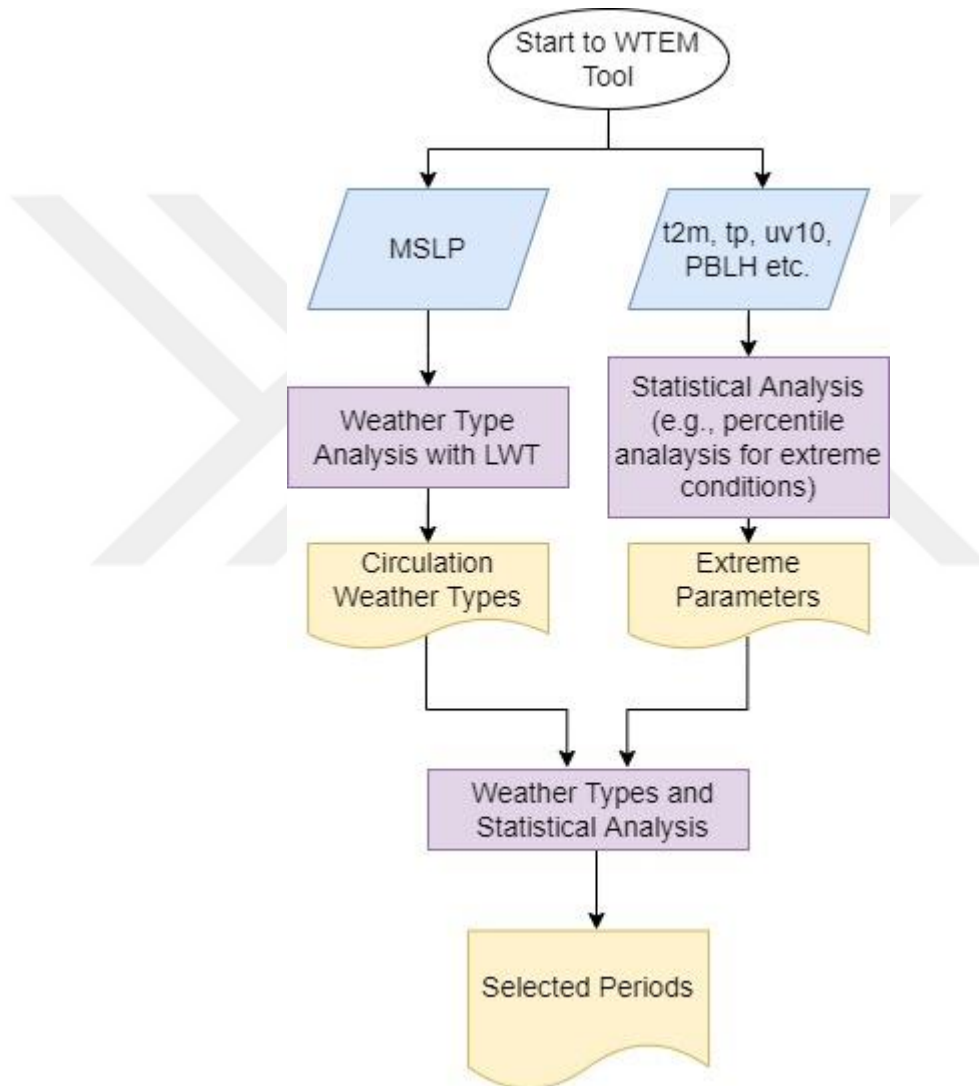


Figure 3.4 Flowchart of WTEM analysis tool

The WTEM uses mean sea level pressures (MSLP) in 16 locations to estimate the weather types. These 16 locations are selected on a homogenous grid and are represented in Figure 3.5, centered on the study area. In the original study for the

British Isles near the North Pole (Lamb, 1972), longitudes and latitudes were chosen at 10° and 5° intervals, respectively. In studies for Serbia (Putniković & Tošić, 2018) and Turkey (Akkoyunlu et al., 2019; Baltacı et al., 2015), the longitudes were also set at 5° intervals.

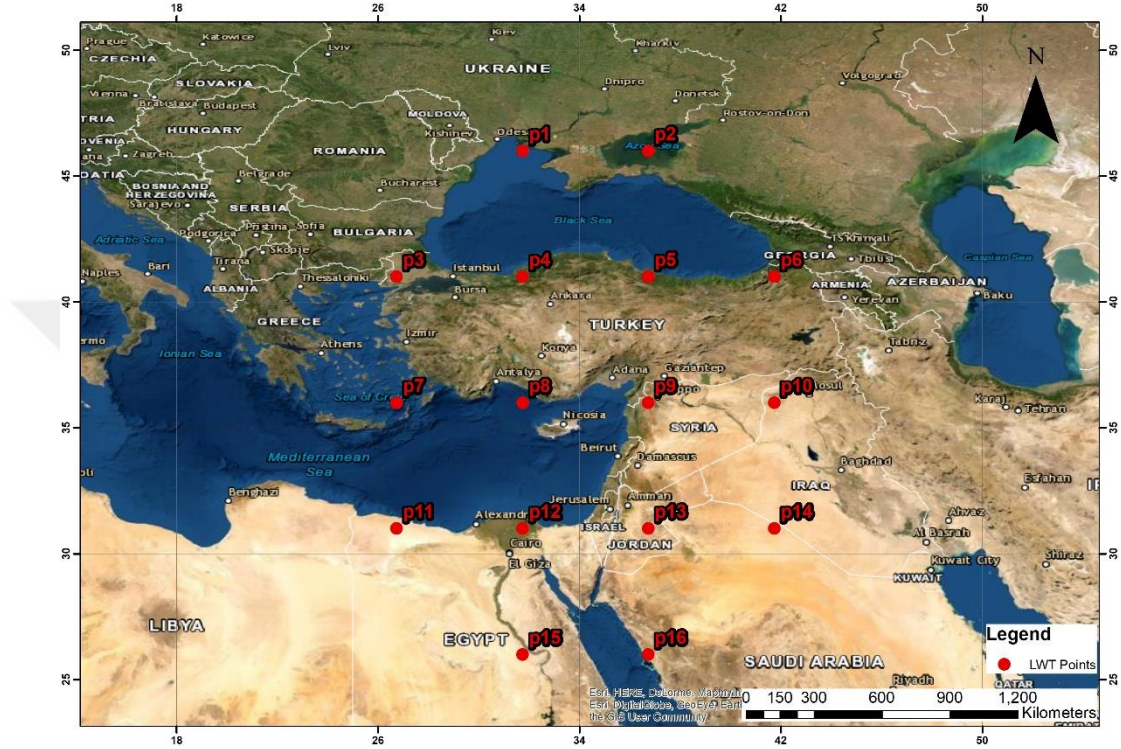


Figure 3.5 Locations of mean sea level pressures used in LWT estimations

In the LWT estimation, flows and vorticities are estimated (P. D. Jones et al., 2013). Westerly flow (W) is calculated with,

$$W = [0.5 * (p_{12} + p_{13}) - 0.5 * (p_4 + p_5)] \quad (3.45)$$

where p is the location of MSLP illustrated in Figure 3.5. Southerly flow (S) is estimated with,

$$S = \frac{1}{\cos(\psi)} * [0.25 * (p_5 + 2 * p_9 + p_{13}) - 0.25 * (p_4 + 2 * p_8 + p_{12})] \quad (3.46)$$

where ψ is the central latitude for 16 locations (P. D. Jones et al., 2013). Total flow (F) is calculated with following equation (P. D. Jones et al., 2013):

$$F = (S^2 + W^2)^{1/2} \quad (3.47)$$

Westerly shear vorticity (ZW) and Southerly shear vorticity (ZS) are calculated with the following two equations (P. D. Jones et al., 2013):

$$ZW = \frac{\sin(\psi)}{\sin(\psi-5)} * [0.5 * (p_{15} + p_{16}) - 0.5 * (p_8 + p_9)] - \frac{\sin(\psi)}{\sin(\psi+5)} * [0.5 * (p_8 + p_9) - 0.5 * (p_1 + p_2)] \quad (3.48)$$

$$ZS = 1/(2 \cos^2(\psi)) * [0.25 * (p_6 + 2 * p_{10} + p_{14}) - 0.25 * (p_5 + 2 * p_9 + p_{13}) - 0.25 * (p_4 + 2 * p_8 + p_{12}) + 0.25 * (p_3 + 2 * p_7 + p_{11})] \quad (3.49)$$

Total shear vorticity (Z) is then calculated to be equal to the sum of Westerly shear vorticity and Southerly shear vorticity (P. D. Jones et al., 2013):

$$Z = ZS + ZW \quad (3.50)$$

After the flows and vorticities are calculated, the WTEM analysis tool calculates the flow direction by $\tan^{-1}(W/S)$. If W is positive, 180° is added to the calculated direction. The relevant direction is determined for each 45° per sector. Then, the circulation type is determined by examining the relationship between Z and F . If $|Z|$ is less than F , the flow is considered a directional (D) type. If $|Z|$ is greater than $2F$, the circulation type is determined by the sign of Z . If Z is negative, it is Anticyclonic (A); if it is positive, it is Cyclonic (C). If $|Z|$ corresponds to a value between F and $2F$, the circulation type is called hybrid. It is expressed as Hybrid Anticyclonic (HYA) or Hybrid Cyclonic (HYC) regarding the sign of Z . Hybrid types also show directional characteristics. All weather-types classes are presented in Table 3.6.

Table 3.6 The 26 classes of CWTs

Directional types (D)	Anticyclonic types (A)	Cyclonic types (C)
NE	ANE	CNE
E	AE	CE
SE	ASE	CSE
S	AS	CS
SW	ASW	CSW
W	AW	CW
NW	ANW	CNW
N	AN	CN
	A	C

The WTEM analysis tool also identifies extreme meteorological periods for defined parameters (e.g., temperature, precipitation). Considering statistical percentile analysis, WTEM estimates threshold values to define extreme values of each meteorological parameter. The threshold value is calculated with the user-defined percentile value. Upper and lower values than the threshold were assumed extreme days for defined meteorological parameters.

Within the scope of this thesis, analyses were made for Akkuyu NPP using the WTEM tool for selected meteorological conditions simulations. For this purpose, daily gridded fields ($5^{\circ} \times 5^{\circ}$ longitude-latitude) of mean sea level pressure (MSLP) from ERA-5 provided by ECMWF were used over Eastern Mediterranean, covering the period January 1979 – December 2021. Daily weather types were determined and analyzed from January 1, 1979, to December 31, 2021.

In addition, extreme meteorological analyses are also conducted for Akkuyu NPP. Because the transport of emissions from severe nuclear reactor accidents occurs on a large scale, it is insufficient to perform extreme period analysis only at the release point. Therefore, ten receptors were defined in a 500 km zone around the Akkuyu NPP. These ten receptors were determined by population density, climatic diversity, and spatial distribution (Table 3.7, Figure 3.6).

Table 3.7 Receptors used in meteorological analysis

#	Name	Country	LON	LAT	Climate Class
1	Akkuyu	TURKEY	33.50	36.25	Csa
2	Lefkosa	CYPRUS	33.50	35.00	Bsh

Table 3.8 Inputs of WTEM tool

p₁ (Lon, Lat)	32.00, 46.00
ΔX, ΔY	5.00, 5.00
Timestep	1 - Day
Start of Analysis	1.12.1979
End of Analysis	31.12.2021
MSLP Data	ECMWF ERA-5
Other Parameters	t2m, tp, u10, v10, PBLH (ECMWF ERA-5)

The WTEM tool was developed as open source with PYTHON programming language. The tool can be accessed from https://bitbucket.org/efem_bilgi/wtem/.

3.6 Dose Calculation

The dose quantities are estimated to evaluate the health effects and biological consequences of radionuclides released after nuclear accidents. In this section, basic dose calculation concepts are introduced, and calculation methods are explained. In addition, the dose calculation and plotting tool developed and used in this study are also presented.

The radiation energy absorbed per unit mass of a substance is called the absorbed dose. Absorbed dose (D) is calculated with the following formula:

$$D = \frac{d\bar{\epsilon}}{dm} \quad (3.51)$$

where $d\bar{\epsilon}$ is the average energy interacting with matter and dm is the mass of the matter (ICRP, 2021). The unit of absorbed dose is $J\ kg^{-1}$ or *gray* (Gy). The absorbed dose amounts for nuclear safety applications are calculated by averaging the doses over the tissue volumes. The average absorbed dose, ($D_{T,R}$) is performed over the mass of a particular organ, tissue, or sensitive tissue area to include the impacts of different radiation types. Separately evaluating the dose values for each organ is quite complicated. For this purpose, the equivalent dose, H_T is used and calculated with the following equation for an organ or tissue.

$$H_T = \sum_R w_R D_{T,R} \quad (3.52)$$

where R is the type of radiation and w_R is the radiation weighting factor (ICRP, 2021). The unit of dose equivalent is Sievert (Sv). Relevant radiation weighting factors for each radiation type are presented in Table 3.9. In radiological analyses, the effective dose (E) is used instead of evaluating the dose values of all tissues or organs. The effective dose is calculated through a weighted sum of tissue-equivalent dose.

$$E = \sum_T w_T H_T \quad (3.53)$$

where T is related tissue or organ and w_T is tissue weighting factor for each tissue (ICRP, 2021). The sum of w_T must be equal to be 1. Tissue weighting factors for each tissue and organ are presented in Table 3.10.

Table 3.9 Recommended radiation weighting factors by ICRP (ICRP, 2007)

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy

Table 3.10 Recommended tissue weighting factors by ICRP (ICRP, 2007)

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

People are exposed to radiation internally and externally. Internal exposure pathways are inhalation of radioactive aerosols and ingestion of contaminated food. External exposure pathways are cloud shine from radionuclides in the air and ground shine from deposited radioactive materials. The sum of the external and internal dose equivalents is called the total effective dose equivalent (TEDE). TEDE is mainly used in radiological evaluations after accidental release (Seibert et al., 2013; UNSCEAR,

1988; WHO, 2012). Besides TEDE, tissue-based thyroid dose is also widely used (Arnold, Gufler, et al., 2012; WHO, 2012). External and internal pathways are illustrated in Figure 3.7. The external and internal dose is calculated by multiplying the exposed radionuclide activity by the dose conversion factor. The ICRP presents radionuclide-based dose conversion factors (DCF) for each pathway. DCF varies by age group, as the effect of radiation differs by age group (ICRP, 2015, 2016, 2017, 2019, 2020, 2022).

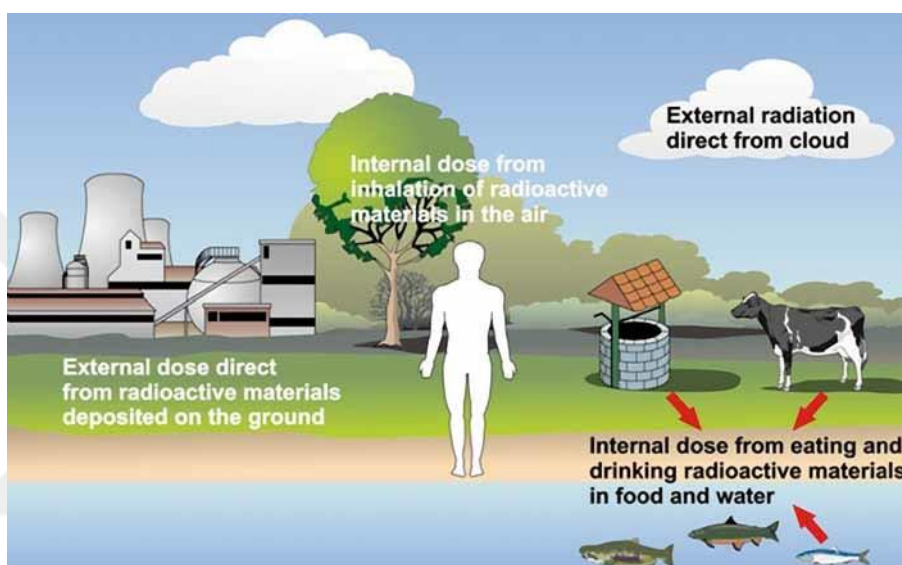


Figure 3.7 External and internal dose exposure pathways (IAEA, 2006; WHO, 2012)

Besides the exposure pathway, another critical parameter is the exposure time to radiation. The health effect of radiation increases cumulatively over time. Therefore, the measured or calculated dose rates are multiplied by the time of exposure to radiation to obtain the “total dose”. ICRP (2007) recommends that TEDE for the public should not exceed 1 mSv per year. This value may be exceeded under certain conditions, but the average over 5 years should not exceed 1 mSv per year. For occupational purposes, it is recommended that this value should not be over 50 mSv per year, and the average of 5 years value should be less than 20 mSv per year (ICRP, 2007). Generally, 1-year and lifetime dose values are calculated in radiological analyses after nuclear releases (Cardis et al., 2006; Seibert et al., 2013; WHO, 2012).

During the transport of radionuclides to the environment, people are not constantly exposed to radioactive materials. Due to the shielding effect of buildings, the population within a structure is less affected by radiation. This reducing effect is called the location factor. Another reducing factor is the time-dependent reduction of ground shine. In contaminated soil, pollutants move towards the lower layers of the soil by various mechanisms over time. This additional reduction mitigates direct exposure over long periods. Therefore, for long-term (e.g., 1 year, lifetime) exposures, reduction factors are used for ground-shine (Seibert et al., 2013).

The ICRP has introduced collective dose amounts to optimize radiological protection (ICRP, 1977, 1991, 2007). These amounts consider the population exposed to radiation and the duration of exposure (ICRP, 1991, 2007). The unit of collective dose is “man sievert.” In appropriate circumstances, the collective dose can be used to plan “radiation protection actions”. However, it is unsuitable for epidemiological risk assessment and official risk projections. In particular, the results will be more misleading than informative in scenarios involving extremely low exposures to huge populations (ICRP, 2007). The collective effective dose, (S), due to individual effective dose values between E_1 and E_2 is defined as:

$$S(E_1, E_2, \Delta T) = \int_{E_1}^{E_2} E \frac{dN}{dE} dE \quad (3.54)$$

where $\frac{dN}{dE}$ denotes the number of individuals who are exposed to an effective dose between E and $E + dE$, and ΔT specifies the time period within which the effective doses are summed (ICRP, 2007).

Within the scope of this thesis, a third tool is developed for dose calculation after radioactive contamination occurs, and its spatial distribution is known: The Simple Dose Estimation and Plotting (SDEP) tool. The tool calculates the effective or tissue-based dose for a specific period (1 week, 1 month, 1 year, lifetime or user-defined). SDEP tool uses time-integrated air activity concentration and surface deposition as inputs in two-dimensional space. If the optional ingestion pathway is to be considered

or the collective dose is to be calculated, additional inputs such as gridded population and consumption are also required. The flowchart of the SDEP tool for dose calculations is illustrated in Figure 3.8.

The SDEP tool calculates the dose for each pathway separately. The effective dose equivalent from cloud shine exposure (D_{cl}) is estimated with (Seibert et al., 2013; Slaper et al., 1994):

$$D_{cl} = \sum_{i=1}^n DCF_{cl,i} * TIAC_i * f_L \quad (3.55)$$

where $TIAC_i$ is the time-integrated (cumulative) activity concentration of radionuclides i , n is the number of radionuclides and f_L is the location factor. Dose Conversion Factors for cloud-shine ($DCF_{cl,i}$) are taken from (ICRP, 2020). Radioactive clouds remain for a few days in a location, and air activity concentration is zero after radioactive clouds leave the site. Therefore, the SDEP calculates D_{cl} independent exposure time (e.g., 1 month, 1 year, lifetime). The effective dose equivalent from ground shine exposure (D_{gr}), on the other hand, is estimated with:

$$D_{gr} = \sum_{i=1}^n DCF_{gr,i} * \frac{DEP_i}{\lambda_i} * (1 - e^{-\lambda T}) * f_L * f_r \quad (3.56)$$

where DEP_i and λ_i are total ground-level deposition and radioactive decay constant of radionuclide i , respectively. T is the exposure time and f_r is the reduction factor due to soil mitigation. Dose Conversion Factors for ground-shine ($DCF_{gr,i}$) are obtained from ICRP (2020). Adding the daughter radionuclides into account, Equation 3.56 becomes:

$$D_{gr} = DEP_i * \sum_{i=1}^n \left\{ DCF_{gr,i} \{ \prod_{j=1}^{i-1} (f_{j,j+1} \lambda_{j+1}) \} \sum_{j=1}^i \frac{1 - e^{-\lambda_j t}}{\lambda_j \prod_{\substack{k=1 \\ k \neq j}}^i (\lambda_k - \lambda_j)} \right\} * f_L * f_r \quad (3.57)$$

where, $f_{j,j+1}$ is the fractional yield of chain member $j + 1$ from the decay of member j (e.g., 0.944 from ^{137}Cs to $^{137\text{m}}\text{Ba}$).

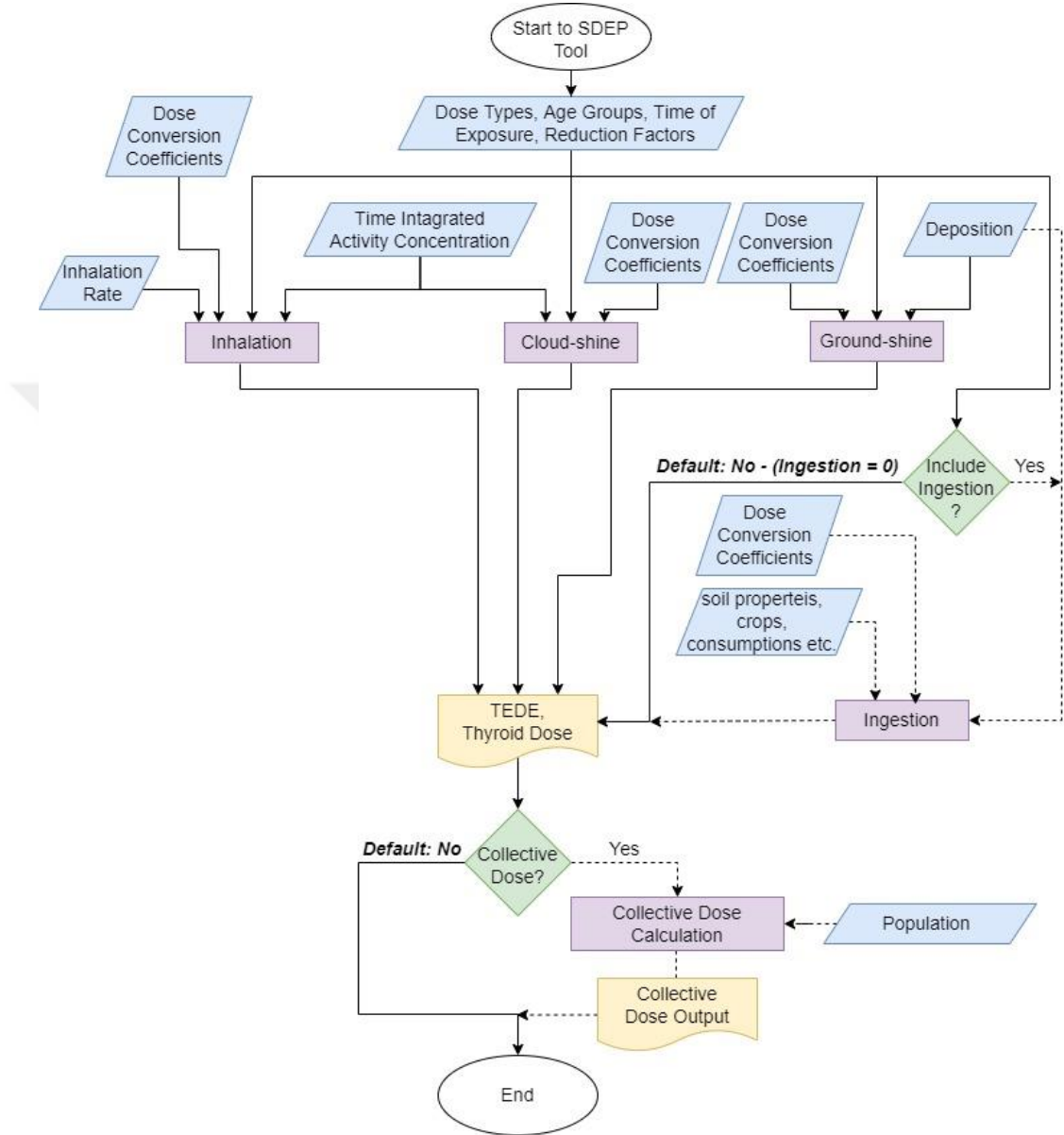


Figure 3.8 Flow chart of SDEP tool algorithm

The effective dose from inhalation calculated with,

$$D_{inh} = \sum_{i=1}^n TIAC_i * IR * DCF_{inh,i} * f_L \quad (3.58)$$

where IR is age dependent inhalation rate taken from ICRP (1995) and $DCF_{inh,i}$ is inhalation dose conversion factors for radionuclide i obtained from ICRP (2015, 2016, 2017, 2019, 2022). SDEP tool calculates the ingestion with the following expression:

$$D_{ing} = \sum_{i=1}^n TIN_i * DCF_{ing,i} \quad (3.59)$$

where $DCF_{ing,i}$ is ingestion dose conversion factors for radionuclide i obtained from ICRP (2015, 2016, 2017, 2019, 2022). TIN_i is total intake of nuclide i and it was calculated with following equation:

$$TIN = \sum_{p=1}^n I_p * f_{b,p} * C_p * e^{-\lambda t_d} \quad (3.60)$$

where I_p , $f_{b,p}$ and c_p are human intake of food products, reduction factor for removal of radionuclides and time-integrated nuclide concentration in food product p , respectively. Furthermore, t_d is time between harvesting / milking / slaughtering and consumption (Slaper et al., 1994). Estimation of c_p in nuclear risk studies is a complicated process.

Intake of deposited radionuclides can be direct consumption of contaminated crops or indirect consumption of milk or meat fed with radioactive pasture or soil. Crops can be directly contaminated by radionuclides deposited or indirectly contaminated by radionuclides transferred from the soil. Therefore, c_p for crops are calculated with the following equation:

$$c_p = \frac{Dep * F_{ip} * (1 - e^{-(\lambda + \lambda_W)t_{a,p}})}{Y_p * (\lambda + \lambda_W)} + c_S + B_v \quad (3.61)$$

where F_{ip} direct interception fraction for crop type p , λ_W is the rate constant for reduction of the concentration of material deposited on the surface of vegetation due

to processes other than radiological decay, $t_{a,p}$ is the time period during the growing season that crops can be contaminated through direct interception of deposition, Y_p is the agricultural productivity or standing crop biomass of the edible portion of vegetation, c_s is time integration concentration of radionuclides in dry soil and B_v is concentration factor for uptake of the radionuclide from soil by edible parts of crops (IAEA, 1982; Slaper et al., 1994). The time-integrated concentration of radionuclides in dry soil, c_s , is calculated with

$$c_s = \frac{Dep}{S * (\lambda + \lambda_1)} * (1 - e^{-(\lambda + \lambda_1) * t}) \quad (3.62)$$

where S is mass of soil in the plough layer per unit area, calculated by multiplying the depth of the plough layer with soil density, and λ_1 is a constant describing removal from plough layer (IAEA, 1982; Slaper et al., 1994). λ_1 constant is estimated with

$$\lambda_1 = \frac{W_R + W_I - W_E}{\theta * h * \left(1 + \frac{K_d * \rho}{\theta}\right)} \quad (3.63)$$

where W is water balance and indexes R , I and E are rainfall, irrigation and evaporation, respectively (Slaper et al., 1994). In addition, θ is volumetric water content of soil, h is thickness of soil, K_d is soil affinity of nuclide and ρ is soil density. Indirect ingestion contribution $c_{p,ind}$ such as milk and meat from the cow is estimated with

$$c_{p,ind} = F_{p,ind} * (I_{cow,grass} * C_{grass} + I_{cow,soil} * C_s) \quad (3.64)$$

where, $F_{p,ind}$ is transfer to milk, $I_{cow,grass}$ is grass intake for cow, C_{grass} is time-integrated nuclide concentration in grass and $I_{cow,soil}$ is soil intake for cow (Slaper et al., 1994).

After dose equivalents are estimated separately for all exposure routes, TEDE is obtained by summing them (Eq 3.65).

$$TEDE = D_{cl} + D_{gr} + D_{inh} + D_{ing} \quad (3.65)$$

In all applications within the scope of this thesis, dose calculations were made with the SDEP tool. One-year TEDE was calculated by considering ^{131}I , ^{134}Cs and ^{137}Cs in all applications. The ingestion pathway is ignored because it requires complex data that is not available in most cases. On the other hand, considering more radionuclides and all exposure pathways, comprehensive and more realistic one-year TEDE were estimated for the worst-case scenarios from selected extreme meteorological conditions simulations. The shielding factor was considered 0.36, as shown in UNSCEAR (1988) and WHO (2012). The reduction factor due to soil mitigation was assumed as 0.8 for 1 year (Seibert et al. 2013).

The SDEP tool was developed as open source with PYTHON programming language. The tool can be accessed from https://bitbucket.org/efem_bilgi/sdep/.

CHAPTER 4

RESULTS AND DISCUSSION

This section presents the results of the preliminary analyses and the applications conducted using the methodology developed in the previous chapter. The FLEXPART model was first validated using the Chernobyl NPP source term in the literature and two reanalysis datasets. Then, the vertical profile of the source term was analyzed using the "source term" tool. Later, applications were conducted based on the results in these two sections. In the third section, the results of the simulations were presented that considered the entire meteorological conditions for Akkuyu NPP. Finally, the last section included the simulation results for selected conditions based on extreme meteorology.

4.1 Validation of the FLEXPART model

This thesis simulated ^{131}I , ^{134}Cs and ^{137}Cs released after the Chernobyl NPP accident to validate the FLEXPART model. For this purpose, three source terms developed by Brandt et al. (2002), Talerko (2005a, 2005b) and Evangeliou et al. (2017) were used:

- Brandt et al. (2002) assumed that the release had 1760 PBq of ^{131}I , 54 PBq of ^{134}Cs and 85 PBq of ^{137}Cs , considering the works of Devell et al. (1995) and De Cort et al. (1998). Six vertical release points were defined as 225 m, 425 m, 715 m, 1090 m, 1575 m and 2225 m, based on Persson et al. (1986) and Hass et al. (1990).
- Talerko (2005b) used a release value of 975 PBq of ^{131}I and Talerko (2005a) considered 73 PBq of ^{137}Cs from four vertical release heights up to 1200 m. Talerko (2005b, 2005a) did not simulate the ^{134}Cs . Thus, for this study, a ^{134}Cs release was assumed, with a $^{134}\text{Cs}/^{137}\text{Cs}$ ratio identical to that of Brandt et al. (2002).
- Evangeliou et al. (2017) estimated 1365 PBq of ^{131}I , 80 PBq of ^{134}Cs , and 86 PBq of ^{137}Cs released using a Bayesian inversion approach after the Chernobyl NPP accident. This study defined six vertical release heights

between 0-3000 m and four aerosol sizes. Besides, Evangeliou et al. (2017) used ERA-Interim and ERA-5 from ECMWF as meteorological input and conducted six simulations. Time-integrated air activity and total surface depositions obtained from the results of six simulations were compared with measurement (Evangeliou et al., 2016) and country-based deposition estimations (De Cort et al., 1998).

Model validations in ADM studies are carried out over various statistical parameters (Brandt et al., 2002; Evangeliou et al., 2017). In this study, Correlation Coefficient (r), Root Mean Square Error (RMSE), Normalized Mean Square Error (NMSE), Mean Bias (MB) and Fractional Bias (FB) parameters were used to evaluate model performance. The correlation coefficient varies between -1 and 1. Values close to 1 or -1 indicate a positive or negative correlation between the model results and the measurement values. RMSE and NMSE are used to measure the accuracy of quantitative data. The closer the RMSE and NMSE to 0, the higher the model's accuracy. MB is the mean bias error, representing a model's systematic error above or below the prediction. MB values close to 0 are an indication of the accuracy of the model. FB is another performance indicator ranging from -2 to +2. FB values close to 0 indicate that the model is successful.

4.1.1 Air Activity Concentration Comparisons

Simulation results demonstrated a satisfactory agreement for ^{131}I air activity concentrations between all simulations and Evangeliou et al. (2016) measurements. The highest correlations were obtained in simulations conducted with Evangeliou et al. (2017) source term, and the lowest was found in Brandt et al. (2002) simulations. On the other hand, the lowest RMSE, NMSE, MB and FB were obtained in Talerko (2005b) simulations. In studies using ERA-Interim as the meteorological input, RMSE, NMSE, MB and FB values were calculated higher than simulations that used ERA-5 (Table 4.1). The simulations with the highest and lowest correlations are illustrated in Figure 4.1.

Table 4.1 Statistical comparison of simulations and Evangeliou et al. (2016) for air activity concentrations of ^{131}I . N is the number of sampling locations used in comparison

Source Term	Reanalysis Input	^{131}I					
		N	r	RMSE	NMSE	MB	FB
Brandt et al. (2002)	ERA -Interim	91	0.37	4122.6	24.35	1567.4	1.37
	ERA - 5	91	0.40	2314.0	12.01	870.6	1.09
Talerko (2005b)	ERA -Interim	91	0.52	1403.5	6.42	486.4	0.80
	ERA - 5	91	0.53	838.0	3.45	200.8	0.43
Evangeliou et al. (2017)	ERA -Interim	91	0.53	3459.7	13.48	2091.3	1.49
	ERA - 5	91	0.55	1879.3	7.29	977.5	1.15

Among 82 simulations that simulated ^{137}Cs , air activity concentrations of ^{137}Cs revealed good agreement with Evangeliou et al. (2016) in five simulations. The highest correlations were obtained in simulations using Talerko (2005a). Moreover, the lowest RMSE, NMSE, MB and FB was obtained in Talerko (2005a) simulations (Table 4.2). On the other hand, the simulation using Evangeliou et al. (2017) as the source term and ERA-5 as the meteorology input provided a very low correlation. The simulations with the highest and lowest correlations are presented in Figure 4.2.

Table 4.2 Statistical comparison of simulations and Evangeliou et al. (2016) for air activity concentrations of ^{137}Cs

Source Term	Reanalysis Input	^{137}Cs					
		n	r	RMSE	NMSE	MB	FB
Brandt et al. (2002)	ERA -Interim	82	0.35	388.5	4.00	191.2	0.88
	ERA - 5	82	0.33	210.3	2.30	38.4	0.27
Talerko (2005a)	ERA -Interim	82	0.43	232.8	2.25	77.9	0.49
	ERA - 5	82	0.48	143.0	1.53	-10.1	-0.09
Evangeliou et al. (2017)	ERA -Interim	82	0.30	319.7	3.65	110.2	0.63
	ERA - 5	82	0.07	254.4	3.46	33.6	0.24

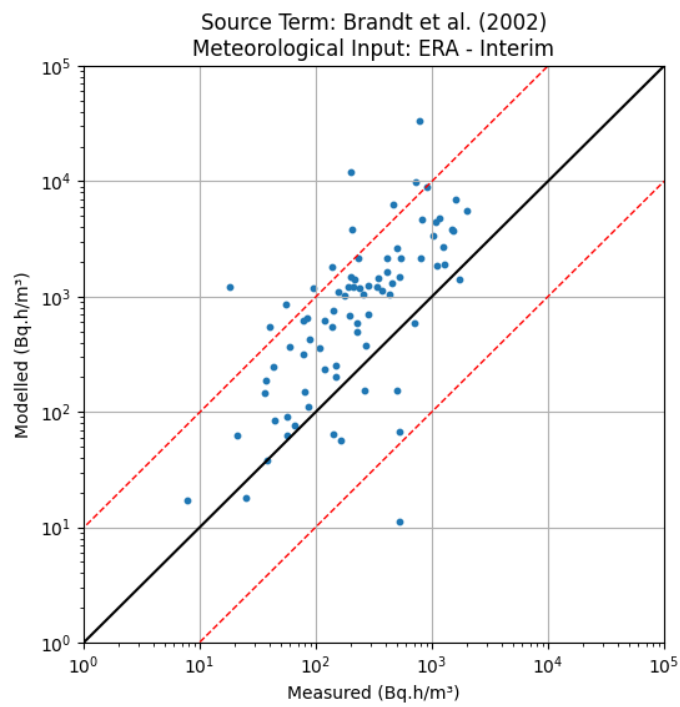
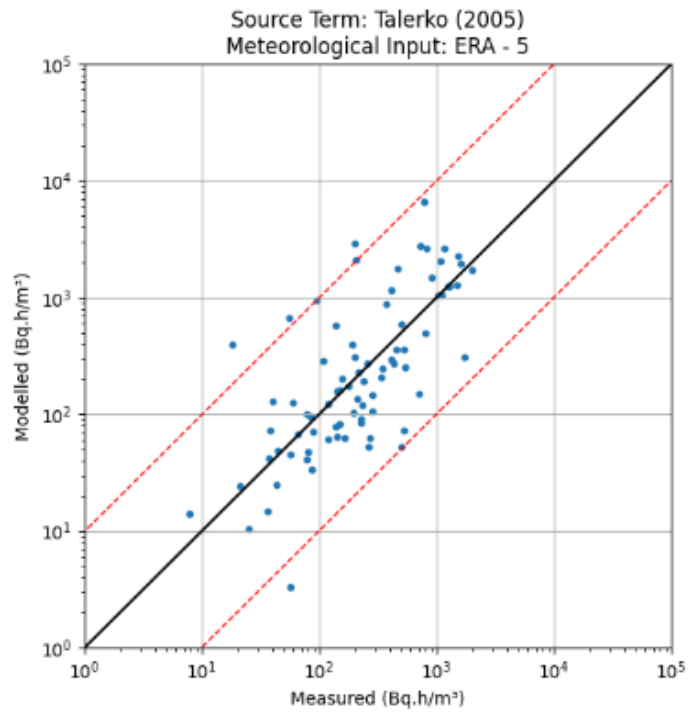


Figure 4.1 Simulations that gave the highest correlations (upper figure), and the lowest correlations (lower figure) for ¹³¹I with Evangeliou et al. (2016)

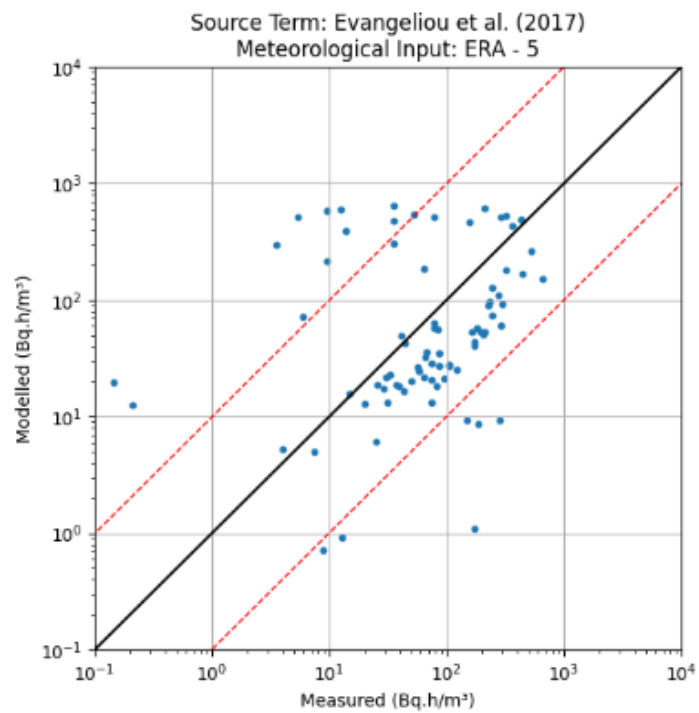
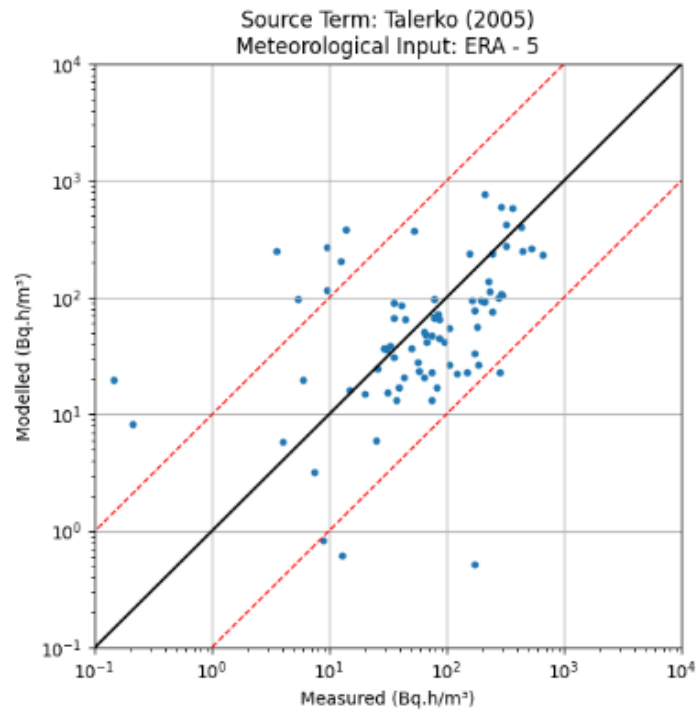


Figure 4.2 Simulations that had the highest (upper) and the lowest (lower) correlations for ^{137}Cs with Evangeliou et al. (2016). The upper figure also gives the simulation with minimum RMSE, NMSE, MB and FB

4.1.2 Total Deposition Comparisons

Relatively well correlations were calculated compared to Evangeliou et al. (2016) for ^{137}Cs deposition in all simulations. The highest correlations were found in simulations using Evangeliou et al. (2017) as the source term. Moreover, lower RMSE, NMSE, MB and FB were calculated for simulations using ERA-5. (Table 4.3). Correlations were calculated lower in simulations using ERA-Interim data as the meteorological input. The simulations with the lowest and highest correlations are visualized in Figure 4.3.

Table 4.3 Statistical comparison of simulations and Evangeliou et al. (2016) for surface depositions of ^{137}Cs in 11024 receptors

Source Term	Reanalysis Input	^{137}Cs					
		N	r	RMSE	NMSE	MB	FB
Brandt et al. (2002)	ERA -Interim	11024	0.32	254.6	44.69	-18.78	-0.48
	ERA - 5	11024	0.47	248.1	19.71	15.61	0.28
Talerko (2005a)	ERA -Interim	11024	0.31	257.7	59.38	-25.62	-0.72
	ERA - 5	11024	0.45	247.8	21.47	10.19	0.19
Evangeliou et al. (2017)	ERA -Interim	11024	0.49	252.3	73.37	-30.78	-0.93
	ERA - 5	11024	0.49	235.5	30.93	-11.75	-0.27

Evangeliou et al. (2016) report point measurements, and all comparisons were conducted with these point values. In addition, De Cort et al. (1998) also calculated ground-level depositions of ^{137}Cs for European countries. Thus, in addition to point-wise comparisons, country-wise comparisons based on country-averaged deposition values were also used to test the performance of the FLEXPART model. Country-based comparisons with De Cort et al. (1998) indicated good correlations for all simulations. Simulations using ERA-5 as meteorological inputs gave higher correlations with De Cort et al. (1998) than with ERA-Interim simulations. In simulations that used Brandt et al. (2002) and Evangeliou et al. (2017) as source terms and ERA-5 as meteorological input, the correlation was calculated to be 0.88. Simulations using Talerko (2005a) gave the lowest correlation (both of them are 0.82). Moreover, lower RMSE, NMSE, MB and FB were calculated for simulations using ERA-5 (Table 4.4). The simulations with the lowest and highest correlations are presented in Figure 4.4.

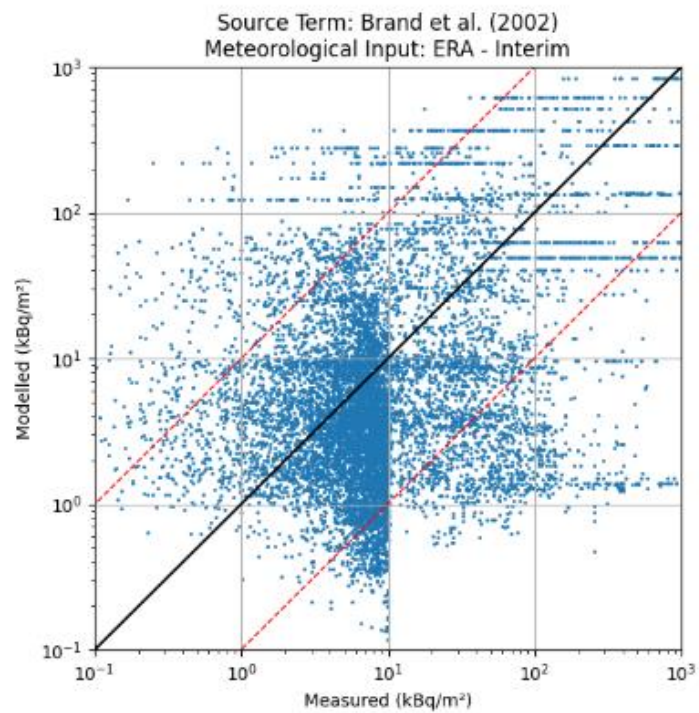
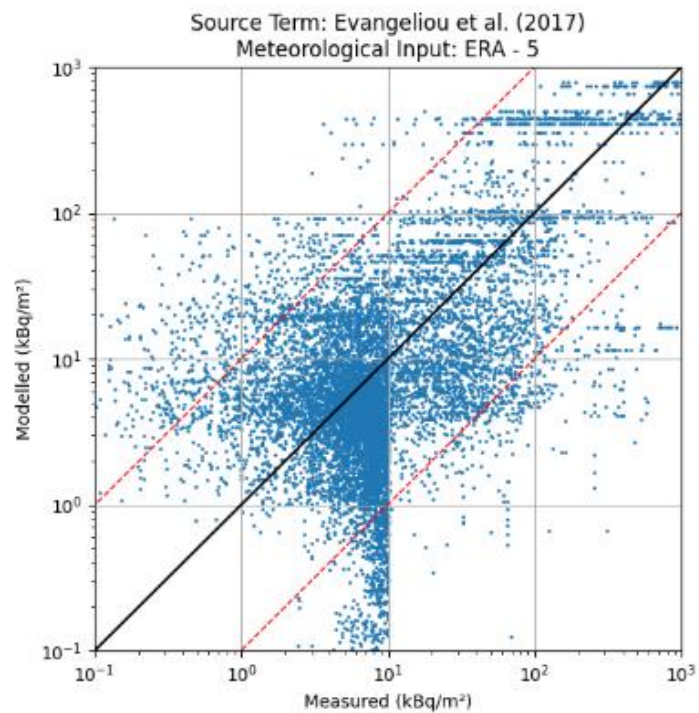


Figure 4.3 Simulations that gave the highest (upper figure) and the lowest (lower figure) correlations for ^{137}Cs depositions with Evangeliou et al. (2016) measurements in 11024 receptor point

Table 4.4 Statistical comparison of simulations and De Cort et al. (1998) for surface depositions of ^{137}Cs (average values of 31 countries)

Source Term	Reanalysis Input	^{137}Cs					
		N	r	RMSE	NMSE	MB	FB
Brandt et al. (2002)	ERA -Interim	31	0.84	3.7	8.35	-1.26	-0.89
	ERA - 5	31	0.88	3.0	4.10	-0.94	-0.60
Talerko (2005a)	ERA -Interim	31	0.82	3.8	10.30	-1.36	-0.99
	ERA - 5	31	0.82	3.2	4.90	-1.02	-0.67
Evangelidou et al. (2017)	ERA -Interim	31	0.83	3.4	6.68	-1.19	-0.82
	ERA - 5	31	0.88	2.9	3.59	-0.92	-0.58

Relatively lower correlations for ^{134}Cs depositions were calculated between the model results and Evangelidou et al. (2016). The highest correlations were detected in simulations using Evangelidou et al. (2017) as the source term. In addition, the correlation of the simulations using ERA-5 as meteorological input was higher. Performance parameters were calculated to be similar in all cases (Table 4.5). The simulations with the highest and lowest correlations are illustrated in Figure 4.5. All other comparison figures for each simulation are presented in Appendix 1.

Table 4.5 Statistical comparison of simulations and Evangelidou et al. (2016) for surface depositions of ^{134}Cs in 2716 receptor point

Source Term	Reanalysis Input	^{134}Cs					
		N	r	RMSE	NMSE	MB	FB
Brandt et al. (2002)	ERA -Interim	2716	0.11	30.8	34.50	-4.84	-0.84
	ERA - 5	2716	0.21	31.0	29.07	-4.16	-0.68
Talerko (2005a)	ERA -Interim	2716	0.14	30.5	35.75	-5.03	-0.88
	ERA - 5	2716	0.22	30.3	30.61	-4.54	-0.76
Evangelidou et al. (2017)	ERA -Interim	2716	0.21	30.3	21.31	-2.94	-0.44
	ERA - 5	2716	0.28	38.4	33.07	-2.77	-0.41

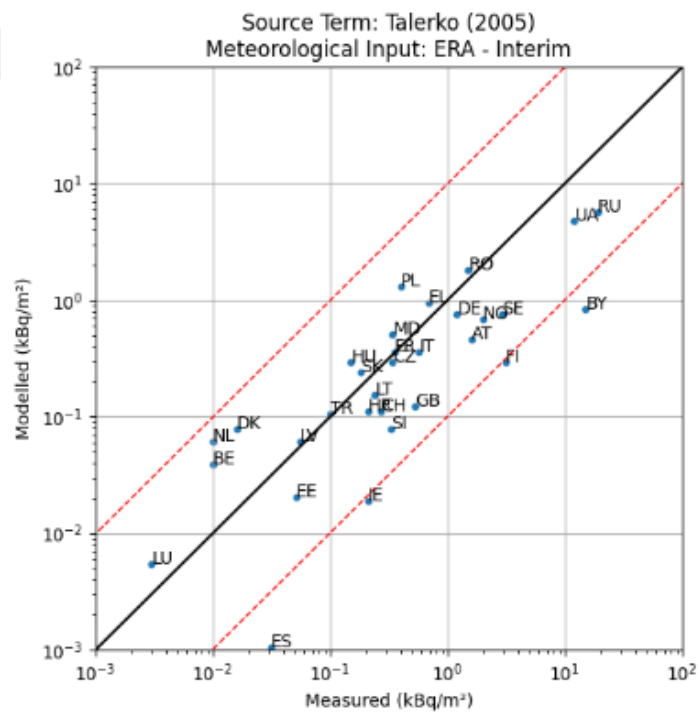
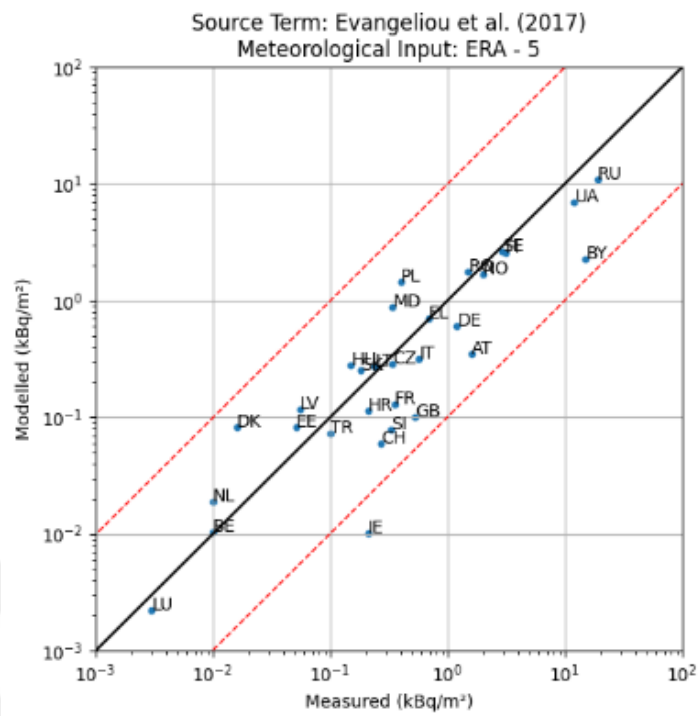


Figure 4.4 Simulations that gave the highest (upper figure) and the lowest (lower figure) correlations for ¹³⁷Cs depositions with De Cort et al. (1998) (average values of 31 countries)

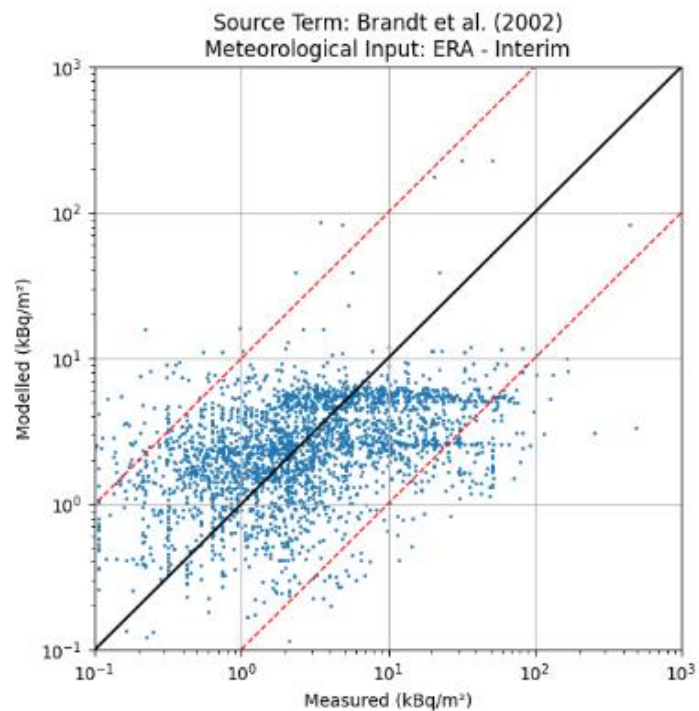
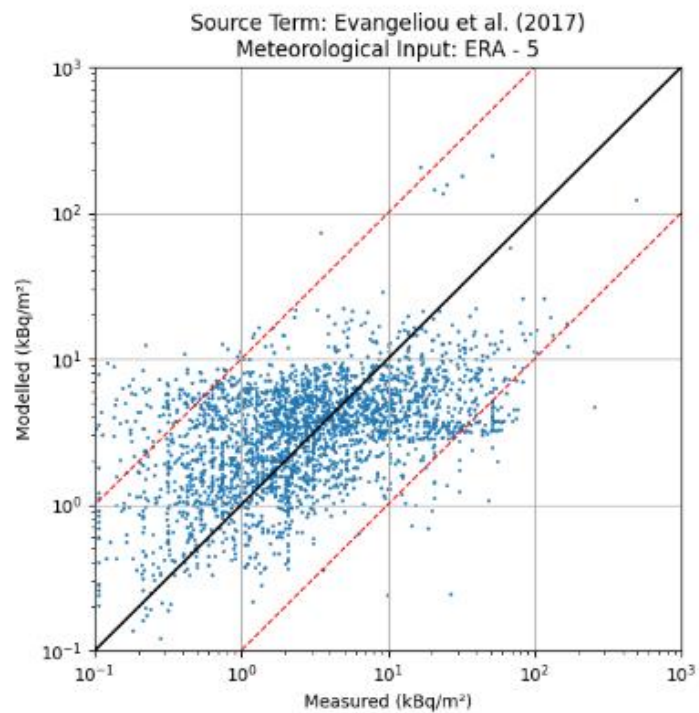


Figure 4.5 Simulations gave the highest (upper figure) and lowest (lower figure) correlations for ^{134}Cs with Evangeliou et al. (2016) in 2716 receptor points

Point-based comparisons are often problematic (Evangeliou et al., 2017). Therefore, relatively lower correlations were obtained. However, similar correlations

were calculated with other studies in the literature (Brandt et al., 2002; Evangeliou et al., 2017). Except for the high deposits in Belarus, comparisons with De Cort et al. (1998) calculations revealed good correlations. Correlations and performance indicators also varied according to the source term and meteorological parameters used. Source terms showed different performances in activity concentrations and deposition calculations. Moreover, the source term gave different performances according to the nuclide. However, in general, simulations using ERA-5 yielded better correlations and performance parameters.

Using the simulations performed in this section, the impact of the Chernobyl NPP accident on Turkey and Southwest Asia was calculated and published in a SCI indexed journal (Bilgiç & Gündüz, 2022).

4.2 Vertical Release Pattern Selection

In this thesis, the effect of the vertical profile of release was investigated. For this purpose, eight different vertical release patterns were determined that mimic Uniform, Dirac Delta, Exponential, LPT III, Gaussian, Triangular, LPT III (2) and CDF distributions. A total of 22 patterns were identified using eight functions for three z_{max} values (2000 m, 3000 m, 4000 m), with a layer thickness value of 100 m (Figure 4.6). Only Dirac Delta is independent of z_{max} as it represents the release from ground level. These functions are adapted to the Chernobyl NPP accident. Starting at 22:23 UTC on April 25, 1986, 86 PBq of ^{137}Cs release was defined for the Chernobyl NPP (Brandt et al., 2002; Evangeliou et al., 2017). The release was assumed to last for 10 days as in Chernobyl NPP accident (UNSCEAR, 2000). The temporal variation of this 10-day release was taken to be the same as Brandt et al. (2002). In all 22 simulations conducted, the vertical pattern remained constant throughout the 10-day release (Table 4.6). In these simulations, the total simulation duration was 20 days. ECMWF's ERA-40 reanalysis product was used as the meteorological input in all simulations.

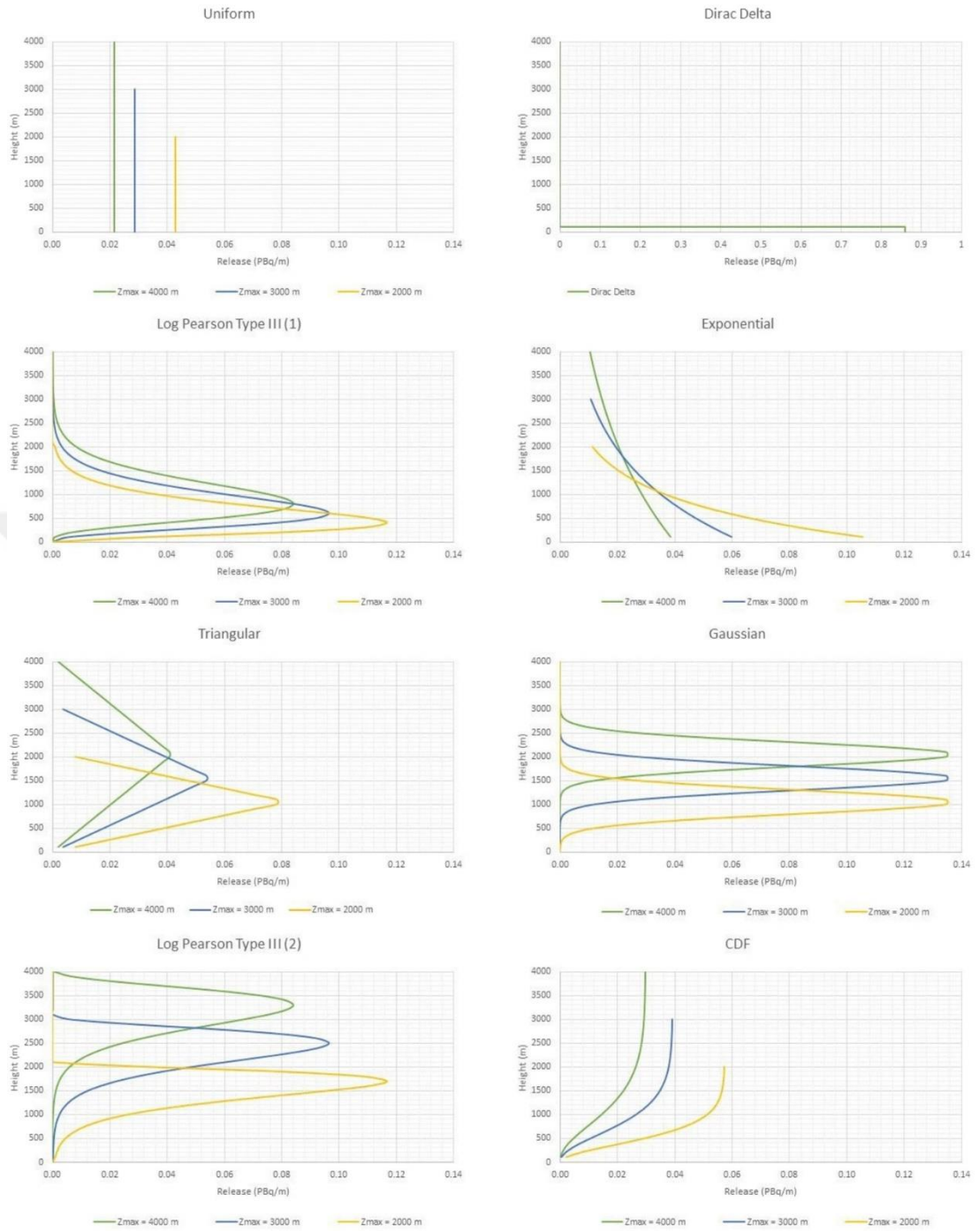


Figure 4.6 Vertical release patterns used in this study

Table 4.6 Release information used in the application

Release Functions	z_{max} (m)	Total Release	Release Duration	Temporal Variation	Meteorological Input	Simulation Duration
Uniform	2000	86 PBq of ^{137}Cs	10 days	Same with Brandt et al. (2002)	ERA-40	20 days
	3000					
	4000					
Dirac delta	100					
Exponential	2000					
	3000					
	4000					
Gaussian	2000					
	3000					
	4000					
Triangular	2000					
	3000					
	4000					
LPT III (1)	2000					
	3000					
	4000					
LPT III (2)	2000					
	3000					
	4000					
CDF	2000					
	3000					
	4000					

Results were compared based on the depositions of ^{137}Cs . Uniform release with 4000 m of z_{max} was assumed as the reference case. The base scenario is illustrated in Figure 4.7. Similar spots occurred for high depositions in all simulations. The highest deposition was detected around the Chernobyl NPP plant at the borders of Ukraine, Belarus and Russia. In addition, higher depositions were also calculated in the Scandinavian countries, around the Alps, the Balkans, and the Eastern Black Sea. Moreover, severe contamination was also observed over central Russia (upper right of the map, about 40° East, 60° North).

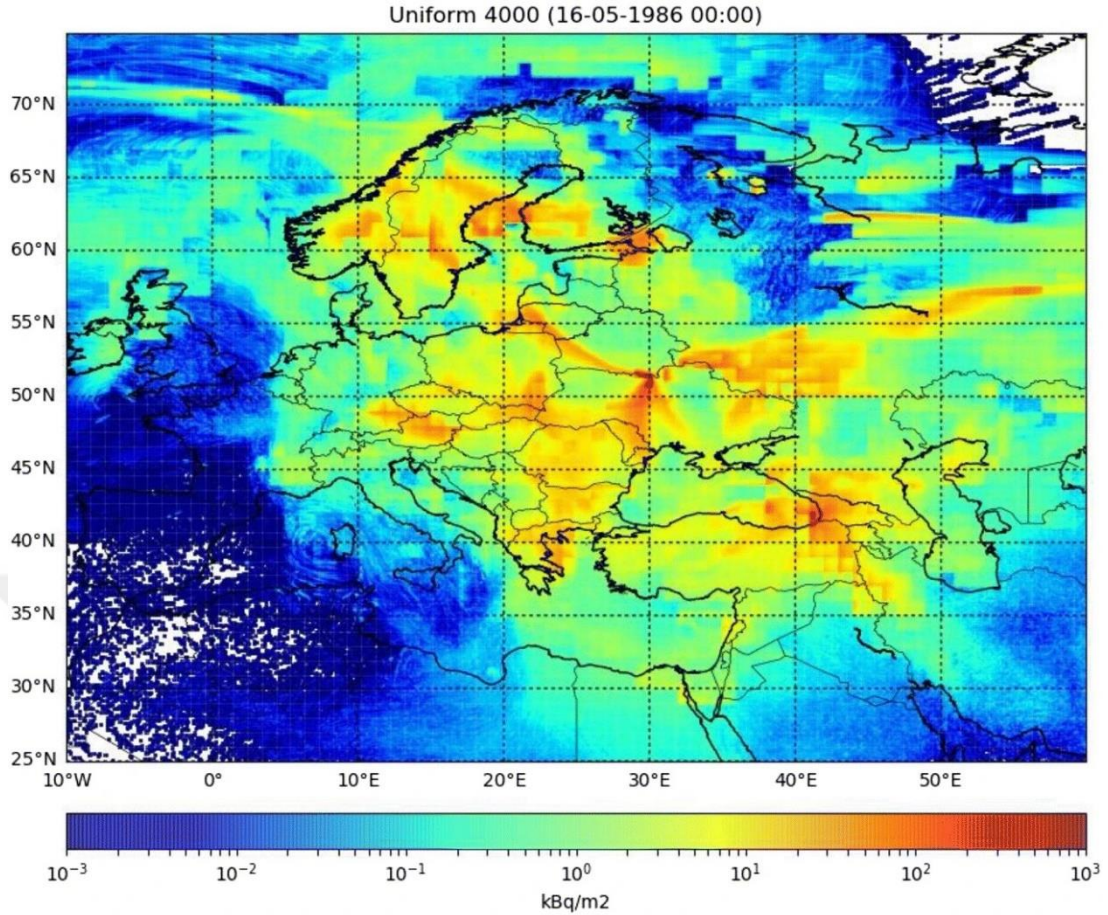


Figure 4.7 Total deposition of ^{137}Cs released in the based scenario, uniform release with 4000 m of z_{max}

Difference maps were plotted considering the base scenario. A comparison of Uniform release with 2000 m and 3000 m of z_{max} scenarios to the baseline scenario is illustrated in Figure 4.8. The difference maps revealed the increase of the deposition as z_{max} closes the ground level around the Chernobyl NPP. The exact relationship cannot be specified directly for spots far from the Chernobyl NPP. For example, lower depositions were detected for lower z_{max} in an area in the Balkan region. On the other hand, higher values were observed around the Eastern Black Sea and Alpine Mountains. However, these high and low values are not as stunning as around the Chernobyl NPP. These conditions are related to the complexity of meteorological conditions as they move away from the power plant.

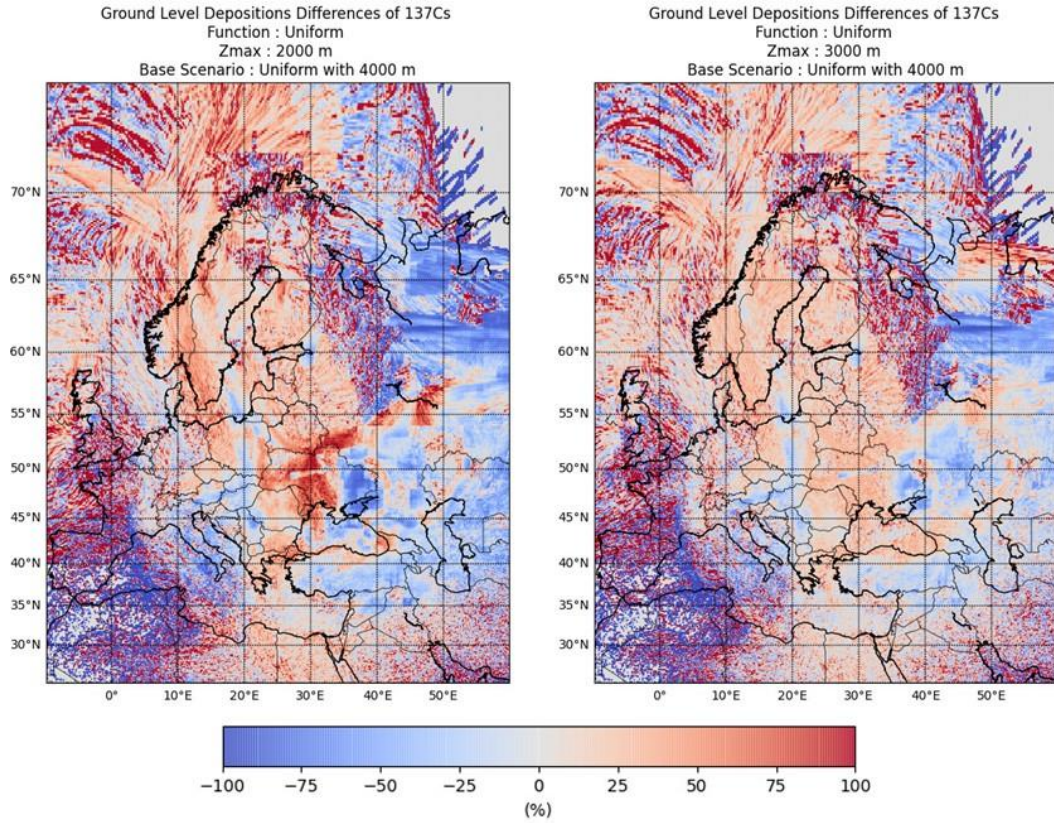


Figure 4.8 Differences map Uniform release with 2000 m and 3000 m of z_{max} compare to based scenario

The altitude impacts on ground-level depositions were also observed in function-based comparisons. Extreme values were estimated near the Chernobyl NPP in the scenarios where the release was close to the ground level. In the scenarios released from higher levels, extreme values were not found considerably. In the Dirac Delta scenario, much higher values were detected around the Chernobyl NPP and Scandinavian countries, which are released directly from the ground level. In the LPT III (2), with 4000 m of z_{max} scenario where radionuclides released from the highest level, much lower depositions were calculated in the same regions compared to the base scenario. In this scenario, higher values were detected in the Eastern regions (Figure 4.9). Other plots are presented in Appendix 2 (Figure A2.1, A2.2, A2.3, A2.4, A2.5 and A2.6).

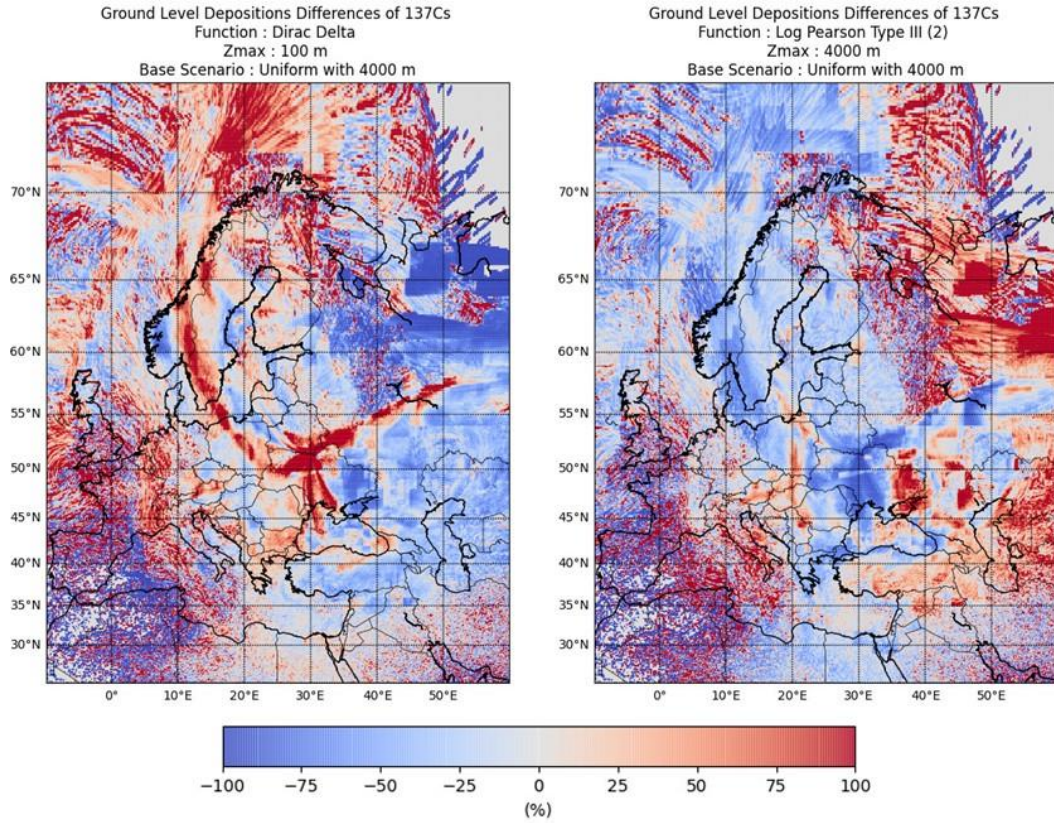


Figure 4.9 The scenarios use vertical profiles Dirac Delta (left) and LPT III (2) with 4000 m of z_{max} release

The results were also analyzed statistically. The most extreme values were detected in scenarios where releases were close to ground level. The highest maximum, average and standard deviation values were found in Dirac Delta and Exponential scenarios. The lowest maximum, mean and standard deviation values were obtained in LTP III (2) and CDF scenarios. In release scenarios from higher altitudes, ^{137}Cs deposition means in the domain are found lower. These lower deposition means are associated with radionuclides travelling long distances and moving out of the domain. A low standard deviation indicates a relatively homogeneous spatial distribution. High maximum and standard deviation values indicate extreme values (Table 4.7). Moreover, the highest percentages were found in releases close to the ground level at high deposition intervals ($>100 \text{ kBq/m}^2$ and $1-10 \text{ kBq/m}^2$). This is another proof that extreme values are more influential at altitudes close to ground level. On the other hand, percentages in extreme value ranges gave the lowest values in releases near ground level (Table 4.8).

Table 4.7 Statistical results of each scenario

	Uniform			Dirac delta			LPT III (1)			Exponential		
	2000	3000	4000	100			2000	3000	4000	2000	3000	4000
Maximum	3836	2567	1936	13663			5084	4937	4581	9495	9523	9518
Average	2.52	2.46	2.24	2.57			2.54	2.53	2.52	2.56	2.56	2.56
Median	0.25	0.27	0.26	0.22			0.25	0.25	0.25	0.23	0.23	0.23
Standard Deviation	13.3	10.0	8.04	37.4			16.2	14.6	13.5	27.8	27.9	27.9
	Triangular			Gaussian			LPT III (2)			CDF		
	2000	3000	4000	2000	3000	4000	2000	3000	4000	2000	3000	4000
Maximum	4342	2391	1371	5080	2166	573	2100	321	115	3307	1703	966
Average	2.52	2.49	2.35	2.52	2.49	2.48	2.49	2.42	1.92	2.51	2.43	2.17
Median	0.25	0.26	0.27	0.24	0.25	0.28	0.25	0.27	0.23	0.25	0.27	0.26
Standard Deviation	13.3	9.8	7.5	14.2	10.3	7.9	10.2	7.2	5.2	11.6	8.3	6.2

Table 4.8 Percentage distribution of each scenario in related deposition intervals

Intervals kBq/m ²	Percentage of the interval in a related scenario											
	Uniform			Dirac delta			LPT III (1)			Exponential		
	2000	3000	4000	100			2000	3000	4000	2000	3000	4000
> 100	0.10	0.06	0.04	0.14			0.13	0.12	0.11	0.14	0.14	0.14
10–100	6.22	6.33	5.98	5.50			6.14	6.20	6.28	5.77	5.80	5.81
1–10	23.2	23.9	24.5	22.50			23.2	23.2	23.2	22.7	22.8	22.8
0.1–1	30.7	30.6	30.2	30.70			30.6	30.6	30.5	30.7	30.6	30.6
< 0.1	39.8	39.0	39.3	41.16			39.9	39.9	39.9	40.6	40.6	40.7
Intervals kBq/m ²	Percentage of the interval in a related scenario											
	Triangular			Gaussian			LPT III (2)			CDF		
	2000	3000	4000	2000	3000	4000	2000	3000	4000	2000	3000	4000
> 100	0.11	0.08	0.04	0.11	0.09	0.07	0.09	0.06	0.00	0.09	0.06	0.02
10–100	6.23	6.34	6.25	6.24	6.27	6.35	6.28	6.23	4.74	6.29	6.35	5.81
1–10	23.2	23.7	24.4	23.0	23.3	24.0	23.3	24.2	23.8	23.2	24.1	24.5
0.1–1	30.5	30.7	30.3	30.5	30.6	30.5	30.6	30.7	31.5	30.6	30.5	30.5
> 0.1	39.9	39.2	39.0	40.1	39.8	39.0	39.7	38.8	39.9	39.8	38.9	39.2

4.3 Pre-processes of Simulations

Turkey's first nuclear power plant, Akkuyu NPP, is being built in Mersin on the Mediterranean coast. Akkuyu NPP will consist of four VVER 1200 model PWR type reactors, and the first unit will start to generate electricity in 2023. It is planned to produce 30 billion kWh of electricity annually. After all its units are commissioned, it will be the most potent power generation facility in Turkey, costing approximately 20 billion US dollars. Akkuyu NPP is the first nuclear power plant established with the BOO model (Build - Own - Operate). Russian Rosatom company will operate the NPP for 60 years (Dokay, 2014).

In this study, two nuclear risk studies are conducted for Akkuyu NPP: 1) a series of simulations for the entire meteorological conditions and 2) numerous simulations under selected extreme meteorological conditions. For this purpose, in the first step, the source term of Akkuyu NPP was analyzed, and domains and receptors were determined. Three domains (i.e., calculation domain, mother domain and nested domain) were defined with different spatial extents. Domain boundaries are illustrated in Figure 4.10. In the model, dispersion and deposition estimations were conducted in the calculation domain, which is limited by meteorological input. Although the simulations were performed in the calculation domain, model outputs were only produced for the mother domain. In addition, an additional subdomain named “nested” was defined to obtain higher resolution outputs for some particular purpose. In addition, some receptors were determined 2500 km around Akkuyu NPP to evaluate the results. Receptors were determined considering the climate types and populations (Figure 4.11). Receptors are listed in Table 4.9.

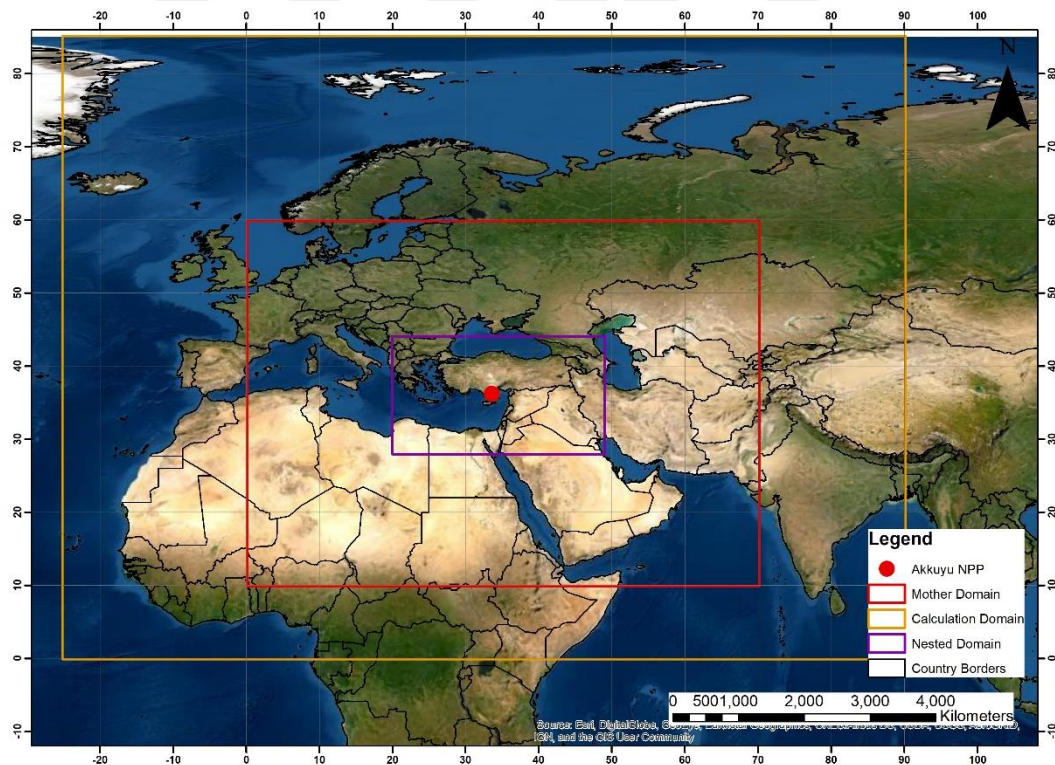


Figure 4.10 Domains defined for the simulations

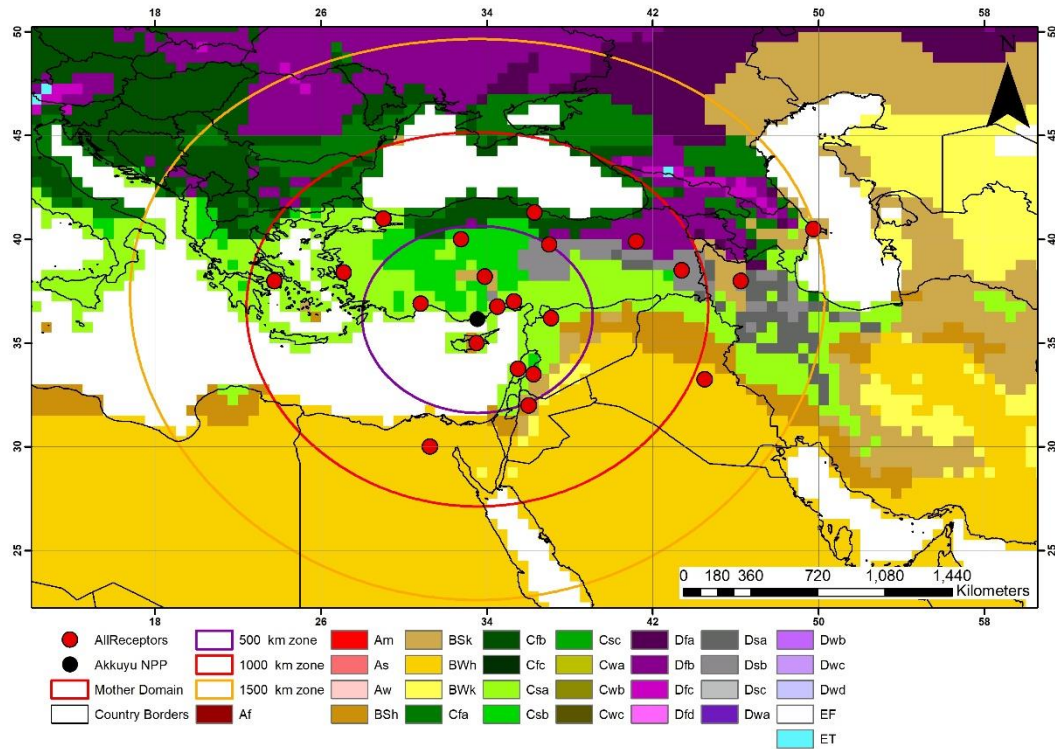


Figure 4.11 Locations of determined receptors for analysis

Table 4.9 List of receptors and the total population in the grid (0.25° x 0.25°) that each receptor is in

#	Name	Country	Population	Class
1	Akkuyu	TURKEY		Csa
2	Nicosia	CYPRUS	143,426	Bsh
3	Mersin	TURKEY	401,071	Csa
4	Adana	TURKEY	832,444	Csa
5	Armutlu/Aksaray	TURKEY	154,215	Bsk
6	Aleppo	SYRIA	1,154,023	Csa
7	Antalya	TURKEY	907,534	Csa
8	Beirut	LEBANON	3,035,460	Csa
9	Damascus	SYRIA	3,861,550	Bsk
10	Ankara	TURKEY	2,177,930	Csb
11	Sivas	TURKEY	375,007	Dsb
12	Amman	JORDAN	2,764,850	BSh
13	Izmir	TURKEY	747,520	Csa
14	Istanbul	TURKEY	5,839,010	Csa
15	Samsun	TURKEY	577,771	Cfb
16	Van	TURKEY	295,921	Dsb
17	Erzurum	TURKEY	153,596	Dfb
18	Athens	GREECE	3,130,120	Csa
19	Baku	AZERBAIJAN	1,390,490	Bsk
20	Baghdad	IRAQ	2,286,270	BWh
21	Tabriz	IRAN	1,054,910	Dsb
22	Cairo	EGYPT	12,634,800	BWh

Then, a source term is defined for Akkuyu NPP with the RARE tool using inputs given in Table 3.4. Three radionuclides (^{131}I , ^{134}Cs and ^{137}Cs) were considered in all simulations. In the last step, however, twenty radionuclides were applied in the worst-case conditions for a more comprehensive dose calculation. These twenty radionuclides were divided into two groups as noble gases and aerosols. Noble gases were considered to have no deposition. The estimated release and their properties are presented in Table 4.10. Analysis conducted for vertical patterns demonstrated that Dirac delta releases gave extreme depositions. Thus, Dirac delta patterns were defined for vertical distribution with 150 meters of vertical height. All the radionuclides are assumed to be released instantaneously.

Table 4.10 The RARE tool estimations and source terms used in the model

Release of radionuclides	1189 PBq of ^{131}I 80 PBq of ^{134}Cs 49 PBq of ^{137}Cs
Vertical Pattern	Dirac Delta with 150 m of z_{max}
Temporal Variation	Pulse release
Aerosol properties	Particle Density: 1880 kg/m ³ , Mean Particulate Diameter: 1×10^{-6} m Variance of Particulate Diameter: 2

After the source term was defined, a meteorological analysis was performed. Akkuyu NPP is located on the Mediterranean coast of Turkey, South of the Taurus Mountains. Mediterranean climate (Csa and Csb) is dominant in the study area along the Mediterranean and Aegean Sea coasts (Lebanon, Syria, Turkey and Greece), with mild and rainy winters and hot and dry summers. There are drier continental climate types East of the Mediterranean and North of the Taurus Mountains. In the North, on the shores of the Black Sea, the oceanic climate (also called the Black Sea climate) is dominant, with four seasons of rain. Arid climates prevail in the South (Egypt, Jordan) and East (inner Syria, Iraq) of the Mediterranean.

The meteorological features of the study area are shaped seasonally by different air currents. In the winter season, polar weather conditions generally come from the North. Cold and continental masses travel from the Siberian high pressure over Russia and the Icelandic low pressure over Scandinavia. On the other hand, hot air masses generally occur from South to North in summer. Hot air masses come from the

Southeast with the effect of the Basra low pressure and from the Southwest with the effect of the Azores' high pressure from the Sahara.

In this study, the year 1986, when the Chernobyl NPP accident occurred, was accepted as a reference, and 72 simulations were carried out to represent all meteorological conditions of this year. The precipitation data of 1986 were analyzed seasonally. It was observed that there was precipitation in the Eastern Black Sea region for four seasons, while the summer season was dry in other regions. In addition, low precipitation amounts were detected in all seasons in the semi-arid regions in Central Anatolia and the South and East of the Mediterranean. In regions where the Mediterranean climate is dominant, it was observed that Winter, Spring and Autumn months were rainy. In terms of precipitation, it was observed that 1986 represented the general meteorological conditions of all seasons. Further, Dokay (2014) showed that in the Akkuyu NPP region, winds generally blow from south and west directions for long periods. The wind roses plotted for the 1986 were also compatible with Dokay (2014) (Figure 4.12).

In this thesis, a series of simulations for entire meteorological conditions in 1986 was conducted. Each simulation was launched every 5 days from January 1, 1986, and 72 identical simulations were carried out in total in 1 year. All simulations were run for 8 days. Since ERA-5 data needs a lot of disk space, ERA-Interim data, which takes up less space, is used as the meteorological input. The simulations were named according to the month in which they were performed. For example, the simulation between January 1-8, 1986, was named Jan01, and the simulation between January 6-13, 1986, was named Jan02. Six simulations were carried out for each month. In the naming of the simulations, which started in the previous month and ended in the following month, the month in which the majority occurred was considered. For example, the simulation from January 26 to February 2, 1986, was named Jan06, and the simulation from January 31 to February 7, 1986, was called Feb01. All simulation names and start and end dates are presented in Table A3-1 in Appendix-3.

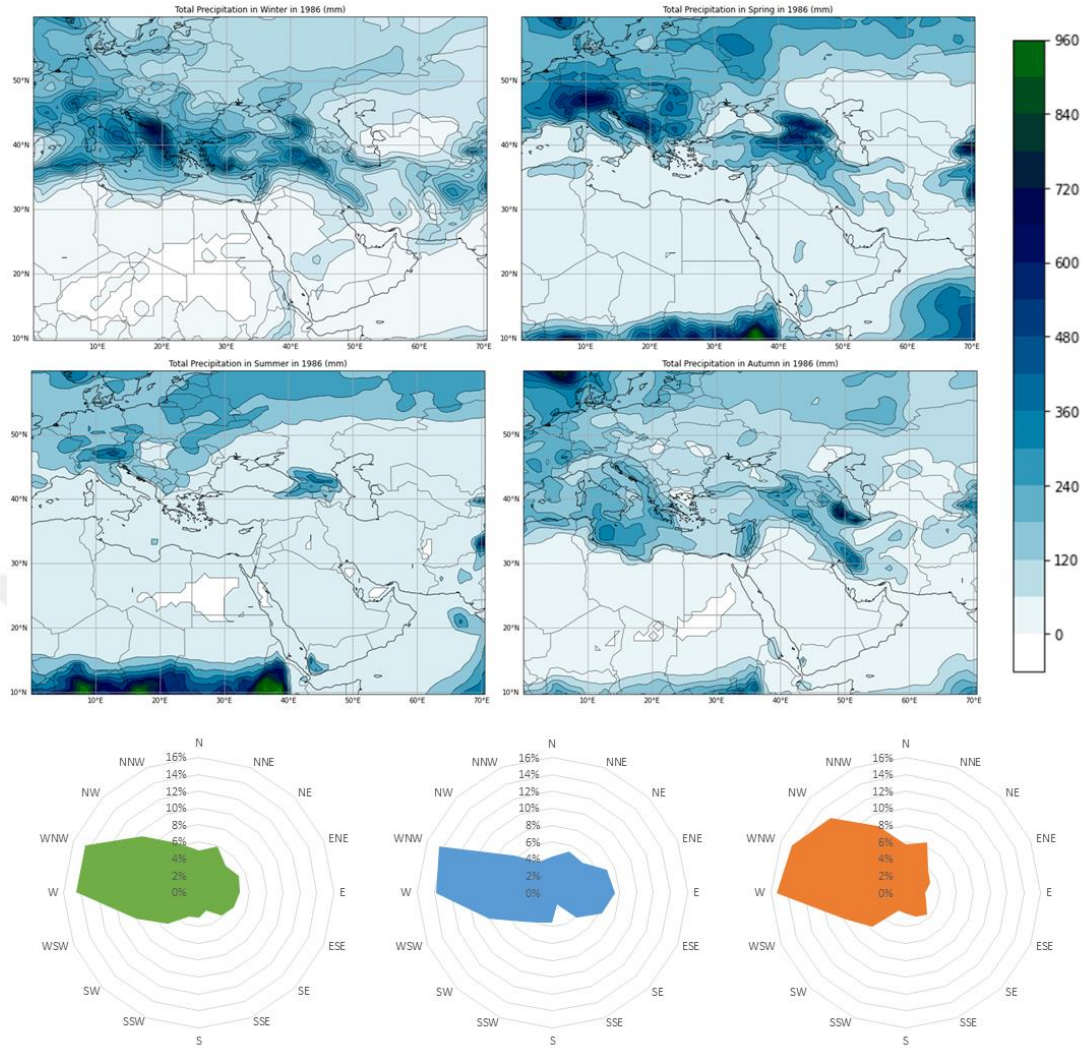


Figure 4.12 Total precipitation map for winter (upper left), spring (upper right), summer (middle left) and autumn (middle right) and wind roses for whole year in 1986 (lower left), autumn and winter seasons in 1986 (lower center) and spring and summer seasons in 1986 (lower right)

This thesis also investigated the impact of extreme meteorological conditions on the atmospheric transport of radionuclides released after nuclear accidents. The WTEM tool was used in the analysis of extreme conditions. With MSLP, synoptic scale circulation types were determined, and the extreme temperature, precipitation and wind velocity periods in the study region were calculated. ERA-5 data for the period 1979-2021 were used in the analyses.

Daily weather types between 1979-2021 were determined using the LWT method. We found that 46.1% of all days (43 years) are U (Unclassified), and about 21.50%

are directional types. 11.5% of A, 4.4% of HYA type were found, while 9.5% of C and 11.5% of HYC were detected. C-type weather was observed mainly in winters; HYC was more observed than C in summers. In addition, cyclones were more common in autumn than in spring. LWT analysis indicated that type A weather was rarely seen in summer. Although there were close distributions in the other 3 seasons, A was most frequently observed in the spring (Figure 4.13).

Table 4.11 Total precipitation, 2-meter temperature, 10-meter wind speed and PBLH of each WT

	D	A	HYA	C	HYC	U	All
tp_{max} (mm)	26.30	7.60	12.63	31.29	22.77	19.11	31.29
tp_{average} (mm)	1.23	0.44	1.50	4.69	1.78	0.91	1.41
t2m_{max} (°C)	30.6	28.5	28.1	30.4	31.6	31.3	31.6
t2m_{average} (°C)	16.3	13.1	11.4	11.9	18.2	18.0	16.2
t2m_{min} (°C)	-3.2	-1.2	-3.0	-0.4	-1.5	-2.0	-3.2
uv10m_{max} (m/s)	5.6	3.7	4.2	6.0	5.8	4.7	6.0
uv10m_{average} (m/s)	2.5	2.0	2.4	2.9	2.7	2.2	2.4
uv10m_{min} (m/s)	1.2	1.1	1.3	1.4	1.3	1.1	0.2
PBLH_{max} (m)	1423	1139	1213	1372	1545	1399	1545
PBLH_{average} (m)	570	445	388	669	650	617	586
PBLH_{min} (m)	52	64	73	116	94	70	52

Forty-three years of data showed that precipitation is dominant in type C and less in type A. Seasonal results revealed low precipitation in summer and the highest average precipitation in winter. Although the autumn and spring precipitation averages were close to each other, the average precipitation in autumn was slightly higher. In addition, the lowest ground level temperature averages were observed in A, HYA and C types. The fact that the average temperature was low in A and HYA types can be associated with the fact that this weather was rarely observed in summer. Type C was seen most frequently in winter (45%) and least in summer (13%). The highest temperature averages were observed in HYC, directional and undefined. This situation can also be associated with the season. While HYC and D were most common in summer, U was most frequently observed in spring and summer. The maximum wind velocity was estimated as 6.0 m/s, and higher values were observed in the winter. The highest wind velocities were estimated in directional, hybrid and cyclonic types. As expected, the lowest value was estimated in U, with A. The vertical profile data in the Akkuyu region demonstrated that the highest PBLH was found in C and HYC types and the lowest PBLH in HYA and A types. Seasonal averages revealed lower PBLH

in winter and autumn and higher PBLH in summer and spring (Table 4.12, Figure 4.13).

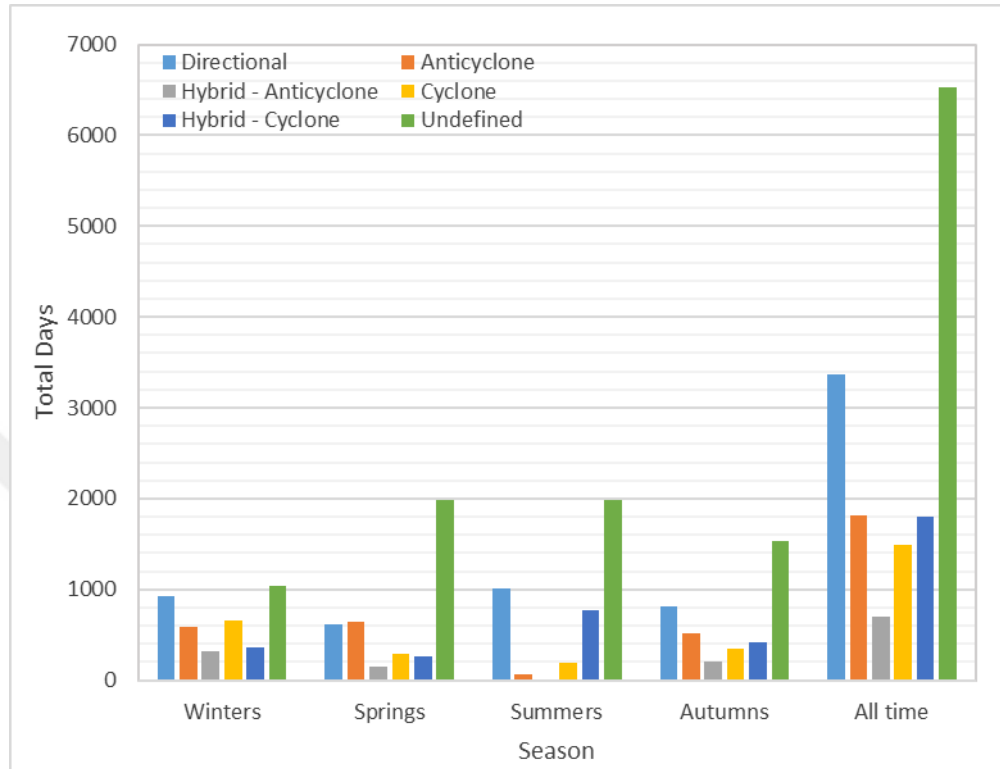


Figure 4.13 Seasonal and annual distribution of weather types

Table 4.12 Total precipitation, 2-meter temperature, 10-meter wind speed and PBLH of each season

	WINTER	SPRING	SUMMER	AUTUMN
tp_{max} (mm)	31.29	28.60	7.06	23.26
tp_{average} (mm)	2.54	1.20	0.21	1.75
t2m_{max} (°C)	19.1	28.7	31.6	26.5
t2m_{average} (°C)	7.3	17.5	25.4	14.3
t2m_{min} (°C)	-3.2	2.9	18.2	-0.1
uv10m_{max} (m/s)	6.0	5.4	4.4	5.8
uv10m_{average} (m/s)	2.5	2.4	2.5	2.2
uv10m_{min} (m/s)	1.1	1.4	1.5	1.1
PBLH_{max} (m)	1399.4	1423.2	1545.0	1447.7
PBLH_{average} (m)	413.8	718.8	753.1	446.4
PBLH_{min} (m)	51.7	139.9	426.6	70.0

Some threshold values were estimated to define the extreme values of each meteorological parameter using a statistical percentile analysis. Ninety-nine percentile of data was assumed as the threshold value. Upper and lower daily means than the threshold were assumed extreme days for the related meteorological parameter. Because leaving the radionuclides released from the accident region take a few days,

daily means may not be enough to evaluate the worst cases. Thus, for each meteorological parameter, further analyses were conducted for a moving average of 3 days. Both upper than daily and 3-day threshold values were assumed as extreme meteorological periods.

The upper threshold for daily mean cumulative precipitation was calculated as 12.79 mm, and the lower threshold was not estimated because the number of no-precipitation days was high. Further, 9.47 mm of precipitation was estimated for the three-day mean cumulative precipitation's upper threshold. Total precipitation higher than the upper threshold was assumed to be a Wet day, and no-precipitation days were assumed to be dry (Figure 4.14). After the percentile analysis, a total of 55 extreme Wet day situations were found. Most of these extreme situations were observed under cyclonic conditions (28 of C, 13 of HYC). Also, 13 directional types and 1 undefined type were found. Because of the seasonal conditions, temperatures were usually lower in this period. These 55 extreme Wet episodes also included some windy days. In light of all this information, simulations were conducted for 55 extremely Wet days presented in Table A3.2 in Appendix 3.

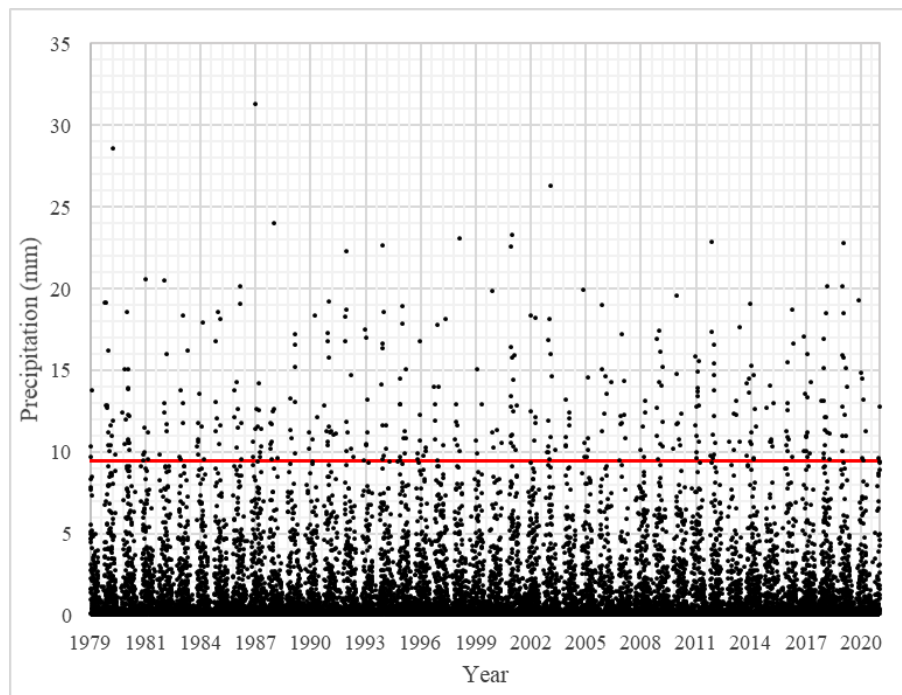


Figure 4.14 Long-term daily total precipitation (Red line represents upper threshold)

The upper and lower threshold for daily mean wind speed was calculated as 4.32 m/s and 1.32 m/s, respectively. Further, the three-day mean wind speeds' upper and lower thresholds are found to be 3.80 m/s and 1.46 m/s, respectively. Wind speeds higher than the upper threshold were assumed to be windy days, and less than the lower threshold were considered as Stagnant days (Figure 4.15). After statistical analysis, 61 Stagnant situations were found. All Stagnant days were observed as either Anticyclonic (30 situations for A-type) or Undefined (30 situations). Also, 1 situation was found as a directional type. 2-meter temperatures were lower on Stagnant days because neither was found in Summer. No precipitation was observed in almost all of these 61 situations, and pertinent information about these simulations is listed in Appendix 3 (Table A3.3).

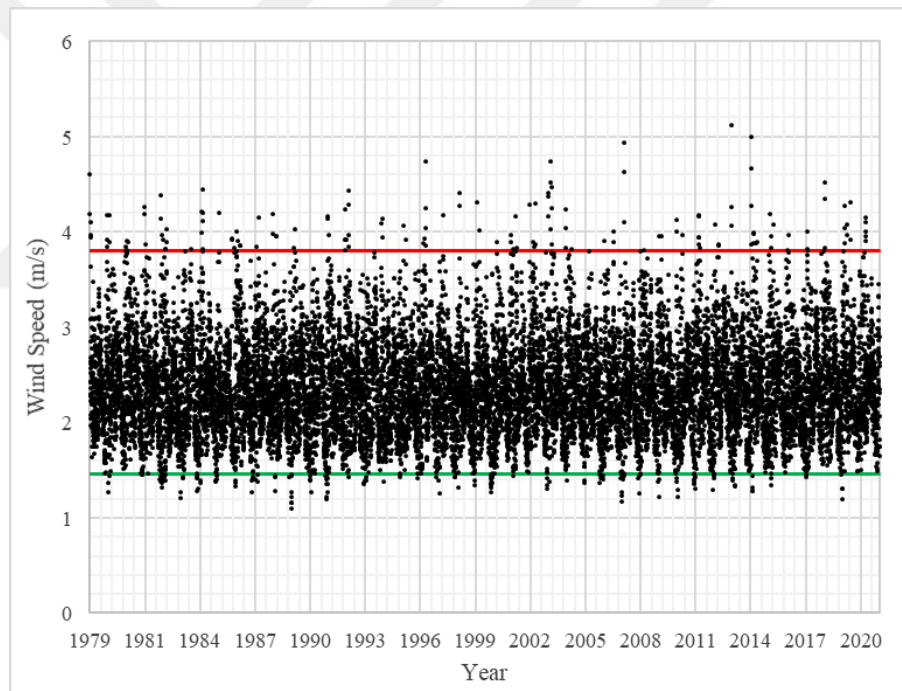


Figure 4.15 Long-term daily 10-meter wind speeds (Green) and red lines represent the lower and upper thresholds, respectively)

The upper and lower thresholds for a daily average temperature were calculated as 28.6°C and 1.17 °C, respectively. Similarly, upper and lower thresholds for three-day averages were found to be 28.5°C and 1.56 °C, respectively. Temperatures higher than the upper threshold were assumed to be Heatwaves, and those less than the lower threshold were assumed as Coldwave (Figure 4.16). The analysis gave 113 Heatwave

periods. Because the sum of Wet and Stagnant periods (total 116) mentioned above does not include warm days, these 113 periods were also simulated. Simulations are listed in Table A3.4 in Appendix 3.

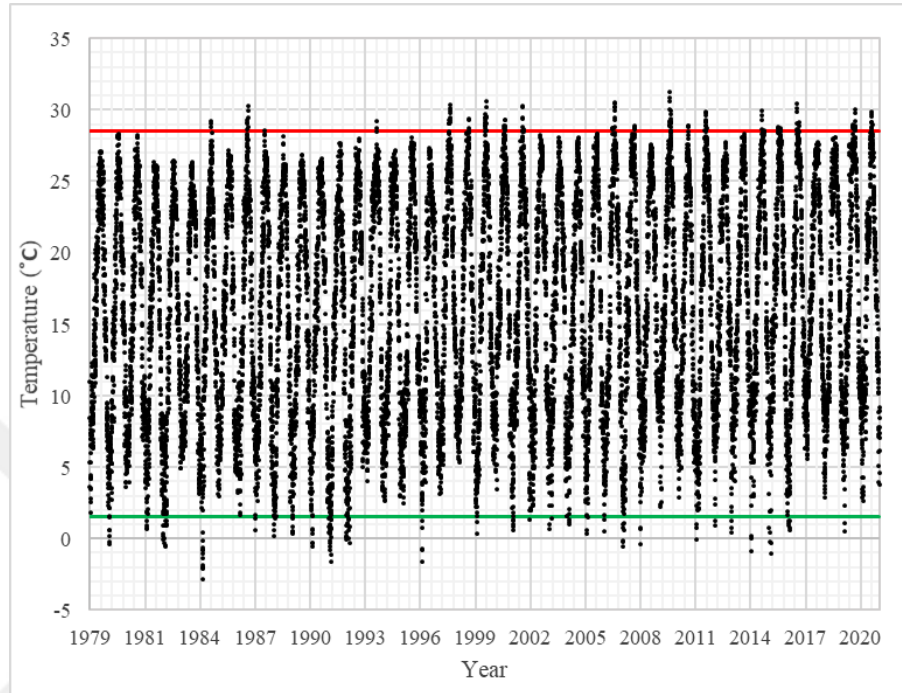


Figure 4.16 Long-term daily 2 meter temperature values (Green) line represents lower threshold, red line represents upper threshold)

After the meteorological analysis was completed, all simulations in 1986 and extreme periods were conducted using FLEXPART. Atmospheric dispersion and surface deposition results are presented in section 4.4. Then, TEDE values were calculated for all conditions and results and evaluations are presented in section 4.5. Furthermore, five worst-case simulations also were carried out additionally for simulating selected cases from extreme conditions. In these five cases, the accident was assumed to occur simultaneously in all four reactors. In addition, 20 radionuclides given in Table A4.1 were considered to be released for these five simulations. TEDE doses were also calculated for these five worst cases by including the ingestion pathway.

4.4 Atmospheric Dispersion and Surface Deposition Results of Simulations

4.4.1 Simulation Results under Entire Meteorological Conditions in 1986

Within the scope of this thesis, 72 simulations were conducted in the Akkuyu NPP site considering the conditions of the year 1986. Atmospheric transport and total ground-level deposition of radionuclides from possible accidents were calculated (Figure 4.17). Time-integrated (cumulative) air activity concentration of ^{131}I results demonstrated that the highest values are observed around Akkuyu NPP. Furthermore, it is revealed that concentrations in Southern regions are higher than in Northern regions. The fact that the concentrations are higher in the regions with less precipitation indicates the scavenging effect of precipitation. Total ground level deposition of ^{137}Cs demonstrated that the Mediterranean coasts and Eastern parts of Turkey are more contaminated than the Western parts. After a nuclear release, regions with high precipitation become more contaminated than areas with lower precipitation. For this reason, the opposite of the activity concentration results occurred. Higher ^{137}Cs depositions are detected in Northern regions where precipitation is higher. On the other hand, the Southern regions with less precipitation are simulated to be less contaminated (Figure 4.17).

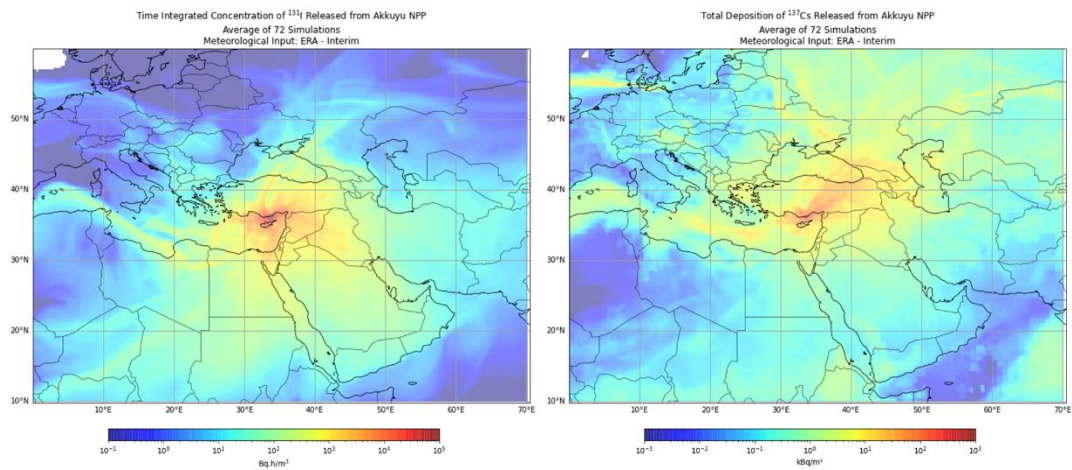


Figure 4.17 Average of 72 simulations for time-integrated concentration of ^{131}I (left) and total deposition of ^{137}Cs (right)

The receptor results showed extreme values around Akkuyu NPP in all simulations. All ^{137}Cs depositions were above 185 kBq/m^2 at the Akkuyu receptor. Eight scenarios in Adana and Mersin, the largest settlements closest to the power plant, presented extreme values. In addition, two scenarios in relatively close locations, Nicosia and one in Antalya, Aleppo, and Damascus offered values over 185 kBq/m^2 . In Ankara and Aksaray, which are close receptors located North of the power plant, ^{137}Cs deposition was below 185 kBq/m^2 in all scenarios. In Sivas, located to the Northeast, ^{137}Cs deposition was in the range of $40\text{-}185 \text{ kBq/m}^2$ in six simulations and was over 185 kBq/m^2 in five scenarios. On the other hand, no excessive depositions were detected in Amman, located in the Southeast at a similar distance to Sivas. In only one scenario, ^{137}Cs deposition was in the range of $10\text{-}40 \text{ kBq/m}^2$. The average of these 12 receptors revealed over 185 kBq/m^2 deposition of ^{137}Cs in six scenarios. In addition, the receptors' average ^{137}Cs depositions within 500 km diameter were found to be very high ($40\text{-}185 \text{ kBq/m}^2$) for 60 scenarios. In the remaining six scenarios, a relatively high ($10\text{-}40 \text{ kBq/m}^2$) ^{137}Cs deposition was calculated (Table 4.13).

On the other hand, one scenario showed severe ^{137}Cs deposition for İzmir and Erzurum, both of which are outside the 500 km diameter. In only three scenarios, high deposition results were obtained in Ankara, which is comparably close to the accident site. On the other hand, far away cities such as Samsun and Erzurum had high deposition results in nine and seven scenarios, respectively. At more distant receptors such as Athens, Baku, Baghdad, Tabriz, and Cairo, ^{137}Cs depositions were detected below 2 kBq/m^2 in most simulations. However, a few scenarios gave very high depositions in all these receptors except Cairo. Moreover, the number of scenarios with no deposition was found to be higher in the Western receptors than in the Eastern ones and higher in the Southern receptors than in the Northern ones. This situation shows that the regions to the West and South of the power plant are at lower risk levels (Table 4.13).

An average of 12 receptors around Akkuyu NPP demonstrated generally high ^{137}Cs depositions. May 03 simulation offered 504 kBq/m^2 of ^{137}Cs deposition, which was the highest. Furthermore, 230 kBq/m^2 , 221 kBq/m^2 , and 215 kBq/m^2 of ^{137}Cs were

calculated in Jan03, Sep01, and Apr03 simulations, respectively. Although two neighbouring cities, Adana and Mersin, gave similar numbers of very high and extreme depositions, a significant portion of these values was at different times. For example, the Apr03 simulation provided the maximum value of ^{137}Cs deposition for Mersin as 1897 kBq/m^2 and gave a relatively lower deposition (22 kBq/m^2) for Adana. Similarly, the Feb03 scenario offered the maximum deposition as 1580 kBq/m^2 for Adana and gave a lower ^{137}Cs deposition (21 kBq/m^2) for Mersin. While the highest values were generally observed in Adana in the winter period, the maximum depositions in Mersin were determined in April, May, and November. On the other hand, the Antalya receptor, which is at a similar distance to Adana but in the West direction, received much lower depositions. Mar04 simulation gave the highest deposition for Antalya as 1152 kBq/m^2 , and high values were detected only in March and April (Figure 4.18).

Table 4.13 Number of simulations between ranges in receptors

Ranges (kBq/m^2)	>1480	185-1480	40-185	10-40	2-10	0-2	No Deposition
Akkuyu	11	61	0	0	0	0	0
Nicosia	0	2	7	4	10	49	17
Mersin	1	7	10	15	8	31	6
Adana	1	7	11	18	10	25	6
Armutlu/Aksaray	0	0	4	6	5	57	25
Aleppo	0	1	4	18	18	31	9
Antalya	0	1	3	7	4	57	29
Beirut	0	0	4	7	17	44	15
Damascus	0	1	2	4	19	46	16
Ankara	0	0	3	6	10	53	33
Sivas	0	5	6	6	11	44	21
Amman	0	0	1	4	16	51	19
<i>Deposition Averages of top 12 Receptors around Akkuyu NPP</i>	0	6	60	6	0	0	0
Izmir	0	1	1	0	3	67	41
Istanbul	0	0	3	3	2	64	48
Samsun	0	0	9	10	4	49	24
Van	0	0	3	12	16	41	7
Erzurum	0	1	7	10	14	40	12
Athens	0	0	1	2	3	66	53
Baku	0	0	1	3	14	54	14
Baghdad	0	0	2	3	10	57	9
Tabriz	0	0	2	9	14	47	9
Cairo	0	0	0	1	9	62	29

Figure 4.19 shows the results in Armutlu-Aksaray, Sivas, Samsun, and Erzurum receptors with climate types Bsk, Dsb, Cfb, and Dfb, respectively. Although the

Armutlu receptor is closer than the other three receptors, it gave the lowest ^{137}Cs depositions. 85 kBq/m², 75 kBq/m² and 57 kBq/m² of ^{137}Cs deposition were calculated in Mar01, Dec04 and Nov03 simulations, respectively. However, the Samsun receptor located further away on the same route (North) presented higher depositions. In Apr05, Mar01, and Oct06 simulations, 145 kBq/m², 134 kBq/m², and 131 kBq/m² of ^{137}Cs deposition were calculated for Samsun, respectively. Calculating higher deposition at the more distant receptor in the same route is an important finding for the effects of climate characteristics. While the Cfb type is an Oceanic climate with rain during most of the year, the Bsk type is a cold semi-arid climate without precipitation. Therefore, the Samsun receptor showed higher depositions. Sivas and Erzurum, located further East than these two receptors, gave higher depositions than Aksaray. High depositions were observed in Sivas, especially in April, May, November, and December. Apr05, Dec06 and May05 simulations in Sivas gave 274 kBq/m², 252 kBq/m², 240 kBq/m² of ^{137}Cs deposition, respectively. In Erzurum, 290 kBq/m², 132 kBq/m² and 78 kBq/m² of ^{137}Cs deposition were calculated in Feb03, May05, and May03 simulations, respectively. Dsb and Dfb climate types are called warm summer continental climates. Winter and spring receive the most precipitation. In particular, Erzurum and Sivas receptors demonstrated the effect of precipitation.

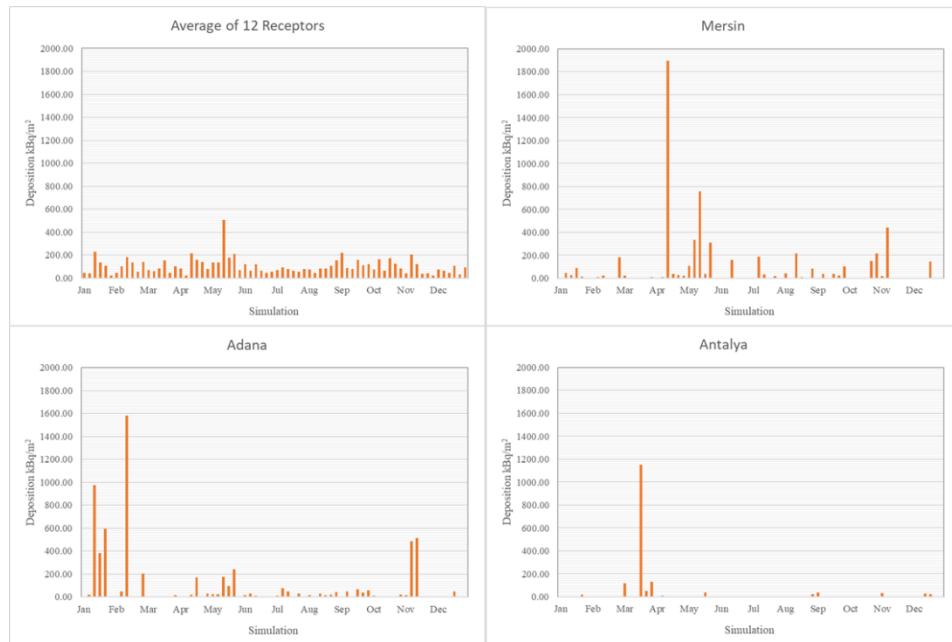


Figure 4.18 ^{137}Cs depositions in all simulations for an average of 12 receptors around Akkuyu NPP, Mersin, Adana and Antalya

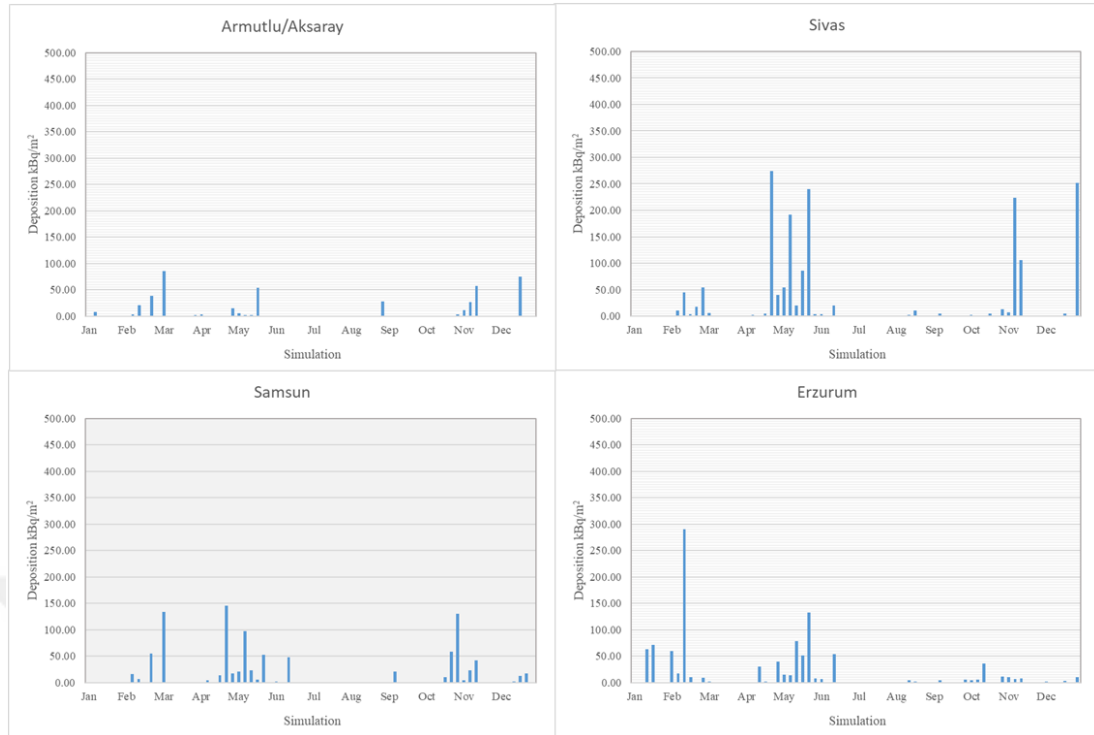


Figure 4.19 ^{137}Cs depositions in Aksaray, Sivas, Samsun and Erzurum for 72 simulations

Figure 4.21 presents ^{137}Cs depositions for distant receptors Athens, Baku, Baghdad and Cairo. No deposition was observed in Athens in 53 of the 72 simulations, while 3 of the remaining 19 simulations gave ^{137}Cs depositions higher than 10 kBq/m^2 . In addition, the Nov01 simulation gave the highest ^{137}Cs deposition with 108 kBq/m^2 in Athens. The number of simulations with no deposition in Baku and Bagdad is very few compared to Athens. Several simulations in both receptors presented relatively high depositions. The Sep05 simulation showed Baku's highest ^{137}Cs deposition as 60 kBq/m^2 . Baghdad's simulations of Feb04 and Feb01 showed 125 kBq/m^2 and 57 kBq/m^2 of ^{137}Cs deposition, respectively. Almost all simulations in Cairo gave low depositions. Oct04 simulation gave the maximum ^{137}Cs deposition as 15 kBq/m^2 . Besides this, in almost half as many simulations, no deposition was calculated in Cairo as in Athens. However, Athens's depositions were higher than Cairo's due to the difference in precipitation.

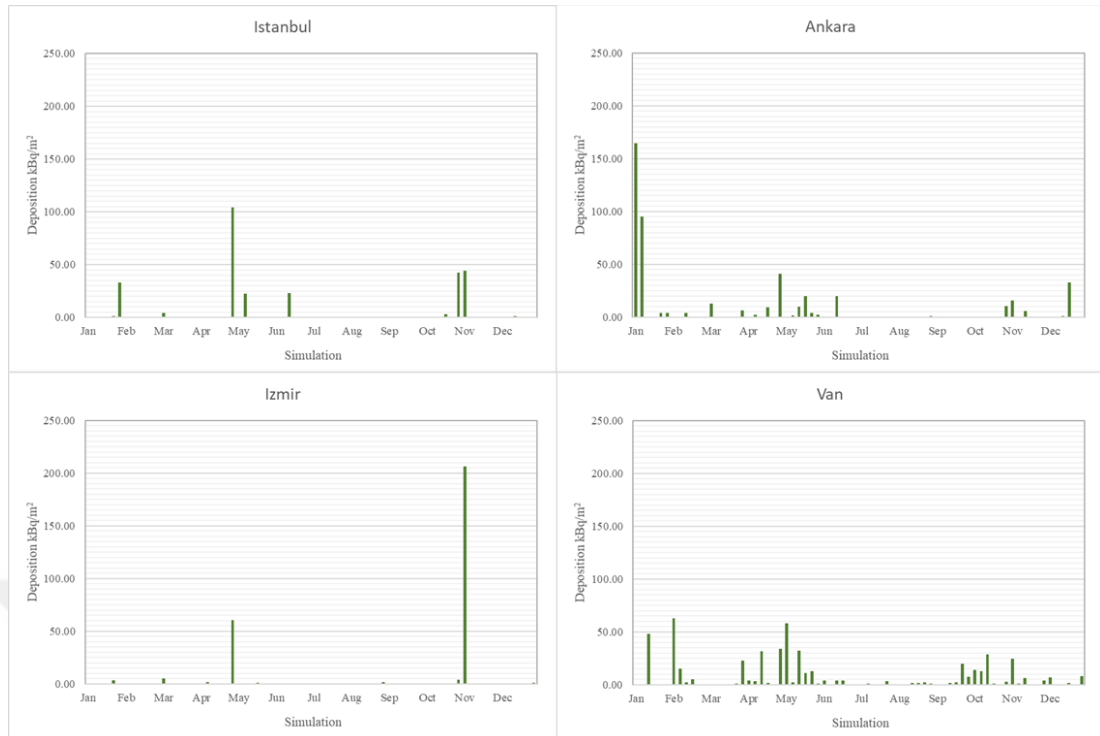


Figure 4.20 ^{137}Cs depositions in Istanbul, Ankara, Izmir, and Van for 72 simulations

The results revealed that wind direction and precipitation are essential factor dispersion of air concentrations and surface depositions of radionuclides. However, the extent of the radioactive cloud can influence the dispersion pattern, and a conduit-like flow structure can sometimes become responsible for very high spatial variations in concentrations and depositions within short distances. For example, the Jan01 simulation gave a maximum of ^{137}Cs deposition for Ankara. However, the average of 12 receptor depositions in Jan01 was one of the lowest scenarios (52 kBq/m^2) because the radioactive cloud moved straight to the North without dispersing too much. Besides, in the Apr06 simulation, radioactive materials were dispersed in the Northwest direction and spread all over Turkey by the changing wind direction. The complex behavior in this scenario resulted in high contaminations for locations very far from each other. The Apr06 simulation gave one of the three highest depositions for the Istanbul, Izmir, Ankara, Nicosia, and Amman receptors. On the other hand, the Apr06 presented relatively low values for Mersin, Adana, and Antalya receptors located on the same coast as Akkuyu. The May03 simulation gave the highest ^{137}Cs deposition for the average of 12 receptors. Contamination was found to be relatively high in Akkuyu, Mersin, and Erzurum directions as there was an East and North

directional transport during the simulation period. However, except for Akkuyu and Mersin, the other eight receptors did not have extreme values. This scenario offered extreme (5047 kBq/m²) depositions for the Akkuyu receptor due to the high precipitation in the source region. The extreme value in Akkuyu caused the average of 12 receptors to be high. Due to the transport in the West and South directions, the Nov04 scenario gave the total deposition of ¹³⁷Cs 0 for all receptors except for the Akkuyu receptor (Figure 4.22).

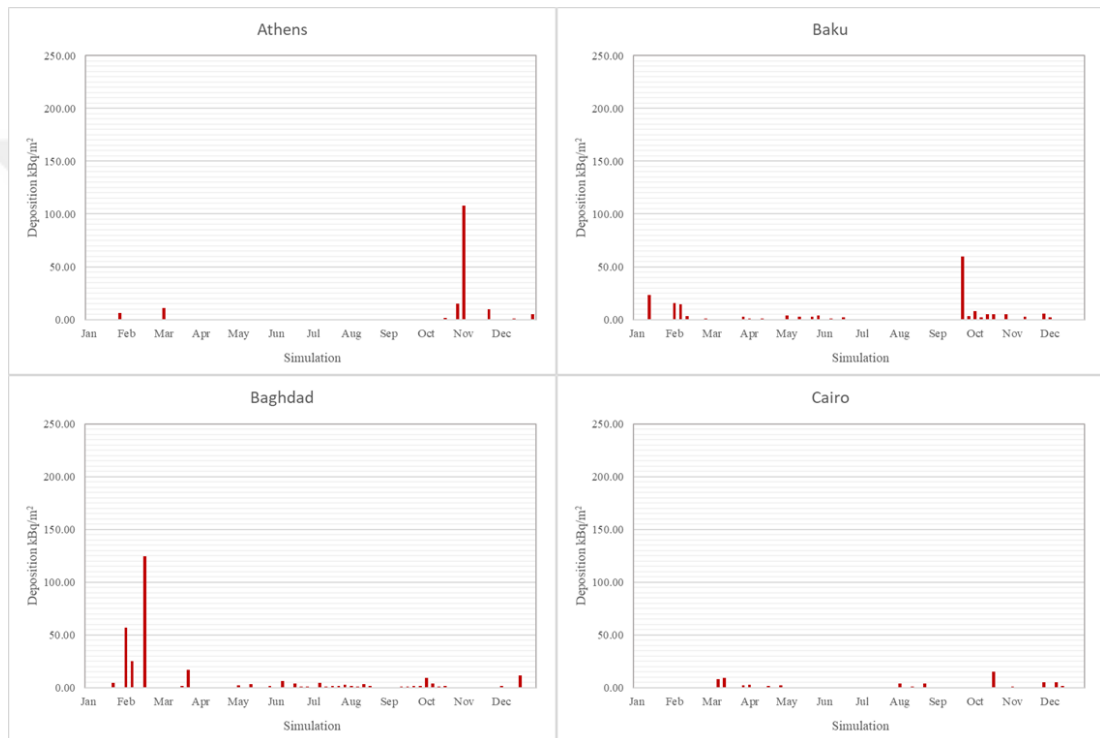


Figure 4.21 ¹³⁷Cs depositions in Athens, Baku, Baghdad and Cairo for 72 simulations

4.4.2 Simulation Results under Extreme Meteorological Conditions

In this thesis, a total of 222 simulations were also conducted to evaluate the impact of extreme meteorological conditions on contamination after a severe nuclear power plant accident. A total of 55 Wet (extreme precipitation) periods were determined, but simulation Wet051 could not be done due to technical problems. Similarly, a total of 113 Heatwave simulations were completed, but six of them (Heat062, Heat063, Heat064, Heat065, Heat066, Heat067) could not be conducted due to the same reason. All 61 Stagnant period simulations were carried out without any problems.

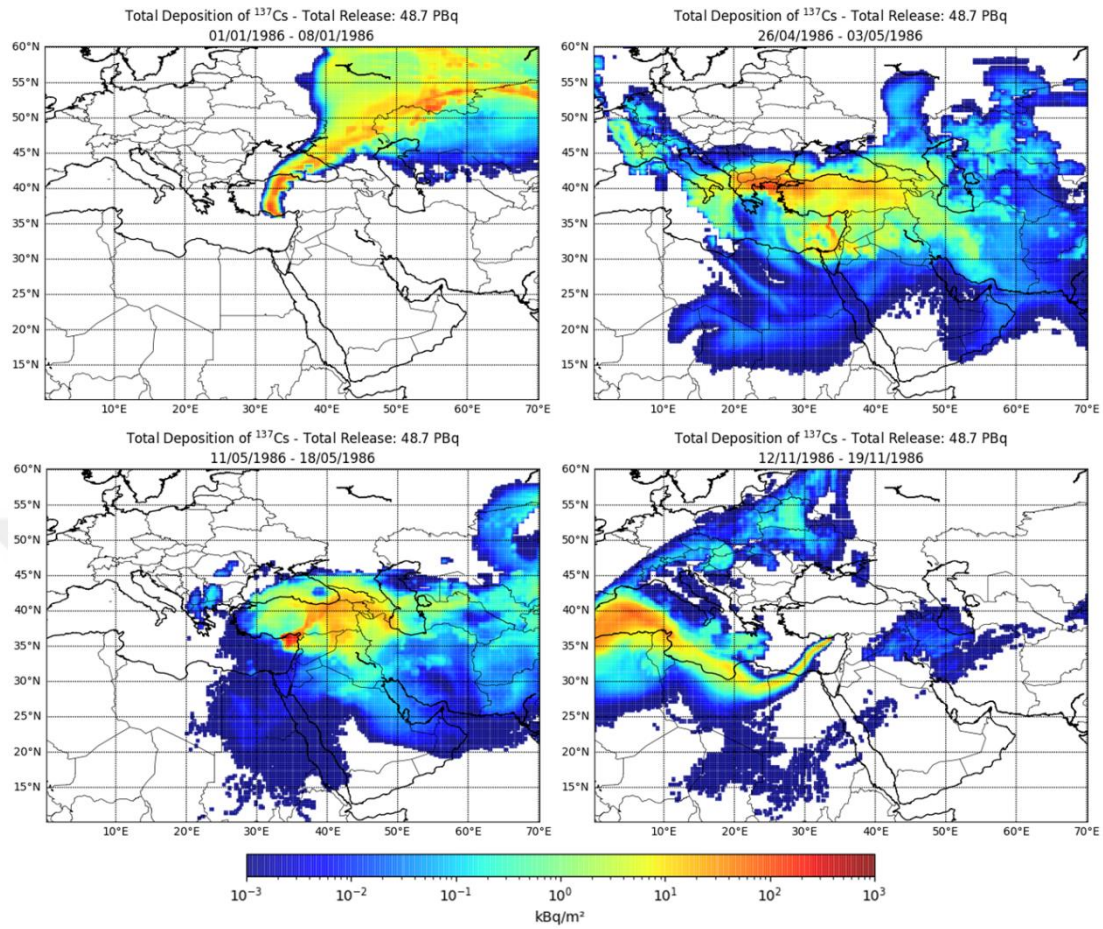


Figure 4.22 Total ground deposition of ^{137}Cs released from Akkuyu NPP in Simulation Jan01 (upper left), Apr06 (upper right), May03 (lower left) and Nov04 (lower right)

In the Wet scenarios, the time-integrated activity concentration of ^{131}I and the total deposition of ^{137}Cs were the highest in Western Anatolia. The average of the 54 Wet scenarios showed the effects of climatic characteristics on transport and deposition. In addition, the higher precipitation in the North also led to higher depositions. ^{137}Cs depositions were higher in the North, as the atmospheric flows were predominantly Northward. The time-integrated concentration of ^{131}I in the North of the Black Sea was lower than in the South of the Mediterranean Sea due to Wet scavenging (Figure 4.23).

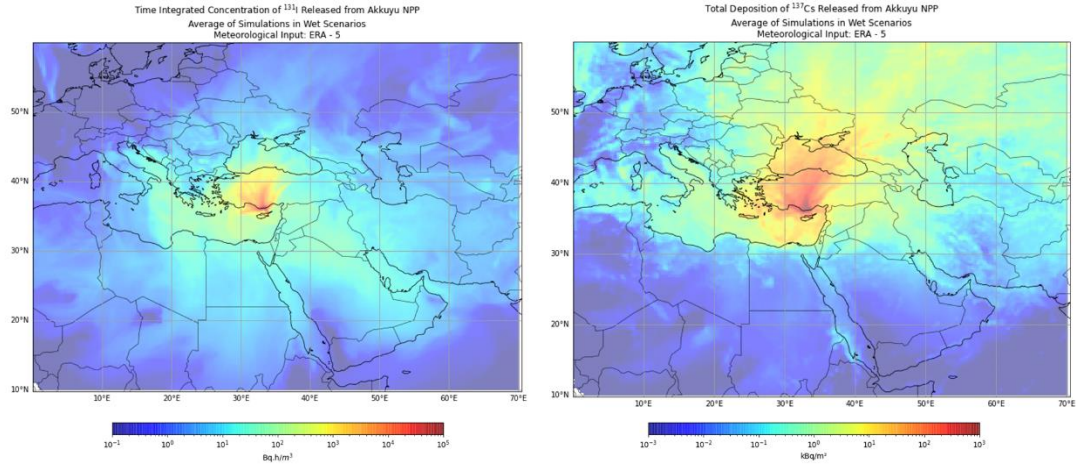


Figure 4.23 Average of 54 simulations in Wet scenarios: time integrated concentration of ^{131}I (left) and total surface deposition ^{137}Cs

The transport of Stagnant scenarios was mainly towards the South. Since there was less precipitation around the power plant, more ^{131}I were transported to remote locations than in Wet scenarios. Due to wind direction and lack of precipitation, ^{131}I was higher in Africa than in Eastern Europe and Russia. On the other hand, ^{137}Cs deposition was also high in the North, although there was relatively little transport as precipitation was high (Figure 4.24). Similar results to Stagnant scenarios were also obtained in Heatwave scenarios. Because Heatwave scenarios occurred during dry periods, depositions were calculated lower than in Stagnant conditions (Figure 4.25).

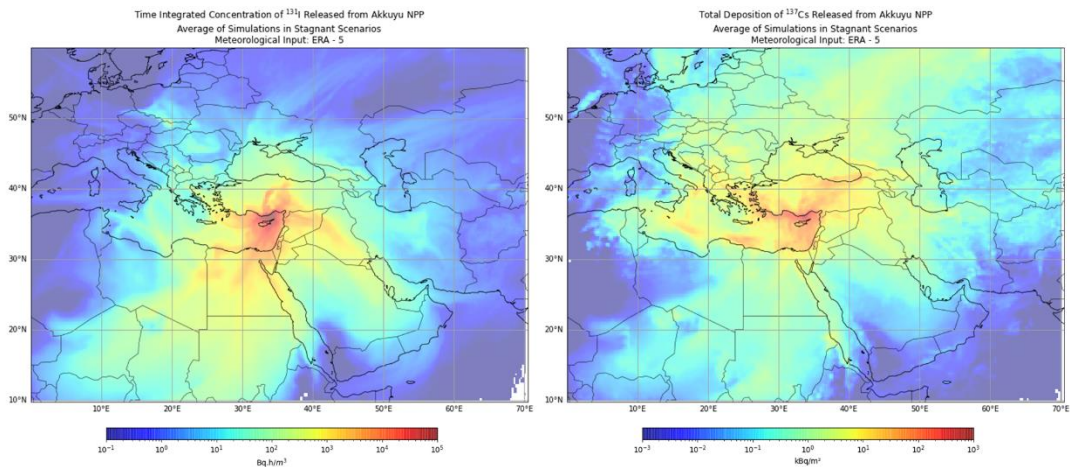


Figure 4.24 Average of 61 simulations in Stagnant scenarios: time-integrated concentration of ^{131}I (left) and total surface deposition ^{137}Cs

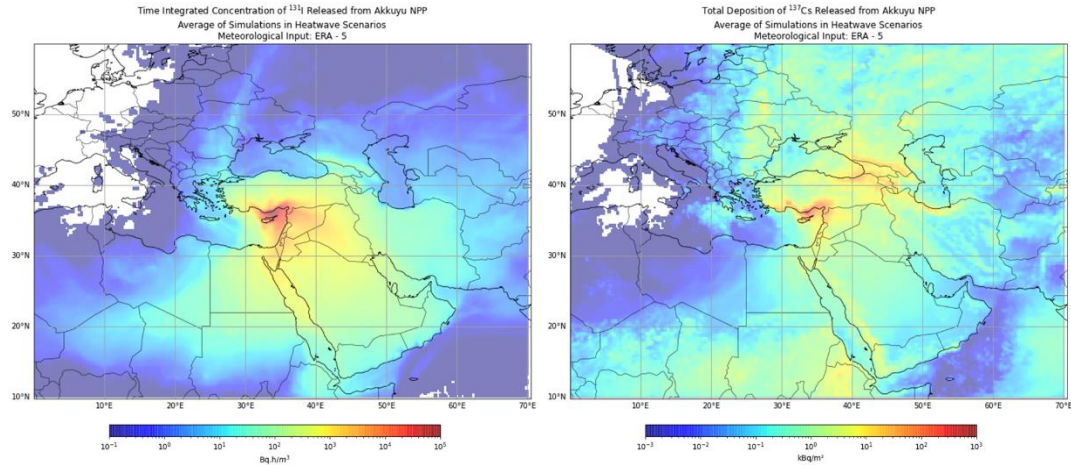


Figure 4.25 Average of 107 simulations in Heatwave scenarios: time-integrated concentration of ^{131}I (left) and total surface deposition ^{137}Cs

Figure 4.26 shows the deposition averages of ^{137}Cs in 12 receptors, where meteorological analyzes were performed for 222 simulations. In general, higher ^{137}Cs depositions were calculated in Wet scenarios. The average ^{137}Cs deposition of 54 simulations was calculated to be 121 kBq/m^2 . Similar results were obtained in the Stagnant and Heatwave scenarios. The mean of ^{137}Cs deposition in 61 Stagnant simulations was 29 kBq/m^2 . In the applied 107 Heatwave simulations, an average 28 kBq/m^2 of ^{137}Cs deposition was calculated. Although ^{137}Cs depositions were generally low in Heatwave conditions, the highest value among 222 simulations was obtained in the Heat103 simulation. While there was no value exceeding 250 kBq/m^2 of ^{137}Cs deposition in the other 221 simulations, 489 kBq/m^2 deposition was calculated in the Heat103 simulation.

Extreme ^{137}Cs deposition ($>185 \text{ kBq/m}^2$) was detected at the Akkuyu receptor in 50 of the 54 Wet scenarios. Out of 222 simulations, extreme values were calculated in 104 simulations in Akkuyu. Depositions of less than 2 kBq/m^2 have been calculated in most scenarios (42) in Nicosia, South of the Akkuyu NPP, as the transport was more towards the North and West in the Wet period scenarios. In contrast, 43 of the 61 Stagnant simulations were higher than 10 kBq/m^2 . On the other hand, depositions higher than 10 kBq/m^2 was calculated in 25 Wet scenarios at the Armutlu receptor located to the North of Akkuyu NPP. No Heatwave and eight Stagnant simulations gave higher than 10 kBq/m^2 of ^{137}Cs deposition for the same receptor. Similar

situations have been found at other receptors in the North and West. Higher depositions were detected in Wet scenarios than in other scenarios for receptors located North and West of Akkuyu NPP, such as Ankara, Istanbul, Izmir, Antalya, and Athens. ^{137}Cs deposition was calculated to be the highest in Stagnant simulations and the lowest in Wet simulations in Adana and Mersin, located just East of the Akkuyu NPP. Higher ^{137}Cs were detected in Wet simulations in Samsun and Sivas, located in the North and East, compared to the power plant. Further, in Erzurum, higher depositions were calculated in Stagnant simulations. Similarly, the highest ^{137}Cs deposition was calculated in Stagnant simulations at Beirut and Aleppo in the Eastern Mediterranean. Table 4.14 presents the number of simulations in a defined range in each receptor for 222 simulations. In addition, detailed tables for each extreme condition are presented in the appendices (Table A5.1, Table A5.2, Table A5.3).

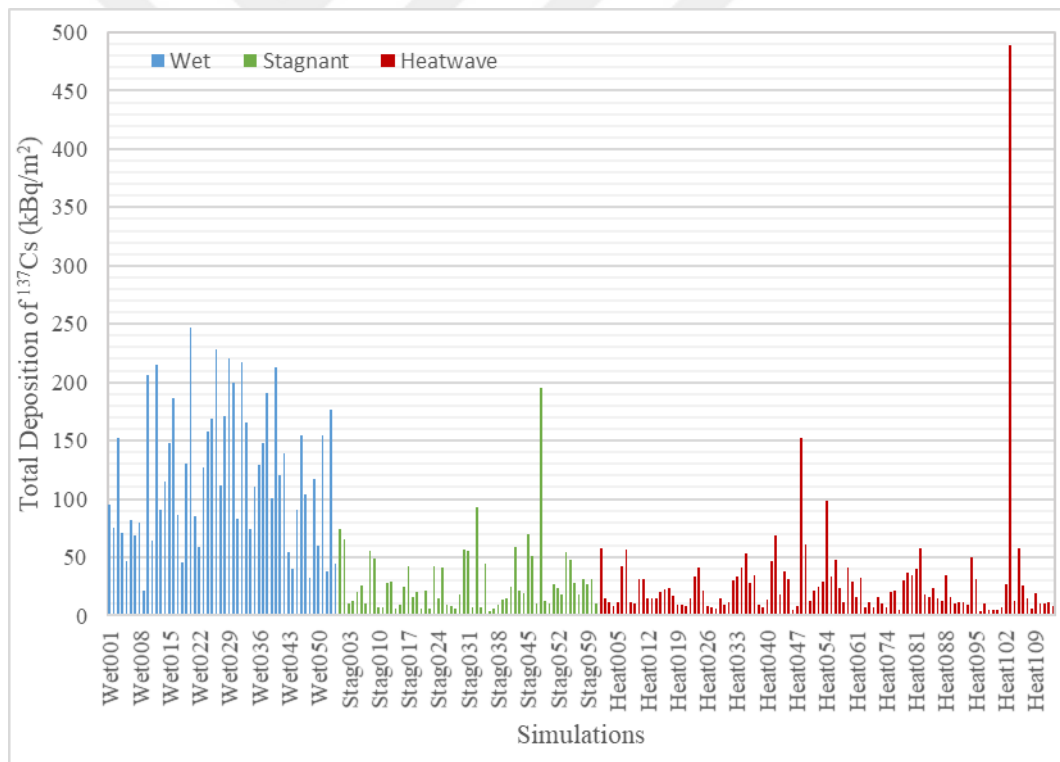


Figure 4.26 Average ^{137}Cs deposition of 12 receptors considered in meteorological analysis

^{137}Cs deposition results were also analyzed based on meteorological parameters. The relationship between total precipitation and ^{137}Cs depositions is presented in Table 4.15. Since all of the Stagnant and Heatwave simulations took place in the dry period,

the total precipitation amounts of all simulations remained in the range of 0-4 mm. Since the Wet deposition is over 12 mm in all scenarios, all rows above 12 mm in Table 4.15 are a Wet simulation. Table 4.15 reveals the effect of precipitation on deposition. Fewer ^{137}Cs were calculated during periods of low precipitation. In scenarios with high precipitation, the number of intervals with high deposition was higher.

Table 4.14 Number of simulations at defined ^{137}Cs deposition intervals at receptors

Ranges (kBq/m ²)	>1480	185-1480	40-185	10-40	2-10	0-2	No Deposition
Akkuyu	23	81	106	12	0	0	0
Nicosia	0	1	16	39	48	104	14
Mersin	0	18	47	59	40	51	7
Adana	0	3	37	54	41	78	9
Armutlu/Aksaray	0	5	11	17	20	127	42
Aleppo	0	0	2	51	54	104	11
Antalya	0	7	19	19	27	95	55
Beirut	0	0	2	22	70	116	12
Damascus	0	0	0	4	41	165	12
Ankara	0	3	12	15	25	102	65
Sivas	0	1	5	9	33	146	28
Amman	0	0	0	5	33	172	12
<i>Deposition Averages of top 12 Receptors around Akkuyu NPP</i>	<i>0</i>	<i>12</i>	<i>74</i>	<i>97</i>	<i>39</i>	<i>0</i>	<i>0</i>
Izmir	0	1	6	10	17	99	89
Istanbul	0	0	1	11	18	99	93
Samsun	0	1	7	19	35	119	41
Van	0	0	0	11	36	161	14
Erzurum	0	0	0	13	32	165	12
Athens	0	0	1	4	5	88	124
Baku	0	0	0	1	5	190	26
Baghdad	0	0	0	2	18	181	21
Tabriz	0	0	0	3	18	183	18

The relationship between surface temperature and deposition is summarized in Table 4.16. In simulations with high temperatures (28-32°C), primarily low depositions were detected. Simulations were usually conducted during dry periods, as high temperatures mainly occurred during summer. Thus, the depositions were lower in higher temperatures. Both very low and very high depositions were detected in the low-temperature period. High depositions were detected on rainy and cold days and low on dry and cold days.

Table 4.15 The number of simulations in related intervals for total precipitation (tp) and ^{137}Cs deposition

tp (mm)	^{137}Cs Deposition (kBq/m ²)				
	0 - 25	25 - 50	50 - 75	75 - 100	>100
0 - 4	98	44	19	2	5
4 - 8	0	0	0	0	0
8 - 12	0	0	0	0	0
12 - 16	1	2	2	3	8
16 - 20	0	2	3	3	17
20 - 24	0	0	1	2	7
24 - 28	0	0	0	1	0
>28	0	1	0	1	0

Table 4.16 The number of simulations in related intervals for surface temperature (t2m) and ^{137}Cs deposition

t2m (°C)	^{137}Cs Deposition (kBq/m ²)				
	0 - 25	25 - 50	50 - 75	75 - 100	>100
0 - 4	3	2	0	0	1
4 - 8	12	10	5	1	12
8 - 12	13	4	7	7	15
12 - 16	6	4	3	2	5
16 - 20	0	0	0	2	1
20 - 24	0	0	0	0	0
24 - 28	0	0	0	0	0
28 - 32	65	29	10	0	3

Table 4.17 presents the PBLH intervals and the corresponding ^{137}Cs depositions. In extreme meteorology simulations, release height has been assumed to reach 150 m. At PBLH, less than 150 meters, most radionuclides were transported to distant locations by mixing with the free atmosphere. Therefore, predominantly low depositions have been calculated in the 0-150 m PBLH range. All emissions occurred under ABL conditions at PBLH values greater than 150 meters. Vertical transport of radionuclides became more complicated at PBLH values close to this level. Therefore, higher depositions were calculated when the PBLH was just over 150 meters. As the PBLH value increases, unstable conditions were observed and vertical transport increased. Therefore, at higher PBLH ranges, lower ^{137}Cs depositions were calculated.

Table 4.17 The number of simulations in related intervals for PBLH and ^{137}Cs deposition

PBLH (m)	^{137}Cs Deposition (kBq/m ²)				
	0 - 25	25 - 50	50 - 75	75 - 100	>100
0 - 150	4	1	0	1	1
150 - 300	19	10	8	3	13
300 - 450	8	8	3	4	12
450 - 600	4	1	1	2	2
600 - 750	2	1	4	1	3
750 - 900	13	14	3	1	2
900 - 1050	19	10	3	0	3
1050 - 1200	18	1	2	0	1
>1200	12	3	1	0	0

4.5 TEDE Results of Simulations

Because the radiological impact of the concentration is also significant, evaluations cannot be limited to deposition results. As the precipitation is low, the time-integrated concentration of radionuclides is higher in dry periods and lower in Wet periods. This thesis calculated TEDE values considering ^{131}I , ^{134}Cs , and ^{137}Cs radionuclides for all simulations. TEDE was estimated at one year for adults and infants. Figure 4.27 presents 1-year TEDE values for adults for 1986, Wet, Stagnant, and Heatwave simulations. In general, the highest TEDE was calculated around Akkuyu NPP. In the 1986 simulations, higher TEDE values were calculated in the Northern and Eastern regions than in the Southern and Western areas.

In Wet simulations, TEDE values were higher in the Northern regions than in the Southern regions. However, since the precipitation was very high and the atmospheric flow did not change much, the amount of contaminated area was relatively limited. Therefore, very low contaminations have been detected, especially in the South of the Mediterranean. In Stagnant simulations, the highest TEDE values were seen around Cyprus and the Eastern Mediterranean. Although there is no significant difference between the South and the North, TEDE values were a bit high in the South because the winds were more frequent in that direction. In Heatwave simulations, generally lower TEDE values were calculated compared to other simulations. Since the atmospheric transport were generally towards the South and East, the TEDE values mainly were very low in the North and West. In addition, relatively high TEDE was detected in the Eastern Black Sea, where summers were also rainy.

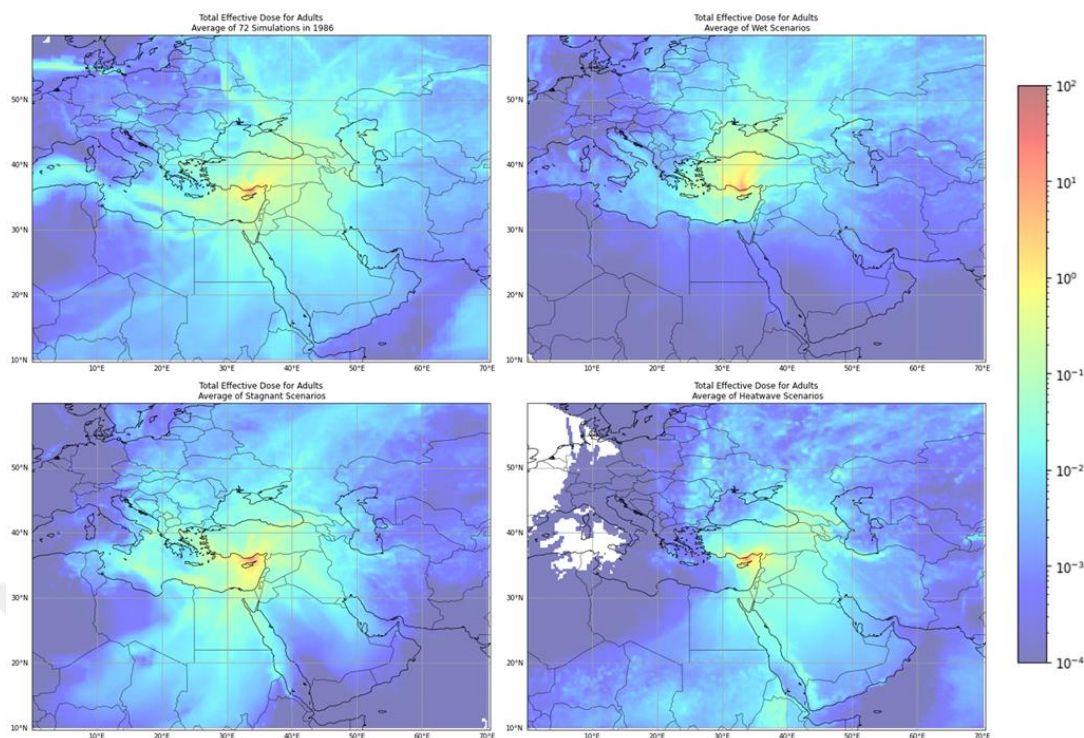


Figure 4.27 1 year TEDE for Adults: Average of 72 simulations in 1986 (upper-left), Wet (upper-right), Stagnant (lower-left) and Heatwave scenarios (lower-right)

Simulations for infants yielded results consistent with those for adults. High values for adults' TEDE values were calculated as high for infants TEDE, while low values for both TEDE were shown in the exact locations. However, infants' TEDE values were calculated higher in all simulations because infants were more susceptible than adults (Figure 4.28).

Each extreme scenario had different effects on different receptors. The averages of 12 receptors were higher in the Heatwave and Stagnant cases than in the Wet case. The worst radiological conditions in the Akkuyu receptor occurred in Heatwave scenarios. Moreover, the highest TEDE averages were calculated in the Heatwave scenarios in Adana, Aleppo, Damascus, and Amman in the Eastern Mediterranean. The highest TEDE averages were observed in the Stagnant simulations in Mersin, Nicosia, Van, and Beirut. On the other hand, the highest TEDE were found in Wet simulations in Armutlu, Antalya, Ankara, Sivas, Izmir, Istanbul, and Samsun receptors.

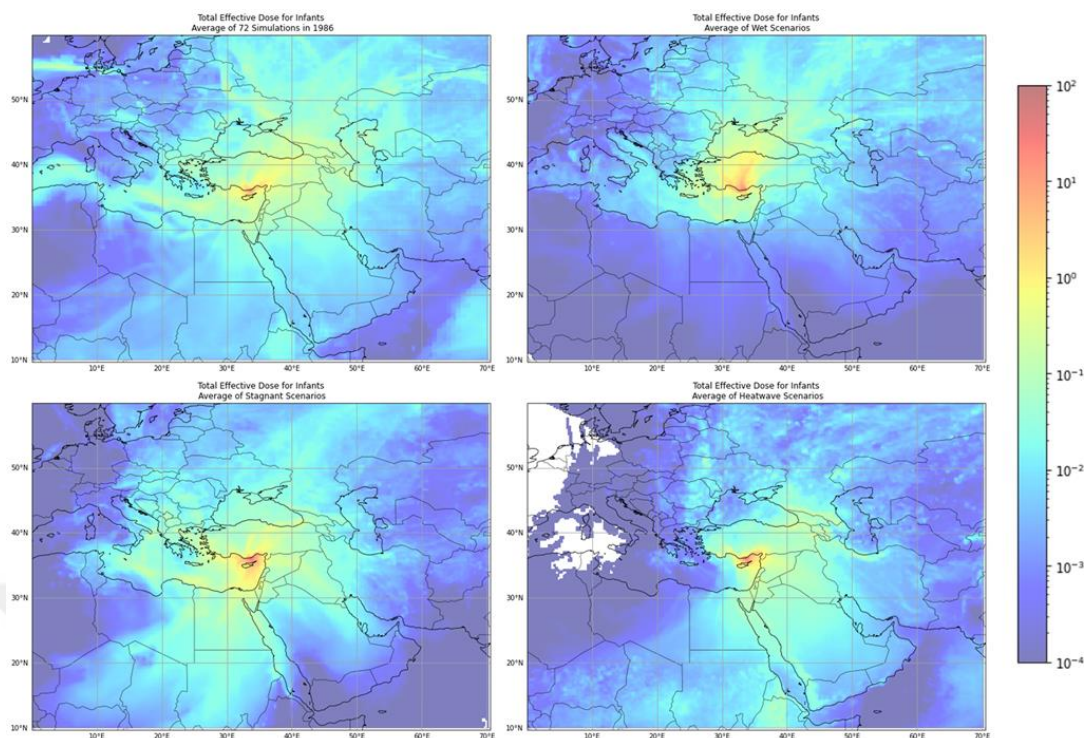


Figure 4.28 1 year TEDE for Infants: Average of 72 simulations in 1986 (upper-left), Wet (upper-right), Stagnant (lower-left) and Heatwave scenarios (lower-right)

This study also carried out five worst-case scenarios, and a more comprehensive one-year TEDE calculation was made. In these scenarios, 20 radionuclides given in Table A4.1 were simulated. In addition, estimations were conducted for the ingestion pathway to achieve more realistic results. In these simulations, the simultaneous accident situation in four reactors was also examined. Therefore, the release amounts of each radionuclide in Table A4.1 were multiplied by four. Selected methods included:

- The scenarios, Heat103, Wet20, and Wet 26, which gave the first, the second, and the third highest averages of ^{137}Cs deposition in 12 receptors, respectively,
- Wet29 which had the highest ^{137}Cs deposition in Istanbul,
- Stagnant45 which had the highest average ^{137}Cs deposition of 500 km around Akkuyu NPP.

In the Heatwave 103 simulation, the atmospheric transport flowed predominantly in the South and East directions. For this reason, a large part of Europe and Turkey were not affected by accident at all. In addition, high TEDE values were observed in Akkuyu, Mersin, Adana, Nicosia, Aleppo, and Beirut receptors. In this scenario, the average of the 12 receptors was calculated as 31 mSv. This value was the second-highest TEDE value among the five simulations (Figure 4.29).

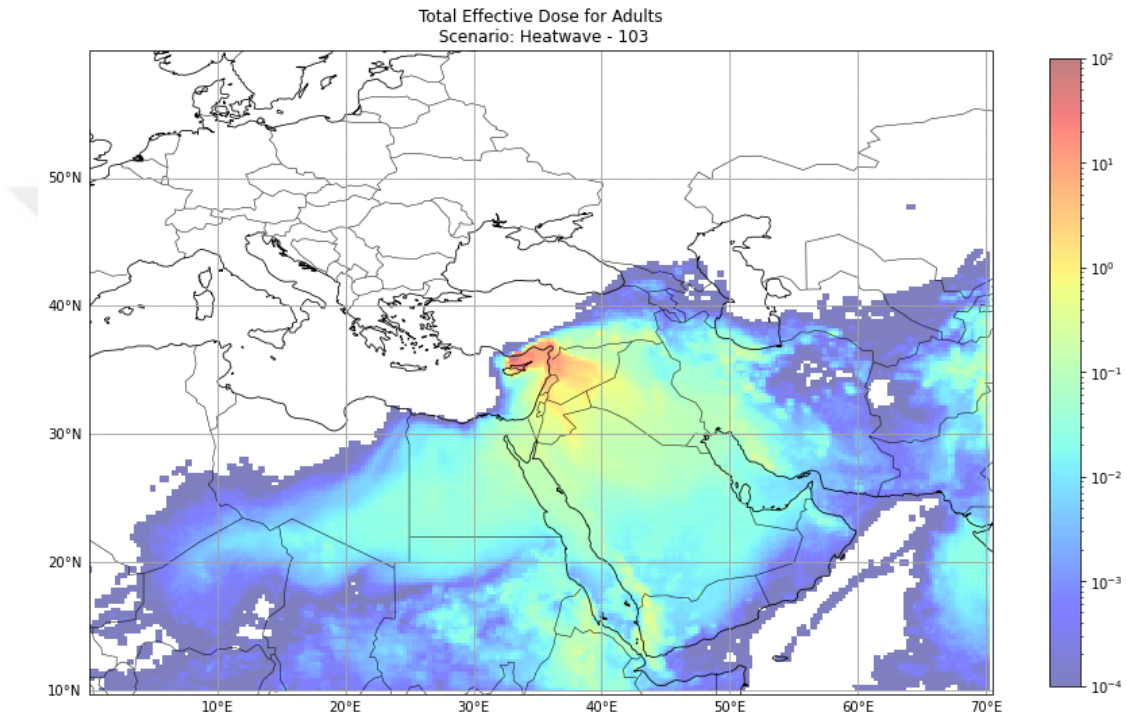


Figure 4.29 1 year TEDE for adults in Heatwave 103 simulation

A complex transport has taken place in the Wet 20 scenario. Radioactive clouds first moved North and West, then moved Eastward with changing wind directions. Therefore, all of Turkey, especially the West, has been affected by this scenario. On the other hand, this accident did not affect most of Europe, Africa, and the Arabian Peninsula. It has caused relatively significant radiological effects in most of Ukraine and Russia. This case had the lowest average TEDE value (14 mSv) of 12 receptors in the five scenarios. In the Wet 26 simulation, radioactive clouds first moved Northward. For this reason, it caused severe contamination in the middle of Anatolia and the Western Black Sea. Later, the dispersed radioactive clouds significantly affected the entire territory of Turkey and the central Mediterranean. While the average of 12

receptors was calculated as 15.5 mSv, the TEDE value was calculated as 14.9 mSv in Ankara, the capital of Turkey, and 3.72 mSv in Istanbul, the largest city (Figure 4.30).

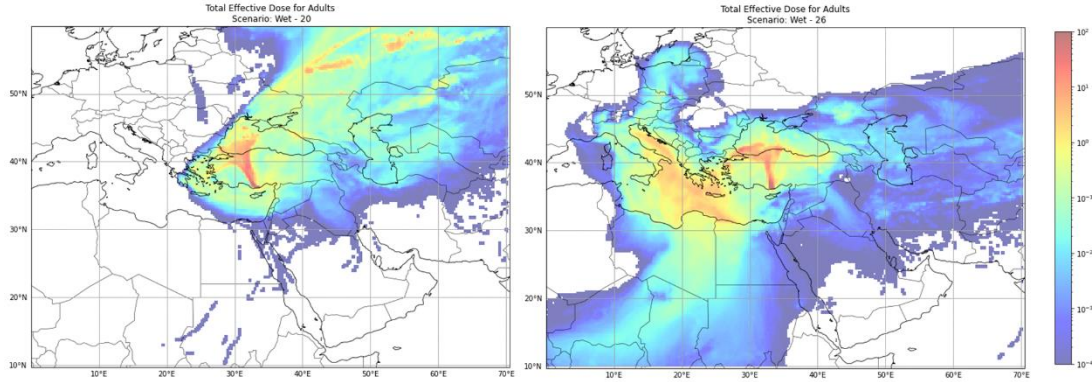


Figure 4.30 1 year TEDE for adults in Wet 20 (left) and Wet26 (right) simulation

In the Stag45 simulation, the South direction was predominantly affected. Radioactive clouds reached Egypt throughout the Mediterranean after creating severe contamination in Akkuyu and Mersin. However, there was a movement to the North, and it affected the entire Turkey. The highest average of 12 receptors, 43.4 mSv, was calculated in this scenario. For Cairo, where very low doses were calculated in many other cases, 3.53 mSv TEDE was calculated in this scenario. In the Wet29 scenario, radioactive materials predominantly moved Northwards. First, Western Anatolia was affected significantly, as there was also transport in the West. In addition, the Western Black Sea, the Balkans, and Ukraine were affected by this scenario. The mean of 12 receptors was calculated as 19.2 mSv. TEDE was calculated as 25 mSv in the capital Ankara, 23.2 mSv in Antalya, 6.5 mSv in Izmir, and 5 mSv in Istanbul. Considering all these populated and economically significant cities, the worst scenario among the five cases for Turkey was the Wet29 scenario (Figure 4.31).

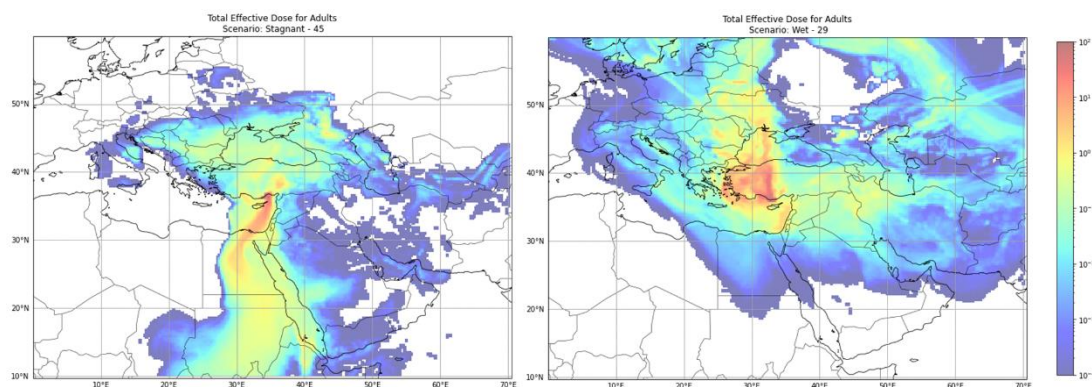


Figure 4.31 1 year TEDE for adults in Stagnant 45 (left) and Wet-29 (right) simulation

Wet scenarios generally presented the worst conditions for the Western and Northern regions. However, Stagnant and Heatwave conditions produced the most extreme results in and around Akkuyu NPP. This is related to the contribution of activity concentrations and wind direction. While precipitation causes radiological consequences by causing deposition, it decreases the activity concentration-induced doses (cloud shine and inhalation) with its scavenging effect.

4.6 Discussion

Entire meteorological conditions in 1986 in Akkuyu NPP showed that the transport was more towards the South than towards the North. However, more ^{137}Cs were deposited in the Northern and Eastern regions with rainy climates. In addition, higher depositions were calculated at the nearby Armutlu/Aksaray, with an arid climate, on the same route but at the farther receptor Samsun, which has a relatively low rainfall climate. This situation indicates the significant effect of precipitation and climate on the deposition pattern. However, no deposition was calculated in many simulations in Western receptors such as Izmir, Istanbul and Athens. On the other hand, no deposition has been found in very few simulations in Eastern receptors such as Van, Erzurum, Baghdad, and Tabriz. This situation is related to the direction of atmospheric transport. In locations where radioactive materials are not transported, there will be no depositions even if there is heavy rainfall. On the other hand, this study revealed that the direction of atmospheric transport towards rainy regions does not always produce high depositions. Because the radioactive cloud is not very dispersed, the deposition

may remain in a minimal area as in the Jan01 simulation. Therefore, besides precipitation and wind direction, the dispersion of the radioactive cloud is also an important parameter.

Fifty-four Wet simulations, representing the extreme rainy period, caused more deposition in the receptors located in the study area than other Heatwave and Stagnant simulations. These simulations also supported the finding that precipitation causes high depositions. Further, the atmospheric transport was mainly towards Turkey in Wet simulations. While almost no significant ^{137}Cs depositions were detected in the South of the Akkuyu NPP, severe ^{137}Cs depositions were detected in most simulations, especially in the densely populated Western Anatolia. Thus, possible accidents in Akkuyu NPP during extreme rainy periods may cause severe risks for Turkey due to heavy rainfall and general atmospheric transport towards the mainland.

Stagnant and Heatwave simulations coincided with dry periods. While all Heatwave scenarios naturally occur in the summer, none of the Stagnant periods is in the summer. Since there was no precipitation, relatively lower depositions were detected in the receptors in the study region in both groups of simulations. In addition, the activity concentrations were high because Wet scavenging was low. Although the lack of deposition reduces the radiological effects of long-time exposures (e.g., lifetime), high air activity concentrations cause significant risks, primarily due to respiratory exposure. Although there were severe contaminations in nearby locations such as Mersin and Adana in both scenarios, this situation caused less risk in densely populated locations such as Istanbul, Izmir and Ankara, as the atmospheric transport direction is predominantly towards South and East.

The relationship between ^{137}Cs depositions and precipitation was also demonstrated in parameter-based comparisons. Moreover, the PBLH effect was observed in these comparisons. Lower depositions were detected when PBLH was too high, while low PBLH caused higher depositions. However, the release is emitted to the atmosphere directly above the ABL height in case of PBLH release lower than the release height. Therefore, depositions decrease when PBLH is extremely low.

One-year TEDE calculations revealed that deposition alone is not sufficient for radiological evaluation. On average, many Wet scenarios with the highest deposition gave a lower one-year TEDE than Heatwave and Stagnant conditions in the receptors located within the first 500 km diameter. On the other hand, with the effect of the wind direction, the highest one-year TEDE Wet depositions were observed in densely populated Western and/or Northern cities such as Antalya, Ankara, Sivas, Izmir, Istanbul, and Samsun. Heatwave simulations gave the highest one-year TEDE in Adana, Aleppo, Damascus, and Amman in the Eastern Mediterranean, whereas Stagnant simulations gave the highest one-year TEDE in Mersin, Nicosia, Van and Beirut.

Very high values were calculated in the comprehensive one-year TEDE calculation for the five worst cases. For the average of 12 receptors closest to Akkuyu, one-year TEDE for adults varied between 14 mSv – 43.4 mSv. In Heat103, the scenario with the highest ^{137}Cs deposition average in 12 nearby receptors, Turkey, was not affected due to the Southeasterly transport direction. However, it has caused severe one-year TEDE in the Eastern Mediterranean (Southeastern Turkey, Western Syria, and Northern Lebanon). Stag45 simulation, which also gave high deposition of ^{137}Cs , was similarly effective in the South and Southeast directions. In this scenario, a high one-year TEDE was detected in Cairo as the atmospheric transport is towards the South direction. In the other three scenarios (Wet20, Wet26, Wet29), the 12 receptors' one-year TEDE average was found to be lower than Stag45 and Heat103. However, since atmospheric transport in these scenarios was towards North and West, they caused high one-year TEDE in some populated cities. For these reasons, it was revealed that the worst scenarios for Turkey took place during periods with extreme precipitation. Moreover, the worst case for Turkey occurred in the Wet29 scenario, where it produced high one-year TEDE in crowded and economically significant cities such as Istanbul, Ankara, Izmir and Antalya.

FLEXPART uses 3D reanalysis products such as ERA-5 for meteorological inputs (e.g., temperature, precipitation, wind components, specific humidity). Reanalysis products have uncertainties for each parameter as they are produced from an approach

that in corporates a weather forecast model. In addition, the FLEXPART model uses various approaches for calculating the properties of the pollutants as well as conditions of the atmosphere, such as pollutant concentrations, dry deposition, wet deposition, turbulence, and ABL height which have their own uncertainites. Therefore, the simulations in this study have a wide array of uncertainties. Despite the fact that FLEXPART is a reliable and validated model widely used in the literature for nuclear risk studies, calculating the total uncertainty is a very complex and comprehensive task which is beyond the scope of this study. In this regard, the assessment of the cumulative uncertainty in FLEXPART can be considered a subject for a further study.



CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A new comprehensive nuclear risk assessment methodology was developed in this study. In the approach developed herein, atmospheric transport and surface deposition simulations for typical radionuclides originating from actual or possible nuclear power plant accidents were conducted for the entire meteorological conditions of a selected year to represent all seasonal normals and for selected meteorological conditions that represent extreme meteorological settings. The year 1986, when the Chernobyl accident occurred, was accepted as the reference year for the entire meteorological conditions, and 72 model runs were performed this year to simulate all possible climatological conditions. Moreover, this study investigated the effect of extreme meteorological conditions on atmospheric dispersion and surface deposition. For this purpose, 222 simulations were carried out to assess the extreme conditions of temperature, precipitation and wind parameters. The determination of these extreme conditions was carried out with a specific tool (WTEM) developed in this thesis.

After verification of the methodology with Chernobyl applications, simulations were conducted for Akkuyu NPP, which is going to be Turkey's first nuclear power plant. A potential accident in Akkuyu NPP was simulated to analyze the atmospheric dispersion and ground-level deposition of selected radionuclides and to determine potential risks for humans and the environment. The release amount and characteristics for Akkuyu NPP simulations were performed with a tool (RARE) developed in this study. TEDE was calculated using activity concentrations and total depositions of ^{131}I , ^{134}Cs and ^{137}Cs from 294 simulations. Finally, a third tool (SDEP) developed in this study was used in TEDE calculations to determine the short- and long-term risks. In addition, a more comprehensive TEDE analysis was also performed considering 20 radionuclides and ingestion pathways for five selected worst-case simulations in Akkuyu.

In simulations for the entire meteorological conditions, the risk can be analyzed by considering the critical part of the general meteorological characteristics of a region.

As different patterns are considered in this approach, the most probable cases and/or worst conditions are revealed. More real risks can be calculated as the number of years simulated increases. However, as the number of simulations increases, the need for processor and disk space capacity also increases. Moreover, since these simulations depend on meteorological datasets, lower-resolution datasets have to be preferred over high-resolution datasets providing results that are more realistic.

Preliminary meteorological analyses can be driven to determine the worst-case conditions, and the number of simulations can be reduced according to the purpose. The present study presented a practical and successful application of this approach. After analyzing the extreme periods, three complementary meteorological conditions (Heatwave, Stagnant and Wet) were defined. Although multiple factors (e.g., precipitation, transport direction, dispersion) are influential in the results, each extreme parameter may have some particular effects on some specific receptor. Due to the transport direction and drought effect, it was determined that the receptors in the South and the East were at greater risk under the Stagnant and Heatwave conditions. It was observed that extreme rainy conditions severely threaten the power plant owner in Turkey and Eastern Europe.

This study revealed that the transport direction and precipitation patterns are the most critical factors that cause the worst cases. Further, PBLH in the accident region was also a decisive parameter for the results. Under situations where PBLH was low but not below the release height, the most dangerous conditions for receptors close to the NPP were produced. On the other hand, no relationship was found between the results and the surface-level temperatures.

This study presented a comprehensive application for the first time for Akkuyu NPP. The effects of different meteorological conditions on Akkuyu NPP were investigated with approximately 300 simulations. While each condition has a different effect, the ^{137}Cs deposition and TEDE calculations showed that the worst case for highly populated areas occurred in the Wet29 scenario.

Besides the above findings, simulations for FLEXPART validation also presented valuable results. As a meteorology input, ECMWF's latest product, ERA-5, generally gave better results. Therefore, in general, ERA-5 can be preferred in atmospheric transport studies. However, because ERA-5 has temporally and spatially high resolution, it requires very high disk space than ERA-Interim. Thus, it is not easy to download ERA-5, which has been used for a long simulation period (e.g., one year). Therefore, using products with lower resolution for the entire meteorological conditions is found to be more practical.

Furthermore, this study revealed that the vertical release pattern is an essential factor. The release gives more extreme values as it gets closer to ground level. Especially in Dirac delta release, very high depositions were detected compared to all other functions. On the other hand, radioactive materials released at higher altitudes show more complex results. These types of emissions affect more areas and more distant locations. However, this effect is not as noticeable as in the Dirac delta, and the extreme value does not occur much. Especially LPTIII(2) and CDF release with very high z_{max} mostly because almost all release is over ABL, and the atmospheric transport takes place in the free troposphere.

Most results in this study revealed that transport direction is a crucial parameter for atmospheric dispersion and surface deposition. Therefore, simple trajectory estimation can be integrated into extreme case analyses. Further, all meteorological analyses in this study were carried out at ground level. Since atmospheric transport takes place in 3D space, these analyses can be applied at different levels of the atmosphere. By adding new parameters (such as humidity and cloudiness), meteorological analyses at different atmospheric levels can be a crucial further study.

Furthermore, this study applied in a coastal region. Due to the characteristics of this region, many extreme events (such as hurricanes) are not observed. For this reason, applying this study to sites situated at other locations with different topographical and climatic conditions will significantly contribute to the literature.

This study was carried out with the FLEXPART model. Each model has its pros and cons. Therefore, these studies can be replicated with other models implementing different solution approaches (e.g., Eulerian). Thus, the uncertainties caused by the models can also be resolved. Moreover, long-range models usually use meteorological data from reanalysis products, which are also model products. Therefore, in addition to model uncertainty, there is also an important meteorological input uncertainty. For this reason, these studies can be performed again with different meteorology inputs (different reanalysis products, WRF outputs, radar or satellite data) and different models.

Another crucial parameter that creates uncertainty in models is the source term. In this risk study for Akkuyu NPP, a general source term was produced by considering the reactor type (PWR) and capacity. More realistic source term analyses can be applied by producing a core inventory that considers different possibilities specific to the VVER-1200 model reactor.

Using the method developed in this study, researchers and practitioners can conduct a nuclear risk assesment in the fastest and most comprehensive way, considering the effect of all actual and extreme meteorological conditions. This methodology can serve as a decision making tool for companies that will establish nuclear facilities or governments that want to see the impact of nuclear plants located within or around their countries. With the WTEM tool developed in this study, the study region's effective circulation types and extreme meteorological periods can be determined. The RARE tool can define different accident types, vertical-temporal release patterns, and describe worst-case or more realistic conditions. The SDEP tool can calculate the radiological impact of different pathways for all radionuclides and different age groups. When combined with a simulation model such as FLEXPART this entire methodology can provide rational systematic for the analysis of environmental impacts of nuclear accidents. With a sufficient budget, this comprehensive methodology can be implemented on large temporal and spatial scales.

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APPENDICES

APPENDIX -1: Model Validation Results

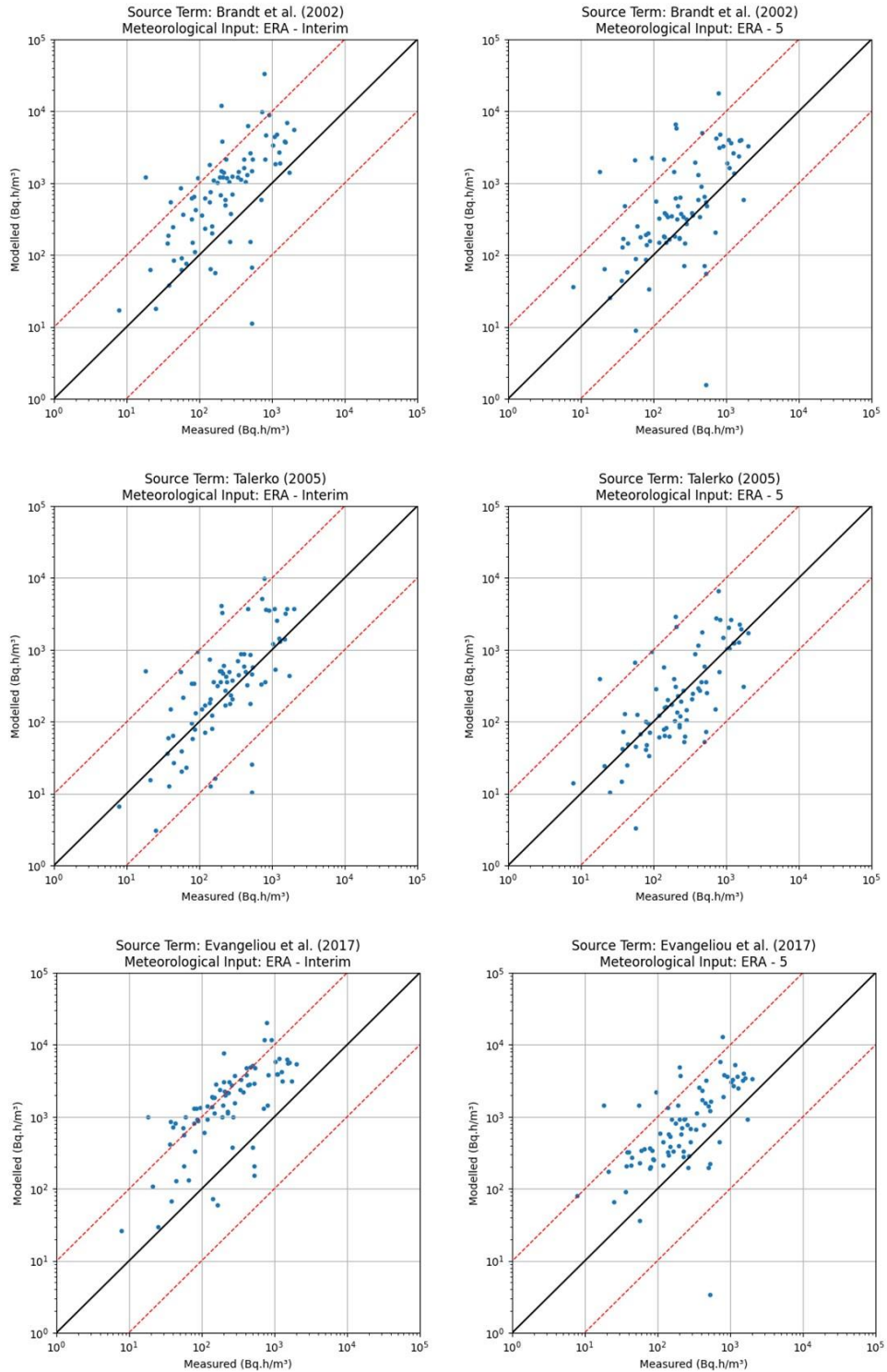


Figure A1.1 Comparison of simulations and Evangeliou et al. (2016) for time integrated air concentration of ^{131}I

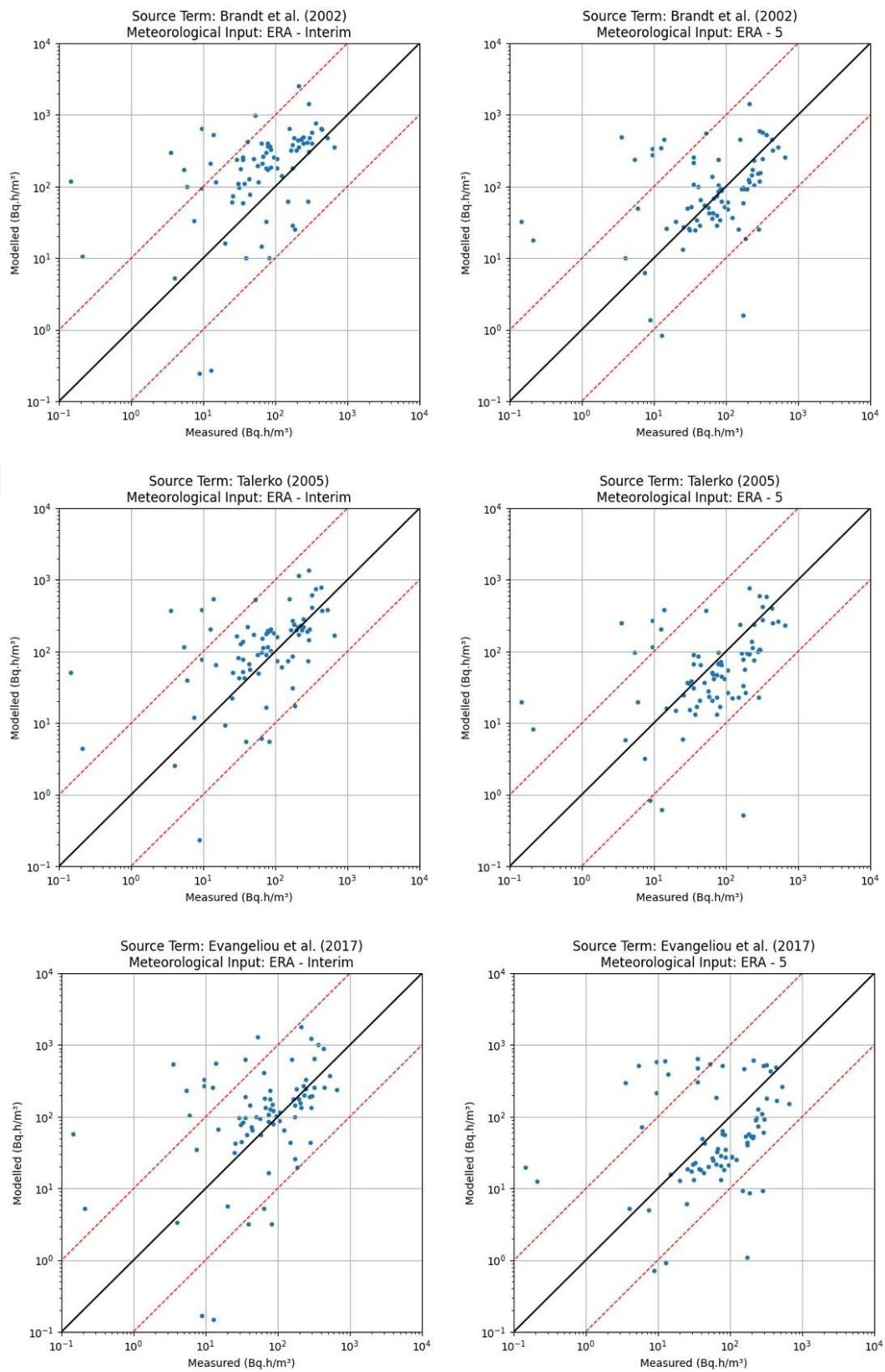


Figure A1.2 Comparison of simulations and Evangeliou et al. (2016) for time integrated air concentration of ^{137}Cs

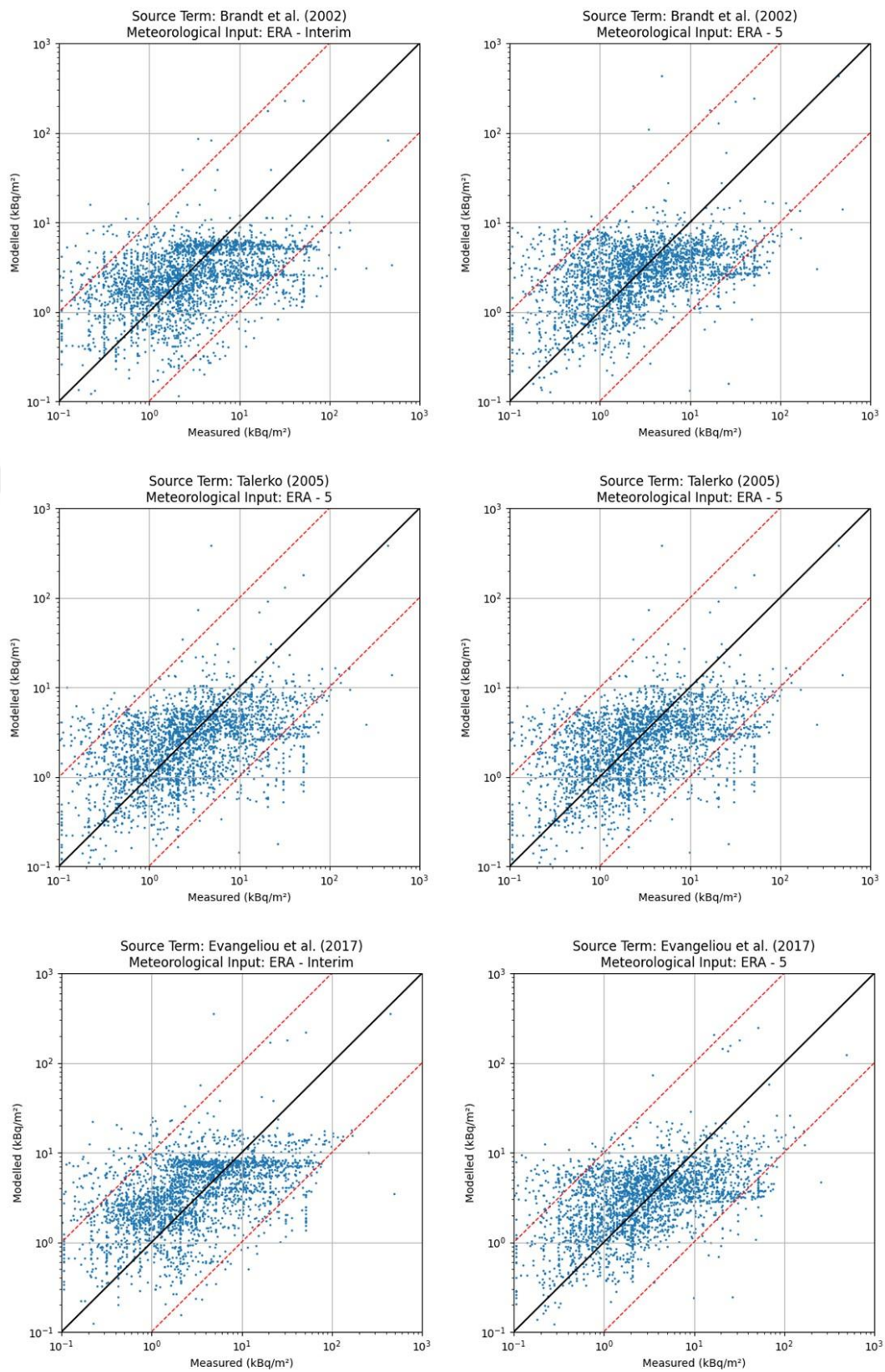


Figure A1.3 Comparison of simulations and Evangeliou et al. (2016) for surface deposition of ^{134}Cs

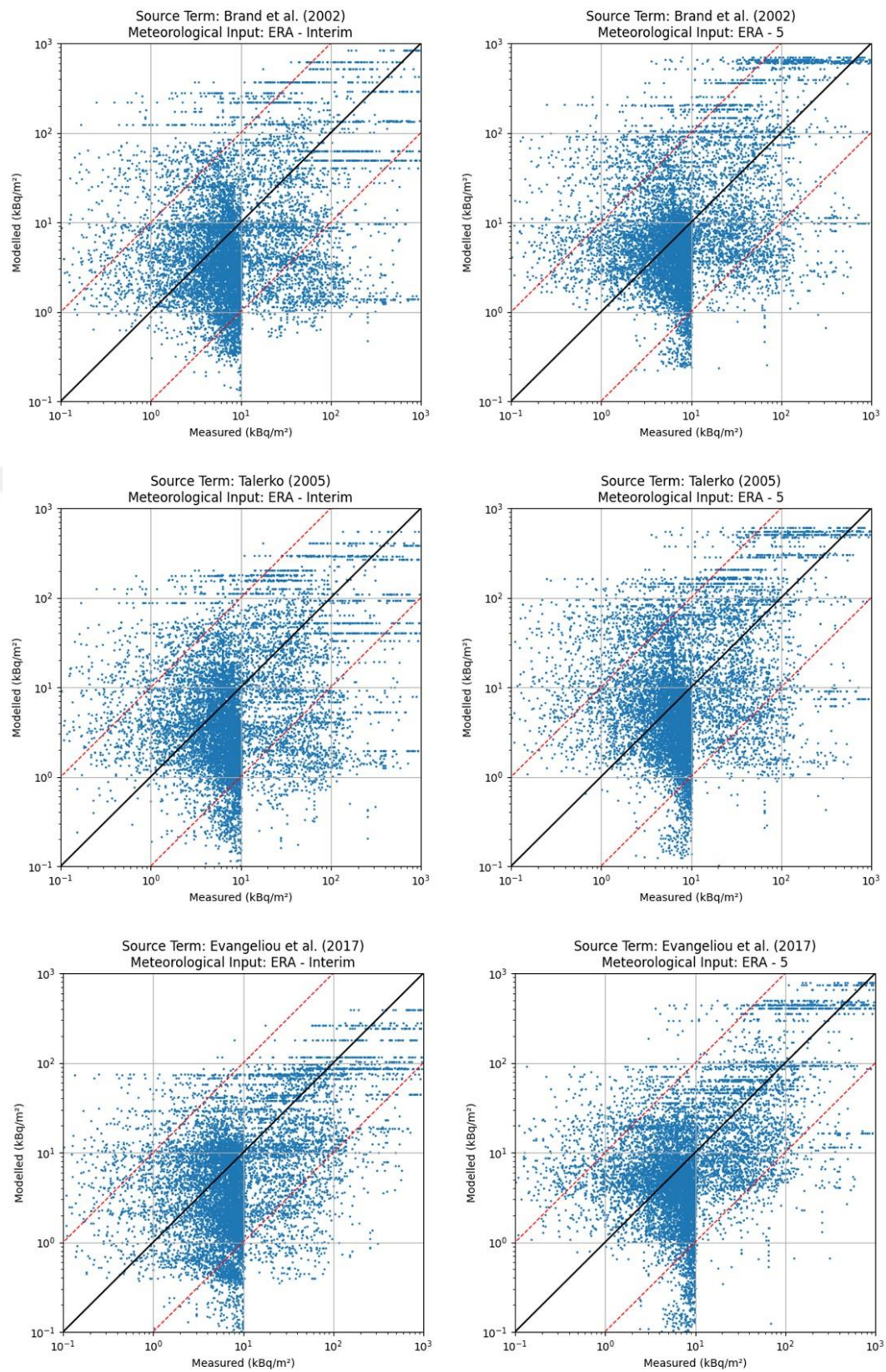


Figure A1.4 Comparison of simulations and Evangeliou et al. (2016) for surface deposition of ¹³⁷Cs

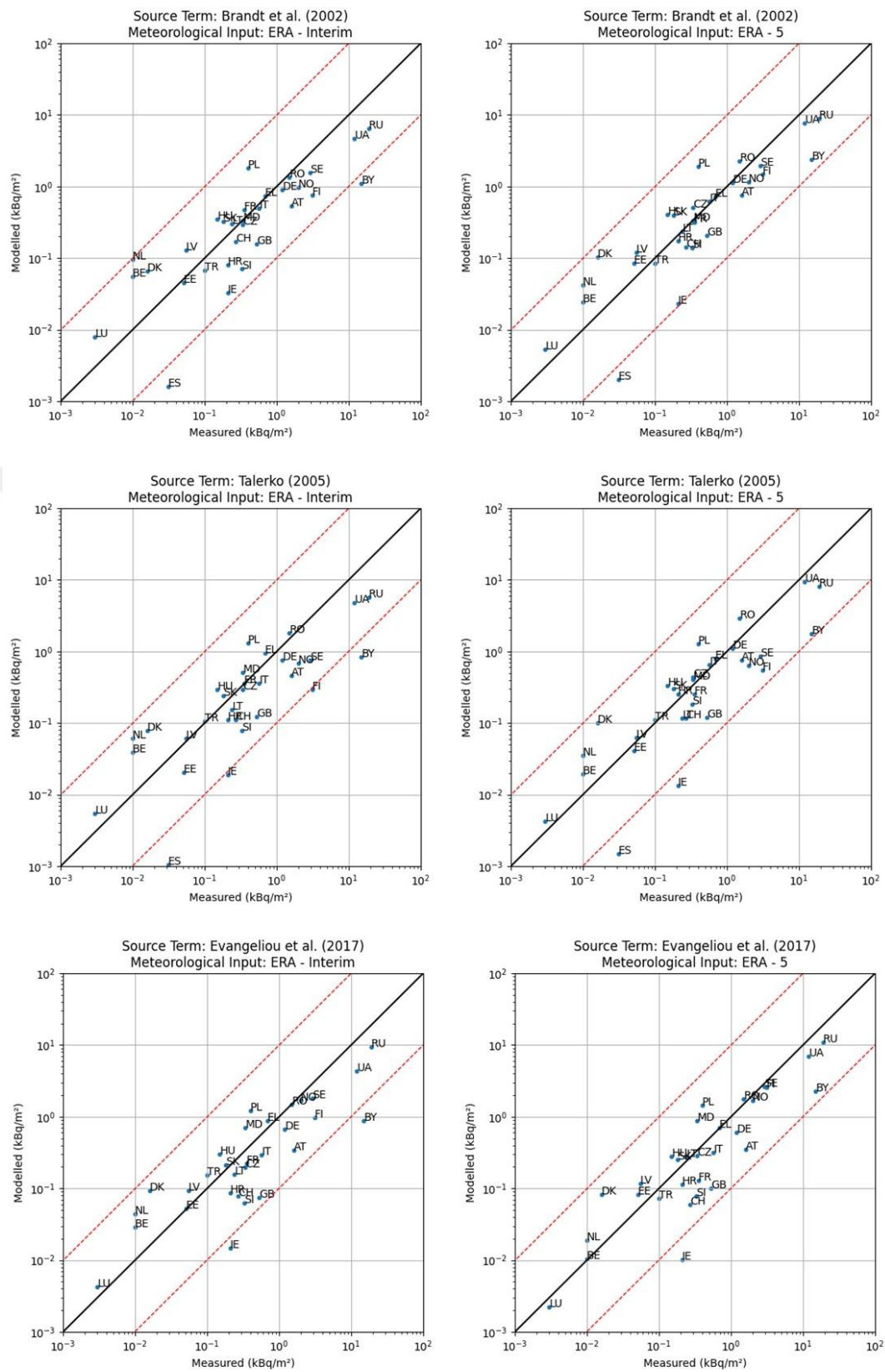


Figure A1.5 Comparison of simulations and De Cort et al. (1998) for surface deposition of ^{137}Cs

APPENDIX-2: Vertical Release Pattern Results

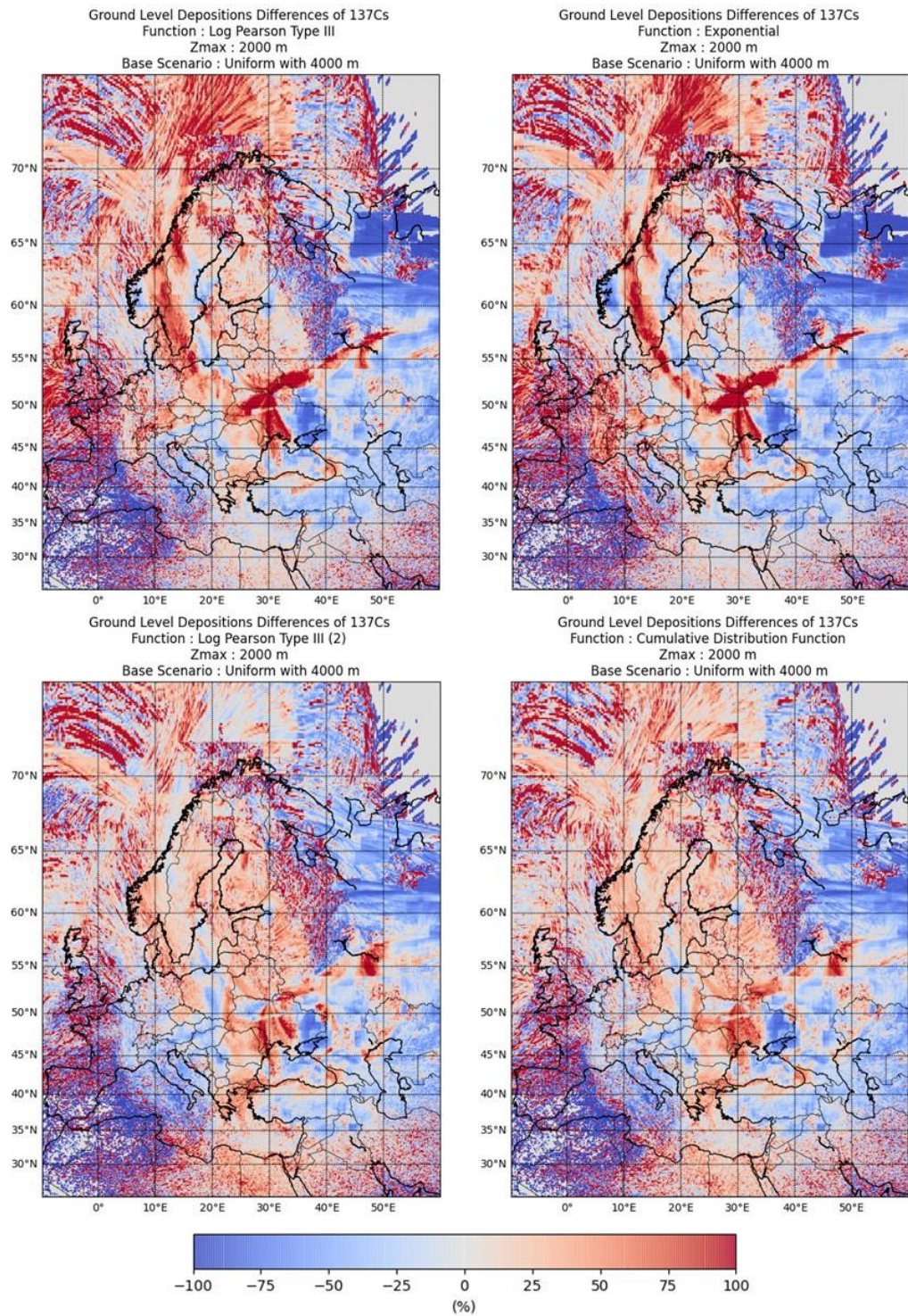


Figure A2.1 The difference plots for vertical profiles LPT III (upper-left), exponential (upper-right), LPT III (2) (lower-left) and CDF (lower-right) with 2000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

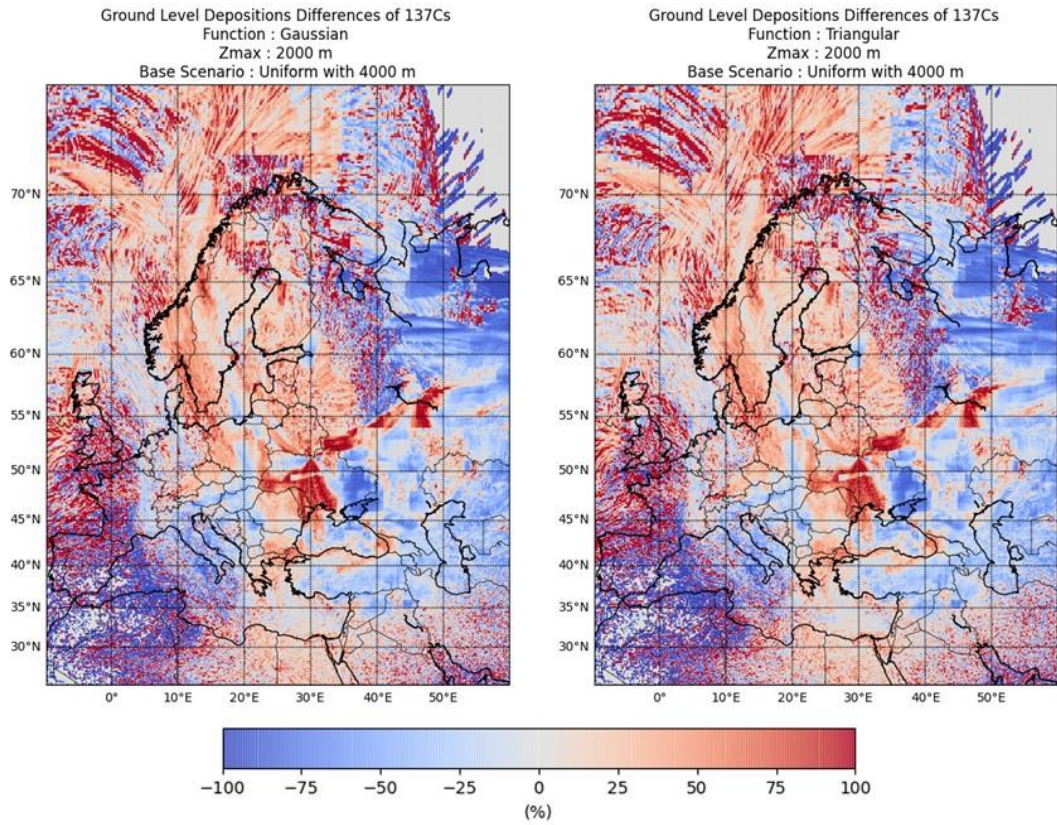


Figure A2.2 The difference plots for vertical profiles Gaussian (left) and Triangular with 2000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

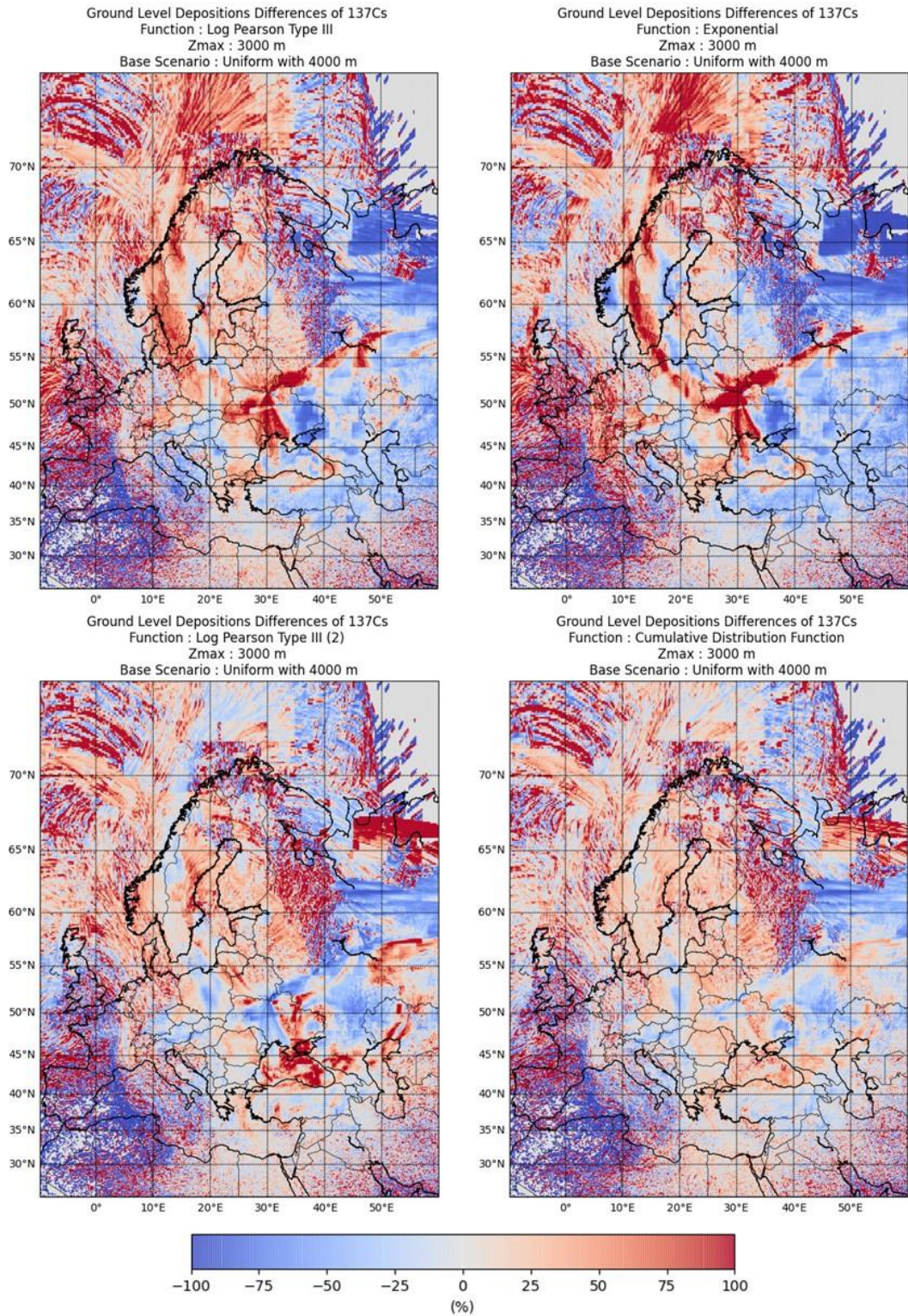


Figure A2.3 The difference plots for vertical profiles LPT III (upper-left),exponential (upper-right), LPT III (2) (lower-left) and CDF (lower-right) with 3000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

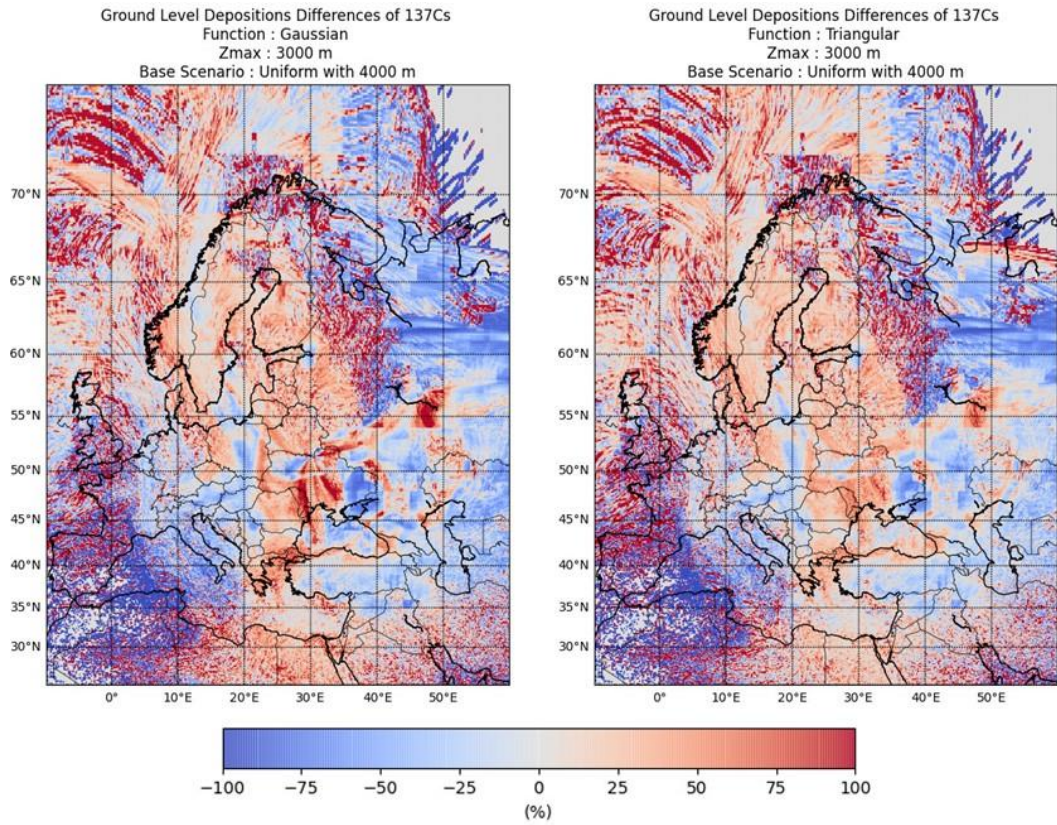


Figure A2.4 The difference plots for vertical profiles Gaussian (left) and Triangular with 3000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

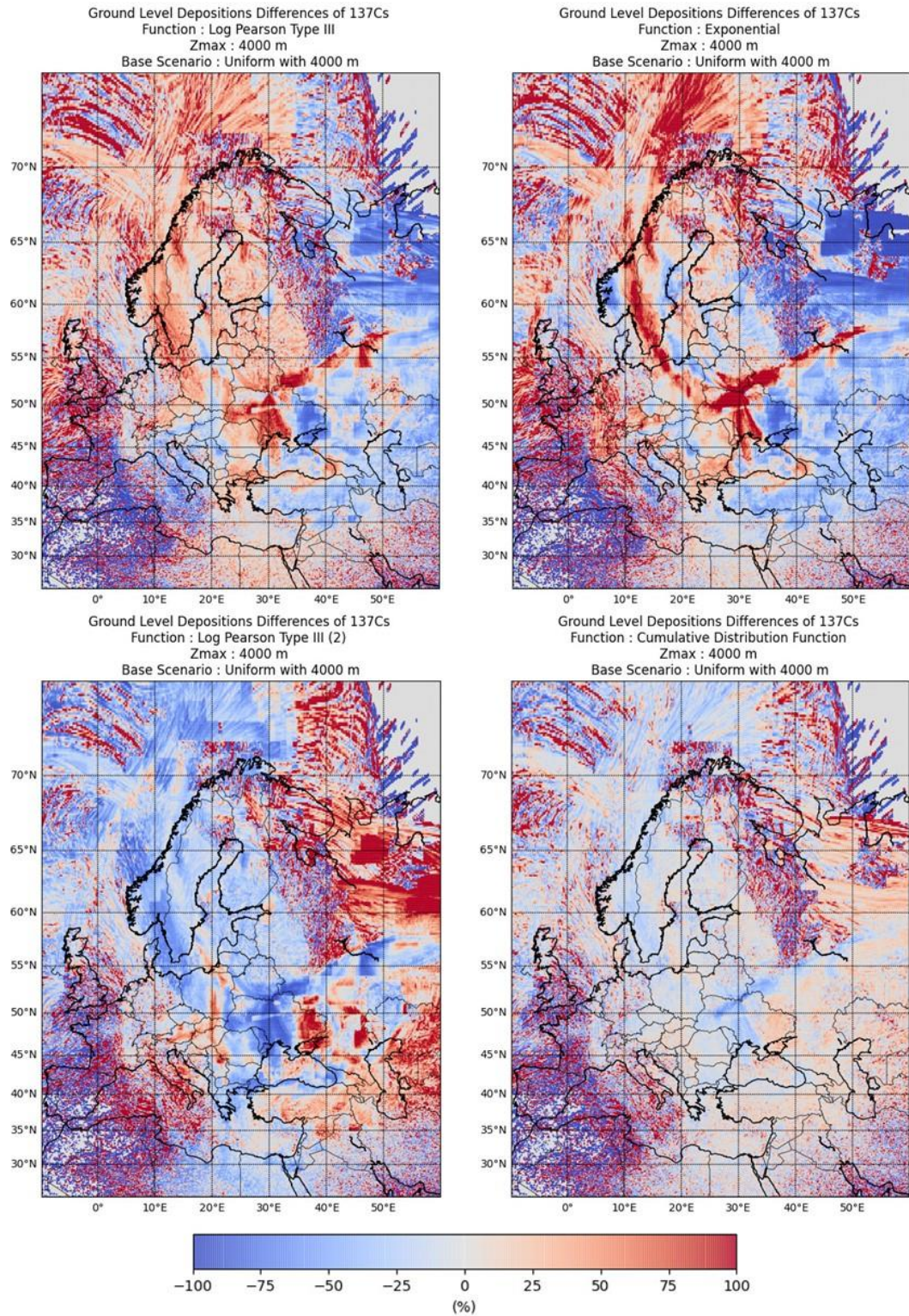


Figure A2.5 The difference plots for vertical profiles LPT III (upper-left),exponential (upper-right), LPT III (2) (lower-left) and CDF (lower-right) with 4000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

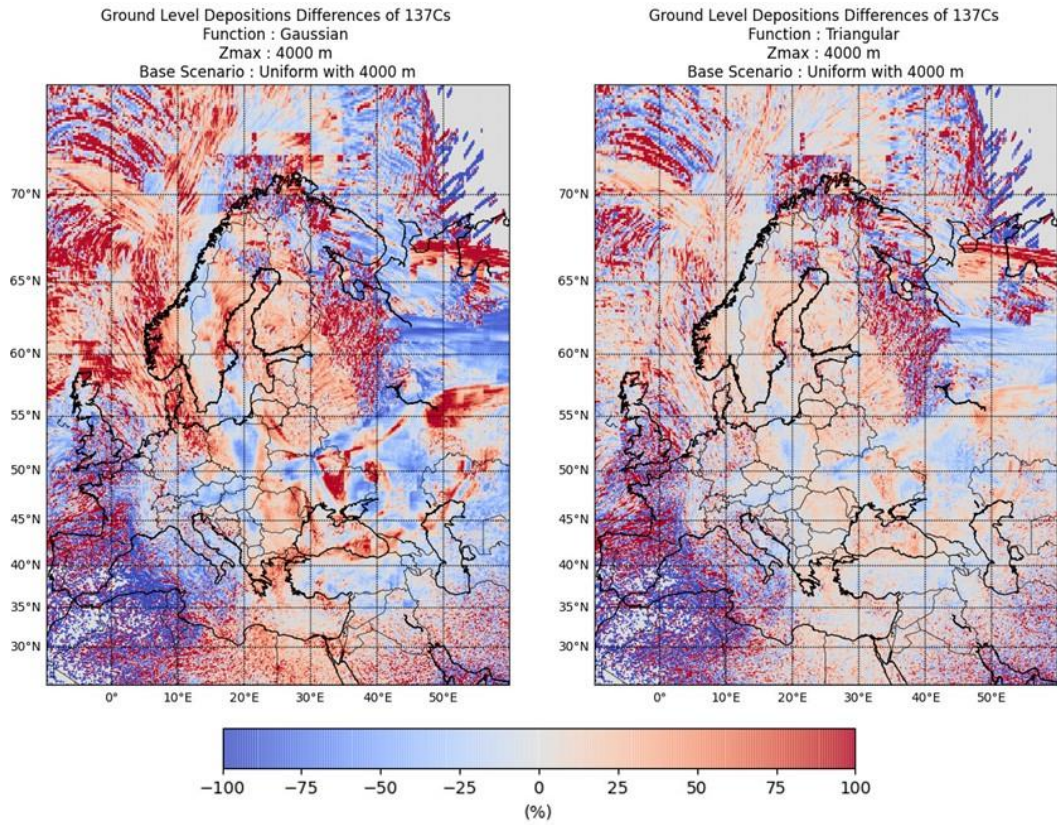


Figure A2.6 The difference plots for vertical profiles Gaussian (left) and Triangular with 4000 m of z_{max} based on May 16, 1986 Uniform results with 4000 m

APPENDIX-3: List of Simulations Performed in the Thesis

TableA3.1 List of the simulations conducted for entire meteorological conditions in 1986

#	Name	Start	End	#	Name	Start	End
1	Jan01	01/01/1986	08/01/1986	37	Jul01	30/06/1986	07/07/1986
2	Jan02	06/01/1986	13/01/1986	38	Jul02	05/07/1986	12/07/1986
3	Jan03	11/01/1986	18/01/1986	39	Jul03	10/07/1986	17/07/1986
4	Jan04	16/01/1986	23/01/1986	40	Jul04	15/07/1986	22/07/1986
5	Jan05	21/01/1986	28/01/1986	41	Jul05	20/07/1986	27/07/1986
6	Jan06	26/01/1986	02/02/1986	42	Jul06	25/07/1986	01/08/1986
7	Feb01	31/01/1986	07/02/1986	43	Aug01	30/07/1986	06/08/1986
8	Feb02	05/02/1986	12/02/1986	44	Aug02	04/08/1986	11/08/1986
9	Feb03	10/02/1986	17/02/1986	45	Aug03	09/08/1986	16/08/1986
10	Feb04	15/02/1986	22/02/1986	46	Aug04	14/08/1986	21/08/1986
11	Feb05	20/02/1986	27/02/1986	47	Aug05	19/08/1986	26/08/1986
12	Feb06	25/02/1986	04/03/1986	48	Aug06	24/08/1986	31/08/1986
13	Mar01	02/03/1986	09/03/1986	49	Sep01	29/08/1986	05/09/1986
14	Mar02	07/03/1986	14/03/1986	50	Sep02	03/09/1986	10/09/1986
15	Mar03	12/03/1986	19/03/1986	51	Sep03	08/09/1986	15/09/1986
16	Mar04	17/03/1986	24/03/1986	52	Sep04	13/09/1986	20/09/1986
17	Mar05	22/03/1986	29/03/1986	53	Sep05	18/09/1986	25/09/1986
18	Mar06	27/03/1986	03/04/1986	54	Sep06	23/09/1986	30/09/1986
19	Apr01	01/04/1986	08/04/1986	55	Oct01	28/09/1986	05/10/1986
20	Apr02	06/04/1986	13/04/1986	56	Oct02	03/10/1986	10/10/1986
21	Apr03	11/04/1986	18/04/1986	57	Oct03	08/10/1986	15/10/1986
22	Apr04	16/04/1986	23/04/1986	58	Oct04	13/10/1986	20/10/1986
23	Apr05	21/04/1986	28/04/1986	59	Oct05	18/10/1986	25/10/1986
24	Apr06	26/04/1986	03/05/1986	60	Oct06	23/10/1986	30/10/1986
25	May01	01/05/1986	08/05/1986	61	Nov01	28/10/1986	04/11/1986
26	May02	06/05/1986	13/05/1986	62	Nov02	02/11/1986	09/11/1986
27	May03	11/05/1986	18/05/1986	63	Nov03	07/11/1986	14/11/1986
28	May04	16/05/1986	23/05/1986	64	Nov04	12/11/1986	19/11/1986
29	May05	21/05/1986	28/05/1986	65	Nov05	17/11/1986	24/11/1986
30	May06	26/05/1986	02/06/1986	66	Nov06	22/11/1986	29/11/1986
31	Jun01	31/05/1986	07/06/1986	67	Dec01	27/11/1986	04/12/1986
32	Jun02	05/06/1986	12/06/1986	68	Dec02	02/12/1986	09/12/1986
33	Jun03	10/06/1986	17/06/1986	69	Dec03	07/12/1986	14/12/1986
34	Jun04	15/06/1986	22/06/1986	70	Dec04	12/12/1986	19/12/1986
35	Jun05	20/06/1986	27/06/1986	71	Dec05	17/12/1986	24/12/1986
36	Jun06	25/06/1986	02/07/1986	72	Dec06	22/12/1986	29/12/1986

TableA3.2 List of the simulations conducted for wet periods. Red lines are simulations cannot be conducted due to technical problems

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Wet001	06/01/2020	13/01/2020	22.8	7.4	4.3	381.7	HYC	S
Wet002	24/12/2019	31/12/2019	20.1	10.7	4	521.2	HYC	SW
Wet003	12/12/2019	19/12/2019	15.9	9.7	3.1	228.1	C	S
Wet004	06/02/2019	13/02/2019	20.1	9.7	4	183.1	D	S
Wet005	15/01/2019	22/01/2019	18.5	8.5	5.2	676	D	SW
Wet006	29/12/2016	05/01/2017	15.5	7.8	3.7	321	C	SW
Wet007	05/01/2015	12/01/2015	15.3	8.2	3.6	655.1	C	SW
Wet008	08/05/2014	15/05/2014	17.6	16.8	2.5	407.4	C	E
Wet009	09/03/2014	16/03/2014	13.1	13.7	2.6	199.3	C	E
Wet010	19/12/2012	26/12/2012	16.6	10.3	3.9	322	C	SW
Wet011	18/12/2012	25/12/2012	15.4	9.2	3.4	220	C	SW
Wet012	09/11/2012	16/11/2012	22.8	14.7	3.1	413.6	C	SE
Wet013	08/11/2012	15/11/2012	17.3	16.5	2.1	490.4	HYC	E
Wet014	28/02/2012	06/03/2012	15.5	7.5	3.9	743.8	C	S
Wet015	25/01/2012	01/02/2012	14.9	6.7	3.6	216.9	HYC	SW
Wet016	11/12/2010	18/12/2010	19.5	9.3	4.7	982.7	C	SW
Wet017	10/12/2010	17/12/2010	14.8	11.5	3.3	372.3	D	SW
Wet018	18/01/2010	25/01/2010	16.1	10.6	3.3	392	C	E
Wet019	11/12/2009	18/12/2009	17.4	10	3.3	293.1	C	S
Wet020	31/10/2006	07/11/2006	15	15.7	3.6	386.9	HYC	S
Wet021	22/01/2004	29/01/2004	26.3	8.3	5.6	632.4	D	SW
Wet022	17/12/2003	24/12/2003	16.9	10.9	5.2	827.7	C	W
Wet023	19/12/2002	26/12/2002	18.3	4.8	3.9	691.8	C	S
Wet024	07/12/2001	14/12/2001	16.4	8.6	3.1	329.6	C	SE
Wet025	02/12/2001	09/12/2001	22.6	10.3	4.1	402.4	C	S
Wet026	28/11/2000	05/12/2000	19.9	12.1	3.8	245.6	HYC	SW
Wet027	18/01/2000	25/01/2000	15.1	4.4	4.6	717.9	HYC	SW
Wet028	07/02/1999	14/02/1999	23	8.2	4.1	506.6	D	SW
Wet029	03/01/1996	10/01/1996	18.9	9.9	3.1	329.2	HYC	SW
Wet030	02/01/1996	09/01/1996	17.8	9.7	3	162.9	D	SW
Wet031	20/11/1995	27/11/1995	14.5	12.4	2.8	335.2	C	S
Wet032	16/12/1994	23/12/1994	18.5	7.7	3.5	244.3	C	S
Wet033	21/11/1994	28/11/1994	16.6	11.7	3.5	464.3	C	SE
Wet034	20/11/1994	27/11/1994	16.3	12.3	2.4	254	HYC	SE
Wet035	19/11/1994	26/11/1994	22.7	13.2	3	289	HYC	SW
Wet036	14/12/1992	21/12/1992	22.3	7.7	3.9	781.8	C	SW
Wet037	01/12/1992	08/12/1992	18.7	6.4	3.9	182.6	C	SE
Wet038	21/11/1992	28/11/1992	18.3	10.6	4	936	C	SW
Wet039	20/11/1992	27/11/1992	16.8	12.7	3.2	289.8	D	SW
Wet040	30/12/1991	06/01/1992	15.8	5.3	2.9	368.7	C	E

TableA3.2 List of the simulations conducted for wet periods. Red lines are simulations cannot be conducted due to technical problems (Continue)

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Wet041	26/12/1991	02/01/1992	19.2	6.7	3.4	390.9	C	SE
Wet042	07/12/1991	14/12/1991	17.3	7.5	4.7	262.8	HYC	S
Wet043	13/02/1990	20/02/1990	17.2	8	3.8	533	D	SW
Wet044	11/02/1990	18/02/1990	13	6.4	2.7	381.4	C	SW
Wet045	21/12/1987	28/12/1987	31.3	9.4	4	890.6	C	S
Wet046	04/03/1987	11/03/1987	20.1	8.8	3.6	379.4	HYC	SW
Wet047	21/12/1985	28/12/1985	18.5	4	4	146.5	HYC	S
Wet048	07/11/1985	14/11/1985	13.1	15.3	2.8	481.8	D	SW
Wet049	25/01/1984	01/02/1984	18.3	8.5	3.9	435.2	D	SW
Wet050	16/01/1983	23/01/1983	20.5	5.7	3.8	309.4	D	W
Wet051	28/01/1981	04/02/1981	15	7.3	3.3	462	C	SW
Wet052	16/01/1981	23/01/1981	13.9	6.8	3.8	199.2	D	SW
Wet053	27/03/1980	03/04/1980	28.6	13.3	4.8	370	C	S
Wet054	27/11/1979	04/12/1979	12.8	11.7	2	253.4	U	SW
Wet055	06/11/1979	13/11/1979	19.1	14.3	3.4	282.4	D	SW

TableA3.3 List of the simulations conducted for stagnant periods

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Stag001	19/12/2019	26/12/2019	0	9.1	1.2	127.2	A	SE
Stag002	18/12/2019	25/12/2019	0	8.8	1.2	176.8	A	S
Stag003	29/01/2016	05/02/2016	0.1	5.2	1.3	298.1	A	W
Stag004	20/01/2015	27/01/2015	0.1	6.9	1.1	76.6	A	S
Stag005	19/01/2015	26/01/2015	0	5.7	1.2	79.8	A	SW
Stag006	06/02/2014	13/02/2014	0	4.5	1.3	268.2	U	E
Stag007	19/12/2013	26/12/2013	0	4.1	1.2	207.6	U	E
Stag008	27/12/2012	03/01/2013	0.2	8.1	1.3	173.7	A	W
Stag009	19/11/2012	26/11/2012	0	12.1	1.3	252.6	U	E
Stag010	12/12/2011	19/12/2011	0	6.5	1.2	160	A	SE
Stag011	11/12/2011	18/12/2011	0	5.3	1.2	171.7	A	SW
Stag012	04/12/2011	11/12/2011	0	6.3	1.3	126.2	A	SW
Stag013	03/12/2011	10/12/2011	0	5.8	1.3	188.5	A	SE
Stag014	24/12/2010	31/12/2010	0	8.5	1.2	286.9	A	W
Stag015	23/12/2010	30/12/2010	0	8.8	1.2	236.6	A	E
Stag016	07/12/2010	14/12/2010	0.2	10.9	1.3	298.9	U	SE
Stag017	24/12/2009	31/12/2009	0.1	10	1.1	191.2	A	W
Stag018	23/12/2009	30/12/2009	0	9.4	1.3	142.1	A	W
Stag019	30/11/2008	07/12/2008	0.4	10.1	1.2	203.2	A	S
Stag020	24/12/2007	31/12/2007	0	4.1	1.1	253.8	U	SE
Stag021	23/12/2007	30/12/2007	0	4.2	1.2	238.8	U	E
Stag022	24/11/2007	01/12/2007	0	8.1	1.3	333.4	U	E
Stag023	18/12/2006	25/12/2006	0	7.5	1.2	133.9	U	SW
Stag024	01/12/2005	08/12/2005	0.1	11.9	1.2	186	A	SW
Stag025	18/01/2004	25/01/2004	0	5.1	1.3	253.3	A	SE
Stag026	28/11/2003	05/12/2003	0.4	10.4	1.3	153.1	U	E
Stag027	03/11/2000	10/11/2000	0.1	13.9	1.3	412.3	A	E
Stag028	02/11/2000	09/11/2000	0	13.5	1.3	458.2	U	E
Stag029	01/11/2000	08/11/2000	0.1	13.3	1.2	465.7	U	E
Stag030	27/10/2000	03/11/2000	0.2	13.4	1.2	378.6	U	SW
Stag031	31/10/1996	07/11/1996	0	12.1	1.3	278.5	A	S
Stag032	06/01/1994	13/01/1994	0	6.8	1.2	151.2	A	SW
Stag033	03/12/1993	10/12/1993	0.1	9.1	1.2	196.3	D	E
Stag034	20/01/1993	27/01/1993	0	3.9	1.3	173	U	E
Stag035	17/12/1991	24/12/1991	0	2.7	1.1	178.5	A	SE
Stag036	22/11/1991	29/11/1991	0	11.2	1.1	326.5	A	E
Stag037	21/11/1991	28/11/1991	0	11	1.1	298.2	U	E
Stag038	20/11/1991	27/11/1991	0.1	11.1	1.3	374.7	A	SE
Stag039	11/11/1991	18/11/1991	0	13.1	1.3	300.4	A	E
Stag040	06/11/1991	13/11/1991	0.1	11	1.2	350.6	U	SW

TableA3.3 List of the simulations conducted for stagnant periods (Continue)

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Stag041	05/01/1991	12/01/1991	0.1	6.6	1.3	192.8	A	W
Stag042	18/12/1990	25/12/1990	0	7.8	1.3	338.4	U	E
Stag043	22/12/1989	29/12/1989	0	7.5	1.1	175.8	A	SE
Stag044	21/12/1989	28/12/1989	0	7.8	1.2	179	U	E
Stag045	20/12/1989	27/12/1989	0.2	8.1	1.1	178	A	W
Stag046	19/12/1989	26/12/1989	0.1	8	1.2	194.6	A	SW
Stag047	05/02/1989	12/02/1989	0	3.7	1.3	237.8	U	E
Stag048	19/10/1987	26/10/1987	1.3	17	1.3	386.1	U	E
Stag049	24/11/1986	01/12/1986	0	8.1	1.3	303.6	U	SE
Stag050	23/11/1986	30/11/1986	0	8	1.3	347.1	U	SE
Stag051	13/11/1985	20/11/1985	0	13.2	1.3	375.4	A	SW
Stag052	27/12/1984	03/01/1985	0.6	5.6	1.2	225.9	U	S
Stag053	08/11/1984	15/11/1984	0.3	12.4	1.2	230.7	U	E
Stag054	20/01/1984	27/01/1984	0.1	6	1.3	302	U	SE
Stag055	18/12/1983	25/12/1983	0	4.7	1.2	356.7	U	SE
Stag056	17/12/1983	24/12/1983	0.2	5.2	1.2	498.1	U	E
Stag057	27/01/1983	03/02/1983	0	-0.3	1.3	225.2	A	E
Stag058	08/12/1982	15/12/1982	0	3.2	1.2	326.8	U	SE
Stag059	27/11/1982	04/12/1982	0.6	6.5	1.3	392.2	U	SE
Stag060	14/11/1982	21/11/1982	0	8.5	1.3	251.7	U	SW
Stag061	21/12/1979	28/12/1979	0	7.1	1.2	227.2	U	SE

TableA3.4 List of the simulations conducted for heatwave periods. Red lines are simulations cannot be conducted due to technical problems

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Heat001	05/08/2021	12/08/2021	0.1	29.8	2.4	1086	HYC	E
Heat002	04/08/2021	11/08/2021	0	30	2.4	1088.4	HYC	E
Heat003	03/08/2021	10/08/2021	0	29.7	2.4	1064.9	D	E
Heat004	02/08/2021	09/08/2021	0	28.9	2.5	1027.5	D	E
Heat005	01/08/2021	08/08/2021	0	28.8	2.7	966.9	HYC	E
Heat006	18/07/2021	25/07/2021	0	29.3	1.9	884.7	U	E
Heat007	17/07/2021	24/07/2021	0	28.7	2.1	988.5	U	E
Heat008	04/09/2020	11/09/2020	0	30.6	2.2	1296.1	U	E
Heat009	03/09/2020	10/09/2020	0	30.6	2.1	1297.3	U	E
Heat010	02/09/2020	09/09/2020	0.1	28.8	1.7	1172.6	U	E
Heat011	31/08/2020	07/09/2020	0	29	1.7	1037.5	HYC	E
Heat012	30/08/2020	06/09/2020	0	29.3	1.8	954.4	HYC	E
Heat013	30/07/2020	06/08/2020	0	29.1	2.4	788.1	D	E
Heat014	29/07/2020	05/08/2020	0	28.7	2.2	844.2	D	E
Heat015	28/07/2020	04/08/2020	0.4	28.8	2.2	1096	D	E
Heat016	27/07/2020	03/08/2020	0	29.3	1.8	1145.8	D	E
Heat017	09/08/2017	16/08/2017	0.1	29.5	2.5	723.6	D	E
Heat018	08/08/2017	15/08/2017	0	29.5	2	867.3	D	E
Heat019	26/07/2017	02/08/2017	0	29.2	2.1	785.7	U	NW
Heat020	03/07/2017	10/07/2017	0	30.6	2.1	1262	U	NE
Heat021	02/07/2017	09/07/2017	0	30.7	1.8	1545	HYC	E
Heat022	01/07/2017	08/07/2017	0	29.9	2.7	917.8	D	E
Heat023	30/06/2017	07/07/2017	0	28.9	2.7	974.5	D	E
Heat024	01/08/2016	08/08/2016	0	28.8	1.9	870.6	U	E
Heat025	23/06/2016	30/06/2016	0.1	28.9	2.3	1040.7	HYC	E
Heat026	22/06/2016	29/06/2016	0	28.8	2.3	1071.1	HYC	E
Heat027	21/06/2016	28/06/2016	0	28.7	2.5	1074.4	HYC	E
Heat028	20/06/2016	27/06/2016	0	28.7	2.4	1173	D	E
Heat029	04/08/2015	11/08/2015	0.1	29.9	1.8	1026.3	U	E
Heat030	03/08/2015	10/08/2015	0.1	30.5	1.9	542.5	HYC	E
Heat031	02/08/2015	09/08/2015	0.3	29.5	2.2	1067.7	D	E
Heat032	27/07/2012	03/08/2012	0.2	29.3	2.7	881.5	U	NE
Heat033	26/07/2012	02/08/2012	0.1	29.3	2.2	908	U	NE
Heat034	25/07/2012	01/08/2012	0.3	29	2.2	828.2	U	E
Heat035	19/07/2012	26/07/2012	0	30.2	2.2	1069.7	D	E
Heat036	18/07/2012	25/07/2012	0	29.8	2	1019.1	D	E
Heat037	17/07/2012	24/07/2012	0	29.7	2.3	865.1	D	E
Heat038	16/07/2012	23/07/2012	0	29.3	2.2	833.2	U	E
Heat039	15/07/2012	22/07/2012	0	28.9	2.6	860.8	D	E
Heat040	15/06/2012	22/06/2012	0	28.7	2.1	1389.6	D	E

TableA3.4 List of the simulations conducted for heatwave periods. Red lines are simulations cannot be conducted due to technical problems (Continue)

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Heat041	30/07/2011	06/08/2011	0	29.2	2	848.1	U	NE
Heat042	29/07/2011	05/08/2011	0	28.7	2.1	604.1	U	E
Heat043	20/08/2010	27/08/2010	0	30.6	2.1	1030.5	D	E
Heat044	19/08/2010	26/08/2010	0	29.6	1.9	876.5	D	E
Heat045	18/08/2010	25/08/2010	0.1	29	2	852.6	U	E
Heat046	17/08/2010	24/08/2010	0	29	2.3	802	U	E
Heat047	16/08/2010	23/08/2010	0	29.2	2.3	941.6	D	E
Heat048	15/08/2010	22/08/2010	0	29.2	2.3	908.3	D	E
Heat049	14/08/2010	21/08/2010	0.1	28.9	2.3	820.1	U	E
Heat050	07/08/2010	14/08/2010	0.1	29.5	2.1	1078.3	U	NE
Heat051	06/08/2010	13/08/2010	0.1	28.8	2	1042.9	U	E
Heat052	05/08/2010	12/08/2010	0.1	28.6	2.4	815.6	U	E
Heat053	04/08/2010	11/08/2010	0.2	29.1	2.3	1010.9	C	E
Heat054	03/08/2010	10/08/2010	0.1	29.9	2	1116.5	HYC	E
Heat055	02/08/2010	09/08/2010	0	31.1	2	1251.4	HYC	E
Heat056	01/08/2010	08/08/2010	0	31.6	2	1491.8	HYC	E
Heat057	31/07/2010	07/08/2010	0	31.1	2	1355.2	HYC	E
Heat058	30/07/2010	06/08/2010	0.1	29	2.2	1079.2	D	E
Heat059	27/08/2008	03/09/2008	0.2	28.9	2.2	868.7	D	E
Heat060	20/08/2008	27/08/2008	0	28.9	2.1	1300.2	D	E
Heat061	19/08/2008	26/08/2008	0	28.7	2.2	897.1	D	E
Heat062	30/07/2007	06/08/2007	0.1	30.4	2.2	1337.4	C	E
Heat063	29/07/2007	05/08/2007	0.2	30.9	2.1	1456.7	HYC	E
Heat064	28/07/2007	04/08/2007	0.1	30.3	2	1234.4	D	E
Heat065	27/07/2007	03/08/2007	0.1	30.2	2.1	1167.9	D	E
Heat066	26/07/2007	02/08/2007	0.1	30.1	2.2	1206.5	D	E
Heat067	25/07/2007	01/08/2007	0	29.6	2	998.9	U	E
Heat068	24/07/2007	31/07/2007	0	28.7	2.3	924	U	E
Heat069	27/06/2007	04/07/2007	0	28.8	2.5	961.1	U	E
Heat070	25/06/2007	02/07/2007	0	28.8	3	1309.6	D	E
Heat071	24/06/2007	01/07/2007	0	29.1	2.4	796.4	U	E
Heat072	12/08/2002	19/08/2002	0	28.9	2.1	702.7	U	E
Heat073	31/07/2002	07/08/2002	0	30.4	2.3	1230.8	U	E
Heat074	30/07/2002	06/08/2002	0.1	30.4	2.5	1379.1	U	NE
Heat075	29/07/2002	05/08/2002	0	29.8	2.5	1263.5	U	E
Heat076	18/07/2002	25/07/2002	0	29	2	996.4	U	E
Heat077	17/07/2002	24/07/2002	0	28.7	2.1	899	U	E
Heat078	11/08/2001	18/08/2001	0	29.4	2.1	805.7	C	E
Heat079	10/08/2001	17/08/2001	0.1	29.5	2.4	785.3	HYC	E
Heat080	09/08/2001	16/08/2001	0.1	28.9	2.8	843.3	D	E

TableA3.4 List of the simulations conducted for heatwave periods. Red lines are simulations cannot be conducted due to technical problems (Continue)

#	Start Date	End Date	tp (mm)	t2m (°C)	uv10 (m/s)	PBLH (m)	WT	Dir
Heat081	29/07/2001	05/08/2001	0.5	29	2.4	958.6	D	E
Heat082	28/07/2001	04/08/2001	0.2	29	2.6	977	D	E
Heat083	30/07/2000	06/08/2000	0	31.3	2	1225.1	U	NE
Heat084	29/07/2000	05/08/2000	0	30.2	1.8	1080.4	U	E
Heat085	28/07/2000	04/08/2000	0	29.2	2.1	941	U	E
Heat086	27/07/2000	03/08/2000	0	29	2.2	959.6	U	NE
Heat087	26/07/2000	02/08/2000	0	28.9	2.2	1030.4	U	E
Heat088	12/07/2000	19/07/2000	0	29.4	2.6	909.5	D	E
Heat089	10/07/2000	17/07/2000	0.1	28.8	2.4	1060.5	U	N
Heat090	09/07/2000	16/07/2000	0	29.1	2.1	1069.9	U	E
Heat091	08/07/2000	15/07/2000	0	29.3	2.2	1085.4	D	E
Heat092	07/07/2000	14/07/2000	0	30	2.4	1142.5	D	E
Heat093	06/07/2000	13/07/2000	0	29.9	2.4	1052.5	U	E
Heat094	20/08/1999	27/08/1999	0.3	29.6	2.1	658.4	U	E
Heat095	19/08/1999	26/08/1999	0	29.8	1.7	904.4	HYC	E
Heat096	09/08/1998	16/08/1998	0	30.4	1.9	1041.2	D	E
Heat097	08/08/1998	15/08/1998	0	30.2	2.8	933.8	D	E
Heat098	07/08/1998	14/08/1998	0.1	30.4	3.1	1138.3	D	E
Heat099	06/08/1998	13/08/1998	0	29.7	2.1	1032.8	HYC	E
Heat100	05/08/1998	12/08/1998	0.1	29.4	2.5	830.6	HYC	E
Heat101	04/08/1998	11/08/1998	0.3	29.3	2.7	893.8	HYC	E
Heat102	03/08/1998	10/08/1998	0.3	29.2	2.5	850.3	HYC	E
Heat103	02/08/1998	09/08/1998	0.3	28.6	2.4	773.6	D	E
Heat104	23/07/1998	30/07/1998	0.2	29.8	2.4	682.8	HYC	E
Heat105	22/07/1998	29/07/1998	0.4	29.1	2.2	912.4	HYC	E
Heat106	15/08/1994	22/08/1994	0	29.7	2.2	877.5	D	E
Heat107	08/08/1987	15/08/1987	0.3	30.1	2	760.4	U	E
Heat108	07/08/1987	14/08/1987	0	30.9	1.9	976	HYC	E
Heat109	06/08/1987	13/08/1987	0	29.7	2	1289.4	U	NE
Heat110	27/07/1987	03/08/1987	0	29.6	2.2	1030	U	E
Heat111	26/07/1987	02/08/1987	0	29.1	2.5	920.1	D	E
Heat112	14/08/1985	21/08/1985	0.1	29.6	1.9	1343.6	HYC	E
Heat113	13/08/1985	20/08/1985	0.2	29	1.8	1060	D	E

APPENDIX-4: Source Term Calculation Result

Table A4.1 The RARE tool estimations and source terms used in the model

Radionuclide	Form	Release
¹³³ Xe	Noble Gas	6202 PBq
¹³⁵ Xe	Noble Gas	1302 PBq
⁸⁷ Kr	Noble Gas	1725 PBq
⁸⁸ Kr	Noble Gas	2498 PBq
¹³¹ I	Aerosol	1189 PBq
¹³² I	Aerosol	1719 PBq
¹³³ I	Aerosol	2343 PBq
¹³⁴ I	Aerosol	2690 PBq
¹³⁵ I	Aerosol	2102 PBq
¹³⁴ Cs	Aerosol	80 PBq
¹³⁶ Cs	Aerosol	31 PBq
¹³⁷ Cs	Aerosol	49 PBq
^{131m} Te	Aerosol	25 PBq
¹³² Te	Aerosol	237 PBq
⁸⁹ Sr	Aerosol	72 PBq
⁹⁰ Sr	Aerosol	3 PBq
⁹¹ Sr	Aerosol	88 PBq

APPENDIX-5: Results of Some Simulations Conducted in the Thesis

Table 5.1 Number of simulations for defined ^{137}Cs deposition intervals at receptors in wet scenarios

Ranges (kBq/m²)	>1480	185-1480	40-185	10-40	2-10	0-2	No Deposition
Akkuyu	20	30	2	2	0	0	0
Nicosia	0	1	1	2	8	40	2
Mersin	0	3	2	9	12	27	1
Adana	0	0	3	8	7	35	1
Armutlu/Aksaray	0	4	10	11	9	20	0
Aleppo	0	0	0	2	7	42	3
Antalya	0	5	6	7	3	31	2
Beirut	0	0	0	3	14	32	5
Damascus	0	0	0	0	3	45	6
Ankara	0	3	12	10	10	18	1
Sivas	0	1	3	1	8	41	0
Amman	0	0	0	0	3	47	4
<i>Deposition Averages of top 12 Receptors around Akkuyu NPP</i>	<i>0</i>	<i>10</i>	<i>41</i>	<i>3</i>	<i>0</i>	<i>0</i>	<i>0</i>
Izmir	0	1	2	2	8	31	10
Istanbul	0	0	1	9	6	31	7
Samsun	0	1	6	7	18	22	0
Van	0	0	0	2	5	43	4
Erzurum	0	0	0	0	4	49	1
Athens	0	0	0	3	3	30	18
Baku	0	0	0	0	1	53	0
Baghdad	0	0	0	0	2	44	8
Tabriz	0	0	0	0	4	45	5

Table A5.2 Number of simulations for defined ¹³⁷Cs deposition intervals at receptors in stagnant scenarios

Ranges (kBq/m²)	>1480	185-1480	40-185	10-40	2-10	0-2	No Deposition
Akkuyu	1	18	40	2	0	0	0
Nicosia	0	0	7	21	15	17	1
Mersin	0	11	15	9	10	14	2
Adana	0	1	9	12	6	29	4
Armutlu/Aksaray	0	1	1	6	4	39	10
Aleppo	0	0	0	9	9	36	7
Antalya	0	1	10	8	8	23	11
Beirut	0	0	2	13	16	28	2
Damascus	0	0	0	1	8	49	3
Ankara	0	0	0	5	8	28	20
Sivas	0	0	2	7	12	32	8
Amman	0	0	0	4	8	45	4
<i>Deposition Averages of top 12 Receptors around Akkuyu NPP</i>	<i>0</i>	<i>1</i>	<i>16</i>	<i>29</i>	<i>15</i>	<i>0</i>	<i>0</i>
Izmir	0	0	4	5	3	25	24
Istanbul	0	0	0	2	8	25	26
Samsun	0	0	1	7	9	34	10
Van	0	0	0	4	14	34	9
Erzurum	0	0	0	5	9	40	7
Athens	0	0	1	1	2	21	36
Baku	0	0	0	0	2	49	10
Baghdad	0	0	0	2	5	42	12
Tabriz	0	0	0	2	4	42	13

Table A5.3 Number of simulations for defined ^{137}Cs deposition intervals at receptors in heatwave scenarios

Ranges (kBq/m²)	>1480	185-1480	40-185	10-40	2-10	0-2	No Deposition
Akkuyu	2	33	64	8	0	0	0
Nicosia	0	0	8	16	25	47	11
Mersin	0	4	30	41	18	10	4
Adana	0	2	25	34	28	14	4
Armutlu/Aksaray	0	0	0	0	7	68	32
Aleppo	0	0	2	40	38	26	1
Antalya	0	1	3	4	16	41	42
Beirut	0	0	0	6	40	56	5
Damascus	0	0	0	3	30	71	3
Ankara	0	0	0	0	7	56	44
Sivas	0	0	0	1	13	73	20
Amman	0	0	0	1	22	80	4
<i>Deposition Averages of top 12 Receptors around Akkuyu NPP</i>	<i>0</i>	<i>1</i>	<i>17</i>	<i>65</i>	<i>24</i>	<i>0</i>	<i>0</i>
Izmir	0	0	0	3	6	43	55
Istanbul	0	0	0	0	4	43	60
Samsun	0	0	0	5	8	63	31
Van	0	0	0	5	17	84	1
Erzurum	0	0	0	8	19	76	4
Athens	0	0	0	0	0	37	70
Baku	0	0	0	1	2	88	16
Baghdad	0	0	0	0	11	95	1
Tabriz	0	0	0	1	10	96	0