

PRECIPITATION EXTREMES AND ANTICIPATED IMPACTS ON THE BLACK
SEA COASTS

by

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B.S., Physics Education, Boğaziçi University, 2021

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Computational Science and Engineering
Boğaziçi University

2025

ACKNOWLEDGEMENTS

This thesis is not merely the product of academic effort; it is also the reflection of a journey during which I grew, questioned, struggled, but ultimately became stronger and more developed. I would like to express my heartfelt thanks to all those who stood by me, believed in me, and contributed to this process.

First and foremost, I would like to express my deepest gratitude to my advisor, Prof. Mehmet Levent Kurnaz, whose guidance illuminated my path from the very beginning to the completion of this study. His profound knowledge, unwavering support, and trust have played a decisive role not only in shaping this thesis but also in my personal growth. The perspective I have gained from him will accompany me throughout my life. I am sincerely thankful for all his encouragement and mentorship.

I am also grateful to Nazan An and Tufan Turp for both their valuable academic input and their kind emotional support, which helped me stay motivated and confident throughout this process.

Additionally, I would like to express my heartfelt gratitude to my mother, Filiz Çelik, my father, Selim Çelik, and my older sister, Başak Türkay, for their support my thesis and educational journey. Their belief in me has always been a sources of strength and encouragement in my life. I would also like to thank my sister Şevval Çelik for her direct contributions with her moral support and scientific support.

Finally, my deepest thanks go to my beloved husband, Çağrı Çelik. His enduring belief in me, his encouragement even in the most challenging moments, and his quiet yet powerful support were the invisible foundation upon which this thesis was built. Despite the all moments I occasionally neglected during our first two years of marriage, I am sincerely grateful to my husband for being by my side and supporting me.

ABSTRACT

PRECIPITATION EXTREMES AND ANTICIPATED IMPACTS ON THE BLACK SEA COASTS

Climate change has increased extreme precipitation events worldwide, leading to significant economic losses in Black Sea coastal countries (Bulgaria, Georgia, Romania, Russia, Türkiye, and Ukraine). This study investigates the relationship between the return periods of such events (2000–2024) and the resulting economic losses, while also projecting future impacts. To this end, the relationship between economic losses and precipitation return periods was analyzed using a logarithmic regression model. Extreme precipitation thresholds were defined based on the 95th and 99th percentile values. Strong and significant relationships were found for Türkiye, Bulgaria, and Romania, while analyses for Russia and Ukraine were limited due to data gaps. For future projections, extreme precipitation trends for 2030–2060 were evaluated using data from the MPI-ESM1-2-LR climate model under the SSP5-8.5 scenario (CMIP6). Based on these projections, economic loss estimates were generated for Bulgaria, Romania, and Türkiye. The study clarifies the economic impacts of extreme precipitation, aiding the estimation of future losses. The logarithmic regression model shows that even small increases in rainfall can cause significant economic consequences. These findings serve as a critical foundation for developing regional adaptation policies and strengthening disaster management strategies. Ultimately, this study elucidates the relationship between the return periods of flooding events, rainfall amounts, and economic losses, offering valuable data and recommendations for policy development in response to climate change.

ÖZET

KARADENİZ KIYILARINDA GÖZLENEN YAĞIŞ EKSTREMLERİ VE ÖNGÖRÜLEN ETKİLERİ

İklim değışikliğı, dünya genelinde aşırı yağış olaylarını artırarak Karadeniz kıyı ülkelerinde (Bulgaristan, Gürcistan, Romanya, Rusya, Türkiye ve Ukrayna) önemli ekonomik kayıplara yol açmaktadır. Bu çalışma, 2000–2024 dönemindeki bu olayların geri dönüş periyotları ile ekonomik kayıplar arasındaki ilişkiyi incelemekte ve gelecekteki etkileri öngörmektedir. Bu doğrultuda, ekonomik kayıplar ile yağışların geri dönüş periyotları arasındaki ilişki logaritmik regresyon modeliyle analiz edilmiştir. %95 ve %99'luk persentil değerleri esas alınarak ekstrem yağış eşikleri belirlenmiştir. Türkiye, Bulgaristan ve Romanya için güçlü ve anlamlı ilişkiler bulunurken, Rusya ve Ukrayna'da analizler veri eksikliği nedeniyle sınırlı kalmıştır. Gelecek projeksiyonları için, CMIP6 kapsamındaki SSP5-8.5 senaryosu altında geliştirilen MPI-ESM1-2-LR iklim modeline ait veriler kullanılarak 2030–2060 dönemi için aşırı yağış eğilimleri değerlendirilmiştir. Bu projeksiyonlara dayanarak, Bulgaristan, Romanya ve Türkiye için ekonomik kayıp öngörülleri oluşturulmuştur. Çalışma, ekstrem yağışların ekonomik etkilerini ortaya koyarak gelecekteki potansiyel kayıpların öngörülmesini kolaylaştırmaktadır. Logaritmik regresyon modeli, küçük yağış artışlarının dahi ciddi ekonomik sonuçlara yol açabileceğini göstermektedir. Sonuç olarak bu çalışma, sel olaylarının geri dönüş periyotları, yağış yoğunlukları ve ekonomik etkileri arasındaki ilişkiyi ortaya koymakta; bölgesel iklim uyum politikalarının geliştirilmesi ve afet risk yönetimi stratejilerinin güçlendirilmesi için bilimsel temelli veriler ve öneriler sunmaktadır.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
ÖZET	v
LIST OF FIGURES	ix
LIST OF TABLES	xiv
LIST OF SYMBOLS	xv
LIST OF ACRONYMS/ABBREVIATIONS	xvi
1. INTRODUCTION	1
1.1. Climate Change and Extreme Precipitation Events	1
1.2. Black Sea Region and Extreme Precipitation	3
1.3. Economic Impacts of Extreme Weather Events	8
1.4. Return Period of Extreme Precipitation and Its Effects on Economic Damage	9
2. METHOD	12
2.1. Data Sources and Preparation	12
2.1.1. EM-DAT Disaster Database	13
2.1.2. ERA5 Reanalysis Data	14
2.1.3. CMIP6 Based Climate Projections (MPI-ESM1-2-LR Model) un- der the SSP5-8.5 Scenarios	15
2.2. Preparation of Data Set	16
2.2.1. Preparation of EMDAT Data	16
2.2.2. Preparation of ERA5 Data	17
2.2.2.1. Calculation of Daily Total Precipitation	17
2.2.2.2. Visualization of Calculated Data on a Map	17
2.2.3. Preparation of CMIP6 MPI-ESM1-2 LR model Data under the SSP5-8.5 Scenario	18
2.3. Determining the Optimum Scale	19
2.4. Grid-Based Extreme Precipitation Analysis of Flood Events	19

2.4.1.	Determination of Flood Point	19
2.4.2.	Correlating Flood Events with Economic Damage Data	21
2.5.	Analysis of Reference Period Data and Determination of the Return Period of Flood Points	22
2.5.1.	Statistical Analysis	22
2.5.2.	Return Period Analysis	22
2.6.	Log-Log Regression Analysis: Relationship between Return Period and Economic Loss	26
2.7.	Future Projections	28
3.	RESULTS AND DISCUSSION	30
3.1.	Study Period (2000-2024) Precipitation Analysis and Economic Losses .	30
3.1.1.	General Assessment of Flood Events on the Black Sea Coast . .	30
3.1.2.	Flood Points Statistics	34
3.2.	Relationship between Return Period and Economic Loss	36
3.2.1.	Black Sea Coasts	36
3.2.2.	Bulgaria	38
3.2.3.	Romania	39
3.2.4.	Russia	40
3.2.5.	Türkiye	41
3.2.6.	Ukraine	42
3.3.	Anticipated Economic Impacts of Future Extreme Precipitation on the Flood Points	43
3.3.1.	Estimation of Future Extreme Precipitation Projections of Flood Points under SSP5-8.5 Scenario	43
3.3.2.	Estimation of Anticipated Economic Impacts of Future Extreme Precipitation	48
3.3.2.1.	Bulgaria	49
3.3.2.2.	Romania	52
3.3.2.3.	Türkiye	55
4.	CONCLUSION AND RECOMMENDATIONS	59
4.1.	Relationship Between Return Period and Economic Loss	60

4.2. Future Projections and Expected Economic Losses (2030–2060)	61
4.3. Recommendations	63
REFERENCE	66
APPENDIX A: ERA5 DAILY TOTAL PRECIPITATION MAPS FOR FLOOD EVENTS BY COUNTRY	76
A.1. Bulgaria	76
A.2. Romania	80
A.3. Russia	87
A.4. Türkiye	93
A.5. Ukraine	97
APPENDIX B: EXTREME PRECIPITATION THRESHOLD RESULTS . . .	99
B.1. Observed Precipitation Events (2000–2024)	99
B.2. Future Projections (2030–2060)	99

LIST OF FIGURES

Figure 2.1.	Selected flood points on the study area.	21
Figure 3.1.	Data completeness of flood events in the black sea countries (2000-2024). a) Comparison of reporting with total flood status and economic damage data, b) Damage data completion percentages by country. Source: EM-DAT, the international disaster database (2024).	31
Figure 3.2.	Monthly distribution of flood events in the study area.	32
Figure 3.3.	Countries by total economic damage (Adjusted).	32
Figure 3.4.	Top 10 flood events by economic damage.	33
Figure 3.5.	Precipitation events categorised by percentile thresholds.	35
Figure 3.6.	Black sea basin relationship between return period and economic loss.	36
Figure 3.7.	Relationship between return period and economic loss in Bulgaria.	38
Figure 3.8.	Relationship between return period and economic loss in Romania.	39
Figure 3.9.	Relationship between return period and economic loss in Russia.	40
Figure 3.10.	Relationship between return period and economic loss in Türkiye.	41
Figure 3.11.	Relationship between return period and economic loss in Ukraine.	42

Figure 3.12. Spatial distribution: intensity of extreme rainfall events (2030-2060).	44
Figure 3.13. Precipitation vs return period (2030-2060).	45
Figure 3.14. Yearly distribution of extreme precipitation events (2030-2060). . .	45
Figure 3.15. Relationship between return period and economic loss (2030–2060).	49
Figure 3.16. Precipitation vs economic loss in Bulgaria.	51
Figure 3.17. Annual economic losses from extreme events in Bulgaria (2030-2060).	52
Figure 3.18. Precipitation and economic loss in Romania.	54
Figure 3.19. Annual economic losses from extreme events in Romania (2030-2060).	54
Figure 3.20. Precipitation and economic loss in Türkiye.	57
Figure 3.21. Annual economic losses from extreme events in Türkiye.	57
Figure A.1. ERA5 daily total precipitation on 2005-07-02.	76
Figure A.2. ERA5 daily total precipitation on 2005-07-03.	77
Figure A.3. ERA5 daily total precipitation on 2005-07-04.	77
Figure A.4. ERA5 daily total precipitation on 2014-06-19.	78
Figure A.5. ERA5 daily total precipitation on 2014-09-04.	78
Figure A.6. ERA5 daily total precipitation on 2014-09-05.	79

Figure A.7. ERA5 daily total precipitation on 2014-09-06.	79
Figure A.8. ERA5 daily total precipitation on 2015-02-01.	80
Figure A.9. ERA5 daily total precipitation on 2005-07-12.	80
Figure A.10. ERA5 daily total precipitation on 2005-07-16.	81
Figure A.11. ERA5 daily total precipitation on 2005-07-17.	81
Figure A.12. ERA5 daily total precipitation on 2005-07-21.	82
Figure A.13. ERA5 daily total precipitation on 2005-07-23.	82
Figure A.14. ERA5 daily total precipitation on 2005-07-24.	83
Figure A.15. ERA5 daily total precipitation on 2010-06-21.	83
Figure A.16. ERA5 daily total precipitation on 2010-06-22.	84
Figure A.17. ERA5 daily total precipitation on 2010-06-25.	84
Figure A.18. ERA5 daily total precipitation on 2010-06-26.	85
Figure A.19. ERA5 daily total precipitation on 2010-06-28.	85
Figure A.20. ERA5 daily total precipitation on 2010-07-02.	86
Figure A.21. ERA5 daily total precipitation on 2010-07-03.	86
Figure A.22. ERA5 daily total precipitation on 2013-09-14.	87

Figure A.23. ERA5 daily total precipitation on 2002-01-21.	87
Figure A.24. ERA5 daily total precipitation on 2002-01-21.	88
Figure A.25. ERA5 daily total precipitation on 2002-08-08.	88
Figure A.26. ERA5 daily total precipitation on 2002-08-09.	89
Figure A.27. ERA5 daily total precipitation on 2002-08-08.	89
Figure A.28. ERA5 daily total precipitation on 2002-08-09.	90
Figure A.29. ERA5 daily total precipitation on 2004-08-29.	90
Figure A.30. ERA5 daily total precipitation on 2010-10-18.	91
Figure A.31. ERA5 daily total precipitation on 2011-05-25.	91
Figure A.32. ERA5 daily total precipitation on 2011-05-26.	92
Figure A.33. ERA5 daily total precipitation on 2012-07-11.	92
Figure A.34. ERA5 daily total precipitation on 2018-10-24.	93
Figure A.35. ERA5 daily total precipitation on 2000-05-27.	93
Figure A.36. ERA5 daily total precipitation on 2009-09-08.	94
Figure A.37. ERA5 daily total precipitation on 2020-08-22.	94
Figure A.38. ERA5 daily total precipitation on 2020-08-23.	95

Figure A.39. ERA5 daily total precipitation on 2021-07-21.	95
Figure A.40. ERA5 daily total precipitation on 2021-08-10.	96
Figure A.41. ERA5 daily total precipitation on 2021-08-11.	96
Figure A.42. ERA5 daily total precipitation on 2006-07-01.	97
Figure A.43. ERA5 daily total precipitation on 2013-09-14.	97
Figure A.44. ERA5 daily total precipitation on 2013-09-15.	98

LIST OF TABLES

Table 2.1.	Summary of datasets that used in the study.	12
Table 2.2.	Precipitation, return periods, and economic losses of flood points. .	24
Table 4.1.	Regression model parameters for regional extreme rainfall events. .	61
Table B.1.	Statistical distribution of extreme precipitation events (2000-2024).	99
Table B.2.	Future precipitation threshold percentiles by location and month. .	100

LIST OF SYMBOLS

E	Economic loss (USD)
R	Return period (years)
α	Intercept parameter in the log-log regression model
β	Slope coefficient representing the impact of return period on economic loss
μ	Location parameter of the GEV distribution
σ	Scale parameter of the GEV distribution
ξ	Shape parameter of the GEV distribution

LIST OF ACRONYMS/ABBREVIATIONS

CDF	Cumulative Distribution Function
CMIP6	Coupled Model Intercomparison Project Phase 6
CRED	Centre for Research on the Epidemiology of Disasters
ECMWF	European Centre for Medium-Range Weather Forecasts
EM-DAT	Emergency Events Database
ERA5	Fifth Generation ECMWF Atmospheric Reanalysis Dataset
GEV	Generalized Extreme Value Distribution
GHGs	Greenhouse Gases
IPCC	Intergovernmental Panel on Climate Change
MPI-ESM1-2-LR	Max Planck Institute Earth System Model, Low Resolution
P95	95th Percentile Threshold for Extreme Precipitation
P99	99th Percentile Threshold for Extreme Precipitation
RCP	Representative Concentration Pathway
SSP	Shared Socioeconomic Pathway
SSP5-8.5	Shared Socioeconomic Pathway 5-8.5 high Emission Scenario
UNDRR	United Nations Office for Disaster Risk Reduction
WMO	World Meteorological Organization

1. INTRODUCTION

1.1. Climate Change and Extreme Precipitation Events

Climate change is one the most crucial global challenges of our time, characterised by significant changes in weather patterns and increase in the frequency and intensity of catastrophic events. These changes are caused by the increased concentration of greenhouse gases (GHGs) in the atmosphere, resulting from human activities such as burning fossil fuels, deforestation, and industrial processes (IPCC, 2022). Extraordinary meteorological conditions are characterised by ever more frequent and severe heat waves, droughts and extreme rainfall events by climate change. These extreme weather events directly affect ecosystems, agricultural production, water resources, and human health and significantly pressure socio-economic systems. The hydrological cycle accelerates and that is directly linked to a 7% increase in atmospheric moisture-holding capacity for every 1°C temperature increase, in accordance with the Clausius-Clapeyron relationship (Algarra *et al.*, 2020; Climate Central, 2024). This situation increased the potential energy of convective systems that cause a 23% increase in monsoon precipitation in the Western Pacific during the period 2000-2024 and a trend of +0.38 mm/h in 24-h maximum precipitation in the Mediterranean Basin during the decade (Lee *et al.*, 2008; Smith *et al.*, 2012). That is why updating climate norms with changing conditions is needed that supported by evidence that historical data are not sufficient to accurately reflect future conditions, and risk-based approaches in engineering design is needed (Gibbs, 2012).

Studies have demonstrated the catastrophic effects of extreme precipitation events on existing flood control structures, indicating that many existing designs are inadequate under new climate norms (Danesh-Yazdi, 2023). Furthermore, the integration of non-structural adaptation strategies, such as early warning systems and climate-resilient infrastructure, is recognised as critical to global flood risk management efforts (Dipu and Snigdha, 2024). Therefore, a multidisciplinary approach that combines

current standards with innovative design and early warning systems is vital to increase community resilience to floods (Oernholt *et al.*, 2024; Schiano-Phan and Puchol-Salort, 2017).

Additionally, climate change is manifesting through water-related impacts, with increases in the frequency and intensity of heavy precipitation among these effects (IPCC, 2022). Therefore, the impact of climate change on extreme precipitation events has been intensely researched in recent years, and studies conducted on a global scale show that climate change significantly alters precipitation patterns and increases the frequency of extreme rainfall events (Laino and Iglesias, 2023). These events can cause floods and inundations, resulting in loss of life and property, as well as significant damage to infrastructure systems, and that is why these events stand out as one of the most evident and destructive consequences of climate change (Kostianaia and Kostianoy, 2021). The impacts of extreme precipitation events are particularly severe in developing countries. In these countries, infrastructure and adaptive capabilities may be limited, so multiple short- and long-term impacts can be seen. Infrastructure deterioration, flooding of residential areas, damage to agricultural areas, and disruption of energy systems are some of the long-term effects of these events that have economic consequences. However, the specific magnitude of these changes is uncertain and depends on factors such as climate sensitivity and emission scenarios (Monier and Gao, 2014).

Global data on flood-related losses from 1980 to 2023 demonstrates the growing economic impact of these events (Figure 2.1). Economic and insured losses from floods have shown a concerning upward trend over the past four decades, with particularly significant spikes in recent years reaching up to 100 billion US dollars in annual losses. For example, the floods that occurred in Pakistan in 2010 were the result of extreme monsoon rains, affecting approximately 20 million people and causing over 2,000 fatalities. Economic losses are estimated to be around 10 billion dollars (World Bank, 2010). Developed nations are not immune to these impacts. Similarly, the heavy rains experienced in the Balkans in 2014 led to major flooding events in Bosnia and Herze-

govina, Serbia, and Croatia; as a result of this event, more than 100,000 people were displaced, and economic losses are estimated to be around 2.5 billion EUR (European Commission, 2014). Hurricane Harvey, which occurred in Texas in 2017, also caused heavy rainfall in the Houston area; this event led to the flooding of over 100,000 homes and resulted in the deaths of more than 80 people. Economic losses are estimated to exceed 125 billion dollars (NOAA, 2018). These cases, along with the trend shown in (Figure 2.1, highlight how extreme precipitation events are becoming increasingly costly for societies worldwide, both in terms of human impact and economic losses.

With these ongoing challenges, the first six months of 2024 saw natural disasters resulting in a total loss of 120 billion USD. Significant events during this period include the floods and flash floods that occurred between May 30 and June 5 in Germany, Italy, Austria, Poland, and the Czech Republic, which caused total losses of 5 billion USD, with insured losses amounting to 2.2 billion USD. Additionally, from April 14 to April 22, flooding, flash floods, and landslides in Oman, Iran, Bahrain, Yemen, and the United Arab Emirates led to total losses of 8.3 billion USD, with insured losses recorded at 2.8 billion USD. In Brazil, flooding from April 29 to May 17 resulted in 7 billion USD in losses, with insured losses estimated at 2 billion USD. Lastly, floods in China during June and July caused losses of 5 billion USD, 0.3 billion USD in insured losses, and resulted in 71 fatalities (Munich Re, 2024).

Climate change causes extreme precipitation events to become more frequent and intense in different regions on a global scale, challenging the adaptation capacity of societies. The effects of these precipitations on cities are increasing, especially with urbanisation and population growth (Memiş and Düzgün, 2016).

1.2. Black Sea Region and Extreme Precipitation

Extreme precipitation events cause disasters such as floods and landslides, resulting in both social and economic consequences. The economic and social impacts of floods in different regions, such as Germany, China, Brazil, and Oman, clearly reveal

the global consequences of climate change. However, the regional reflections of these effects are more complex and depend on local dynamics. The Black Sea Basin stands out as a critical area where geopolitical and climatic dynamics come together. This region is a unique ecosystem with high vulnerability to climate change. Hydrological and meteorological processes in the Black Sea drainage basin increase the vulnerability of this region to climate change. In particular, the increase in sea surface temperatures and the geographical structure of the region strengthen the frequency and effects of extreme precipitation events.

The Black Sea, which has a huge drainage basin of 8.4 million km² between 42°-45° N latitude, is a unique ecosystem fed by the Danube (206 km³/year), Dnieper (52 km³/year) and Don (28 km³/year) rivers (Pokazeev *et al.*, 2021). The region shows a high level of vulnerability to the consequences of extreme precipitation events due to the influence of natural processes as well as human activities. For example, the wind curtain effect of the Caucasus Mountains (5,642 m) and the strengthening of convective storms by the Pontic Mountain Range (3,937 m) can produce extreme precipitation, such as 426 mm of precipitation in 72 hours, as in the 2021 Western Black Sea flood (Kelesoglu *et al.*, 2022). Under conditions of 85% soil moisture saturation, surface runoff increases by 3.7 times, bringing the risk of landslides to catastrophic levels (Ogura *et al.*, 2024). Additionally, the 1.2-1.8 °C increase in sea surface temperatures compared to the 1990s strengthens the frequency and impact of extreme precipitation events in the region (Öztürk *et al.*, 2011). The annual 3.8 mm rise in sea level accelerates coastal erosion, causing 15-20% yield loss in agricultural areas (Ghiardelli *et al.*, 2024; Martellozzo *et al.*, 2024).

The Black Sea Basin is a region where six countries—Türkiye, Bulgaria, Romania, Russia, Ukraine, and Georgia—share coastal boundaries. The geographical and climatic characteristics of this basin render these countries vulnerable to varying levels of climate change impacts. The geographical and climatic characteristics of the region make these countries vulnerable to different levels of climate change. In particular, in the Eastern Black Sea Basin, a 20-46% increase in 24-hour maximum precipitation is

expected by 2100 under the RCP 4.5 scenario (Aksu *et al.*, 2023). This is explained by the warming sea surface increasing lower tropospheric instability and triggering deep convection (Meredith *et al.*, 2015). In addition, the influence of Mediterranean-Black Sea cyclones and the steep mountainous structure of the region increase the combined flood risks (storm waves + heavy precipitation) by 34% (Evstigneev *et al.*, 2022).

Türkiye is located on the southern coast of the Black Sea, with a total coastline of 1,695 km, making it the country with the longest coastline in the region. This coastline extends from Artvin on the Georgian border in the east to Kırklareli on the Bulgarian border in the west, covering a total of 15 provinces. Türkiye's Black Sea coasts exhibit different morphological and climatic characteristics. The Eastern Black Sea region (Artvin, Rize, Trabzon, Giresun, Ordu) is distinguished by steep-sided mountains that run parallel to the sea and range in height from 2,000 to 3,000 meters. This region is one of the rainiest areas in Türkiye, with annual rainfall reaching levels of 2,000-2,500 mm. The climate of the region has humid subtropical characteristics, which significantly affects local ecosystems as well as agricultural activities. The Central Black Sea region (Sinop, Samsun) and the Western Black Sea region (Kırklareli to Kastamonu) have less rugged coastlines. Annual precipitation in these regions varies between 800 and 1,500 mm, and the climate characteristics are milder compared to the Eastern Black Sea. Especially in the Western Black Sea region, Zonguldak and its surroundings are affected by the oceanic climate. While temperatures in coastal provinces vary between 20-25 °C in the summer months, these values decrease to 5-10 °C in the winter months (MGM, 2023). Precipitation and temperature changes on the Black Sea coast of Türkiye significantly affect local ecosystems, agricultural activities, and urban development. While the risk of flooding increases in regions with heavy rainfall; suitable conditions for agricultural production occur in regions with less rainfall. In addition, climatic differences in coastal areas shape the living conditions and economic activities of local people.

Bulgaria is located on the western coast of the Black Sea. The country's Black Sea coastline stretches from its northern border with Romania to its southern border with

Türkiye. This geographical location makes Bulgaria an important Black Sea country in the Balkan Peninsula. Bulgaria's 378 km long Black Sea coastline covers three provinces in the east of Bulgaria: Dobrich, Varna, and Burgas. The region's transitional climate results in annual temperatures of 10–12°C and precipitation of 500–600 mm, peaking in autumn and winter. Bulgaria's proximity to the Black Sea causes humid air masses to move into the region. In addition, rising sea levels and extreme weather events such as storm waves and heavy rainfall have increased the risk of flooding in coastal cities such as Varna and Burgas. Coastal erosion threatens infrastructure and habitats along the coast (Palazov and Stanchev, 2009). Heavy rainfall causes flooding in agricultural land, reducing productivity. Especially agricultural lands in the Danube Delta region are seriously affected by heavy rainfall. It also causes significant damage to infrastructure. Roads, bridges and drainage systems are seriously affected by such events. Moreover, the fact that 35% of the population lives in areas at risk of flooding and 28% of tourism revenues depend on these areas increases economic vulnerability (Földi *et al.*, 2014).

Romania's 245 km coastline is transitional between the humid continental climate of Sulina and the humid subtropical climate of Constanta. The main causes of flooding on the Romanian Black Sea coast and inland are the hydrological cycle accelerated by climate change, sea level rise, heavy rainfall and inadequate infrastructure. In particular, compound flooding events (sea level rise + prolonged rainfall) increase flooding in coastal areas, while inland river flooding and rapid snowmelt increase the risk of flooding (Diakakis *et al.*, 2024). In 2021, compound flooding events in Romanian coastal cities caused loss of agricultural productivity, increasing the country's economic vulnerability. Inadequate drainage systems and infrastructure deficiencies further exacerbated these losses (Palazov and Stanchev, 2009). The economic impacts of flooding events amount to millions of dollars annually, with factors such as reduced agricultural production, infrastructure damage, and inundation of residential areas. This situation highlights the urgent need to develop climate change adaptation strategies in both coastal and inland Romania.

Ukraine is located on the northern coast of the Black Sea and has one of the longest coastlines in this region, with a total of 1,628 km of coastline. The coastline stretches from the Danube Delta to the Sea of Azov and includes many important port cities, most notably Odessa. The Black Sea coast of Ukraine has a humid continental and temperate climate. Although winter temperatures drop to -5°C in this region, the sea maintains a relative mildness. However, especially in recent years, extreme rainfall and flood events have been frequently observed due to the effect of climate change. On the Crimean Peninsula, precipitation decreased by 40% in 2022, causing a loss of 1.2 million tonnes in wheat production (Vykhovanetz and Oprah, 2023). This demonstrates the negative impact on the agricultural sector and economy.

Russia is located on the eastern coast of the Black Sea, with a coastline of approximately 457 km. This coastline is largely within the administrative region of Krasnodar Krai. Krasnodar Krai is Russia's main gateway to the Black Sea and hosts strategic ports and tourist cities along the coast, such as Sochi, Tuapse, and Novorossiysk. The region is located in the humid subtropical climate zone. The average annual rainfall in this region reaches 1,800 mm, while temperatures are high and humidity is high in summer. Extreme precipitation events pose major risks, especially to infrastructure, and the frequency and severity of these events are increasing with the impact of climate change. The mountainous structure of the region, extending parallel to the coast, supports the formation of orographic precipitation. These mountainous areas cause heavy precipitation to accumulate in certain river basins and increase the risk of flooding (Alexeevsky, 2016).

Georgia is located on the eastern coast of the Black Sea and is notable for its coastline of approximately 310 km. This stretches from Batumi on the Türkiye border to the Abkhazian border. The Georgian coastline around Batumi (310 km) is the wettest in Europe, with an annual rainfall of 2,700 mm, exhibiting humid subtropical climate characteristics. The mountainous terrain structure along the coastline causes orographic precipitation to occur and the amount of precipitation to increase. In 2023, the Rioni River flood inundated 17,000 hectares of hazelnut plantations (Tsitelashvili

et al., 2024; Petriashvili *et al.*, 2024). This clearly demonstrates the impacts of climate change on agricultural production and coastal ecosystems. In addition, heavy rainfall in 2022 paralysed the urban transportation network for 72 hours, while landslides in agricultural areas increased (Mastrantonas *et al.*, 2020).

Countries bordering the Black Sea are vulnerable to regional climate change at different levels, with different climate regimes and population dynamics. Climatic changes in these countries have significant impacts on various areas, such as agricultural production, infrastructure, and population displacement. Regional cooperation and adaptation strategies can play a critical role in mitigating these impacts.

1.3. Economic Impacts of Extreme Weather Events

Extreme precipitation triggered by global warming, combined with the geographical and topographic vulnerability of the Black Sea Basin, significantly affects the regional economy. Examining the economic impacts of extreme precipitation events is critical to understanding the regional impacts of climate change. Floods are one of the most devastating natural disasters classified, causing economic losses of more than US\$650 billion and 100,000 deaths between 2000 and 2019, affecting 1.6 billion people worldwide (Koç *et al.*, 2021).

Studies on the intensity of extreme precipitation events and climate change show that we are faced with more extreme precipitation events today than in the past. The 50 mm per hour rainfall capacity of the new sewer system in Samsun, which will be operational in 2024, will not be able to meet the 80 mm of precipitation predicted in 2100 projections. This inadequacy is predicted to cause an additional cost of 120 million USD per year by 2050 (Wasko *et al.*, 2023). The necessity of revising the “50-year flood” criterion in engineering standards to 15-20 year periods carries the risk of increasing the costs of dam and drainage projects in the region by 70% (Wasko *et al.*, 2023). In addition, the United Nations Office for Disaster Risk Reduction (UNDRR) loss estimation model, when applied to severe floods between 2015 and 2020, showed that

the 2020 Giresun flood event alone resulted in a loss of 94.19 million TL (approximately US\$12.81 million), emphasizing the need for improved flood risk management strategies in the region (Koç *et al.*, 2021).

The tourism sector stands out as one of the areas most rapidly affected by flood disasters. The 2023 Batumi Flood Disaster caused a 70% collapse in accommodation revenues and the bankruptcy of 17 hotels in a single season. The 45% decrease in reservations for the 2024 summer season in the Eastern Black Sea Region clearly reveals the dependence of the regional economy on tourism (Diakakis *et al.*, 2024). In addition to tourism, agriculture is also one of the most affected sectors. The effects of floods also create long-term results such as decreased productivity. Infrastructure systems are among the systems that are both most affected and need to be resolved. Because insufficient infrastructure investments can cause transportation and energy infrastructure in many regions to be vulnerable to extreme weather events, which can negatively affect economic recovery after floods (Munzhedzi *et al.*, 2024). When we look at all flood events, the low amount of insured damage also reveals the weakness of the private sector in risk management. In the coming years, economic losses due to floods are expected to reach serious dimensions, and a large portion of these losses are expected to arise from infrastructure repairs and production interruptions (Paprotny *et al.*, 2024).

1.4. Return Period of Extreme Precipitation and Its Effects on Economic Damage

With climate change, the frequency, intensity, and impacts of extreme precipitation events have increased significantly. The economic impacts of extreme precipitation events have been the focus of many studies at both global and regional levels. These studies are generally conducted through climate projections (CMIP5 and CMIP6), disaster databases (EM-DAT, NatCatSERVICE), statistical analyses, and damage functions. It is observed that as the frequency and intensity of extreme precipitation events increase, the economic losses caused by these events also increase. It is stated in the

literature that especially long return periods, which are rare but intense precipitation events, cause large economic losses (Sirisena *et al.*, 2024; Kundzewicz *et al.*, 2014). Studies on the economic impacts of extreme precipitation events show that there is a relationship between the return periods of these events and economic losses. The concept of a “100-year return period rainfall” refers to an event with a 1% probability of occurring in any given year. This concept plays a critical role in fields such as infrastructure engineering, disaster risk management, and insurance. However, due to climate change, rainfall events with a 50-year return period are now occurring every 15–20 years, necessitating a reassessment of both technical and financial planning (Wasko *et al.*, 2023). This shift poses significant threats to key sectors such as infrastructure, agriculture, and tourism, particularly in vulnerable regions like the Black Sea Basin.

Walter (2007) emphasised that the traditional concepts of return period and return level should be reinterpreted under changing climate conditions. In his study, he suggested that these concepts are quite variable in the context of climate change and proposed two possible extension approaches: one based on the expected frequency of events and the other based on the expected waiting time until the next event. These approaches provide an important theoretical framework for the assessment of the economic impacts of extreme events. Walter’s work is important in terms of proposing new methodological approaches for risk assessment and economic loss modeling, especially in non-stationary climate conditions (Walter, 2007).

Lap *et al.* (2023) analysed economic losses from floods in the Ngan Sau River Basin in Vietnam under different climate change scenarios. The findings provide an important example for understanding how economic losses can be associated with changing return periods by projecting the effects of future precipitation changes on flood events.

Jongman *et al.* (2018) analysed the probabilistic trends of flood risk in river basins in Europe using CMIP5 projections and compared the economic impacts of floods with

different return periods. The study indicated that floods with shorter return periods cause disproportionate economic losses. Similarly, a study conducted by Deng and Zhu (2021) in China analysed the relationship between the return periods of extreme precipitation and precipitation durations with GEV distribution and L-moment algorithms. The study estimated the changes in future extreme precipitation under RCP2.6 and RCP8.5 scenarios, revealing that more intense precipitation is expected in the RCP8.5 scenario. Miller *et al.* (2025) examined the effects of downscaling methods on economic damage estimates in the projection data used in these analyses and emphasised the critical role of high-resolution projections in economic analyses.

In the literature review, it was determined that studies integrating economic loss data from global disaster databases such as EM-DAT with high-resolution climate data such as ERA5 are quite limited. This deficiency creates a significant gap that prevents a comprehensive understanding of the past and future economic impacts of flood events in countries bordering the Black Sea, such as Türkiye, Ukraine, Russia, Georgia, Romania, and Bulgaria.

In this context, the main purpose of this thesis is to examine the relationship between return periods of extreme precipitation events and economic impacts within the framework of climate change by focusing on coastal cities and regions in countries bordering the Black Sea and to provide scientific outputs. The findings to be obtained will make significant contributions to the development of more effective and sustainable strategies, especially in disaster risk management, infrastructure planning, and the insurance sector.

2. METHOD

In this section, the methodological approach used to analyse the relationship between extreme precipitation events and economic losses in the Black Sea basin is explained in detail. The study consists of a series of systematic steps: identification of data sources, preparation of data sets, application of analytical methods, and development of future projections.

2.1. Data Sources and Preparation

Three basic datasets covering different periods (1971-2000, 2000-2024, 2030-2060) were used to analyse the economic impacts of extreme precipitation events and model possible future impacts. These datasets were selected and processed in line with the scope and objectives of the study. Table 2.1 summarises the sources, time intervals and intended uses of the datasets used in the study. The obtained data formed the basis for analysing the past and future impacts of extreme precipitation events and estimating economic losses.

Table 2.1. Summary of datasets that used in the study.

Data Set	Data Source	Time Period(s)	Purpose of Use
Emergency Events Database (EMDAT)	Centre for Research on the Epidemiology of Disasters (CRED)	2000-2024 (Study Period)	Analysing economic losses from extreme precipitation.
ERA5 Reanalysis Data	ECMWF (European Centre for Medium-Range Weather Forecasts)	1971-2000 (Reference Period) 2000-2024 (Study Period)	Analysing daily total precipitation and calculating the return period.
CMIP6 – MPI-ESM1-2-LR	Max Planck Institute for Meteorology (MPI-M)	2030-2060 (Future Period)	Analysis of future extreme rainfall events and estimation of economic losses under the SSP5-8.5 scenario.

2.1.1. EM-DAT Disaster Database

EM-DAT is an international database that provides comprehensive data on natural and technological disasters and their socio-economic impacts. It presents data for each country with standard parameters for each event. The database evaluates events that include at least 10 deaths, more than 100 affected people, a declaration of a state of emergency, or an international call for assistance as a disaster (EM-DAT, 2025). It provides information not only on floods but also on other types of disasters. It presents data for each country with standard parameters for each event. Parameters such as the number of deaths, affected people, and economic damages provide the data necessary to analyse the severity and impact of these events. These criteria provide critical information about the geographical extent and temporal distribution of flood events, as well as their impacts in a numerically comparable way (Delforge *et al.*, 2025).

The EMDAT database is a widely used data source for analysing the effects of flood events. Thanks to the economic data it provides, EM-DAT is used in the evaluation of the economic effects of flood events on a global scale and in the estimation modeling of flood-related losses (Taguchi *et al.*, 2022). However, the fact that only 20% of the data it provides includes economic damage information and the failure to meet the EMDAT criteria for the evaluation of regional extreme events is an important factor that limits the scope of economic analyses (Kron *et al.*, 2012). Even if the criteria are met, the data may be insufficient for sectoral or regional analyses since it is at the country level (Guha-Sapir, *et al.*, 2015). Since the data in the database is reported at the country level, it is insufficient for those who want to make more detailed regional or sectoral analyses (Gall *et al.*, 2008). EM-DAT is a useful tool used to understand general trends in economic impact analyses. However, when evaluating the results, the limitations and deficiencies of the EMDAT database are considered.

2.1.2. ERA5 Reanalysis Data

In this study, the fifth generation of European Centre of Medium-range Weather Forecasts (ECMWF) Reanalysis (ERA5) dataset which is provided by the Copernicus Climate Change Service (C3S) is used. The ERA5 dataset provides detailed data of Earth's climate and weather trends from 1950 to now. It is a global product with a spatial resolution of $0.25^\circ \times 0.25^\circ$. It supplies high-resolution data that is extensively utilised in different areas such as meteorology, climate studies, and renewable energy simulation (Hersbach *et al.*, 2020). ERA5 are widely used in climate research for flood risk evaluation and climatological reference though their limitations in capturing local extremes (Glawion, *et al.*, 2024). In the study, the ERA5 dataset was used as the main input for both the flood events analysis study period and the reference period.

The years between 2000 and 2024 were determined as the analysis period for flood events. Daily precipitation data were extracted from the ERA5 data set for the date range of flood events recorded in the EM-DAT database and analysed.

The reference period of 1971-2000 was used as the basic data source in determining historical climatic norms. The selection of 30-year time periods, as suggested by WMO, minimises the impact of short-term fluctuations while also allowing trends to be identified. The selected period provides information about the general state of the climate and provides a basis for understanding changes that have occurred or will occur (Arguez and Vose 2011). In this period, ERA5 data were the main inputs for the calculation of return periods for the selected grids. In addition, daily total precipitation data (monthly specific) were analysed, and 95th and 99th percentile threshold values for extreme precipitation events were calculated. These studies contributed to the establishment of a 30-year climatological basis.

2.1.3. CMIP6 Based Climate Projections (MPI-ESM1-2-LR Model) under the SSP5-8.5 Scenarios

CMIP6 climate projections are built around five core Shared Socioeconomic Pathways (SSPs): SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These scenarios represent different trajectories of greenhouse gas emissions and global development patterns. For example, SSP1-2.6 describes a world with strong climate policies and sustainable development, aiming to limit global warming to below 2°C. SSP2-4.5 reflects a “middle-of-the-road” pathway, where current trends continue without drastic changes. SSP3-7.0 assumes a fragmented world with regional rivalries and weak climate action. Compared to these, SSP5-8.5 represents the most extreme case with very high emissions. It was chosen in this study to evaluate the upper bounds of potential climate impacts and to better understand the consequences of inaction in mitigation strategies.

In this study, precipitation projections of the Max Planck Institute Earth System Model (MPI-ESM1-2-LR), which is a global climate model developed by the Max Planck Institute for Meteorology under the SSP5-8.5 (Shared Socioeconomic Pathway 5-8.5) scenario (Mauritsen *et al.*, 2019), were used. SSP5-8.5 is a scenario characterised by high greenhouse gas emissions on a global scale, in which efforts to prevent the climate crisis are insufficient, and the economy continues to grow with fossil fuels (Riahi *et al.*, 2017). This scenario envisages a future in which carbon dioxide (CO_2) concentrations in the atmosphere are constantly increasing. As a result, it is predicted that global temperatures may increase by at least 4°C by 2100. SSP5-8.5 is considered a pessimistic scenario because it is a scenario focused on economic growth and lacks environmental awareness (Riahi *et al.*, 2017).

In the scope of the study, the horizontal resolution of the previously used ERA5 data was approximately 31 km, while the horizontal resolution of the MPI-ESM1-2-Lr model used was approximately 200 km. To avoid inconsistencies caused by these differences, the resolution of the model data was rescaled to the high-resolution dataset

of ERA5. The rescaling process can be performed by various methods and this process is of critical importance in the analysis phase (Miller *et al.*, 2025). In this way, the analyses became more meaningful at the local level and were modelled more accurately.

2.2. Preparation of Data Set

2.2.1. Preparation of EMDAT Data

The study covers disaster events for the period of 2000-2024. Therefore, events occurring in this time range were filtered. Since the focus of the study is on the Black Sea coast countries, events belonging to Türkiye, Bulgaria, Ukraine, Russia, Romania, and Georgia were selected. However, flood events affecting cities and regions located on the Black Sea coast in these countries were included in the study.

In the EM-DAT database, these countries were selected using geographic filtering, and then events involving coastal cities and regions were manually checked. The provinces of Istanbul, Sakarya, Ordu, Giresun, and Artvin from Türkiye; the provinces of Dobric, Varna, and Burgas from Bulgaria; the provinces of Tulcea and Constanta from Romania; the regions of Odessa, Mykolaiv, Kherson, Zaporizhia, and Donetsk from Ukraine were selected. The Krasnodar Kray region from the Russian Federation was included in the scope of the research. Only flood events were considered. Other disaster types (e.g. earthquake, drought) were excluded from the scope of the study. The other important filtration criteria is that events with net economic damage data in USD are only included. This allowed for the analysis of economic impacts. After this data was filtered, the results were downloaded in Excel format. The downloaded data includes basic variables such as the date of the disaster, location, type of disaster, amount of economic damage (USD), and loss of life.

2.2.2. Preparation of ERA5 Data

The ERA5 reanalysis data set is provided on a grid system with $0.25^\circ \times 0.25^\circ$ resolution, including the total precipitation (tp) variable. For each disaster event selected to cover the Black Sea coastline, the date(s) have been identified by using EMDAT data. ERA5 data has been focused on this period. In order to focus on the regions affected by the event, appropriate latitude-longitude ranges were selected via Google Earth.

2.2.2.1. Calculation of Daily Total Precipitation. Within the scope of the study, considering the selected geographic region and the date range, hourly rainfall data for each day were combined, and daily total rainfall amounts were obtained. During the calculations, ERA5 data, provided in meters (m) for rainfall units, were converted to millimeters (mm). Missing data checks were performed during the analysis. Calculating daily total rainfall values was the first step in assessing the spatial distribution of flood events.

For each flood point, hourly total precipitation values were summed and converted into daily total precipitation by using the following equation:

$$daily_{precip} = daily_{data}[tp'].sum(dim = 'valid_{time}') * 1000$$

2.2.2.2. Visualization of Calculated Data on a Map. The daily total precipitation was visualised on a separate map for each selected day to easily see the flood region. During this process, the maps were created using the Cartopy library and focused on the flood areas on the Black Sea coast. Geographic features such as coastlines, borders, land, and sea areas were added to the maps. Daily total precipitation values were visualised using a colour scale (cmap = 'Blues') on the grid points. This colour scale allowed visually distinguishing precipitation amounts from low to high. Precipitation values in each grid point were also shown numerically on the map. The maps created for each

day were saved in PNG format at high resolution. Total precipitation data calculated for each day were exported in table format as well as maps. For all flood points, maps have been presented in Appendix A.

2.2.3. Preparation of CMIP6 MPI-ESM1-2 LR model Data under the SSP5-8.5 Scenario

In this study, the Max Planck Institute Earth System Model (MPI-ESM1-2-LR) data was adapted to the grid system of ERA5 reanalysis data. To compare MPI-ESM's projections with ERA5's historical data, temporal and spatial scale compatibility is required (Yamagami *et al.*, 2017). During this process, the bilinear interpolation method was used, and as a result, ERA5 and MPI-ESM data sets were provided to be in the same unit and grid system. This process was performed using the Climate Data Operators (CDO) program. Regridding function is implemented using the -remapbil function of the CDO software. This interpolation is done by calculating the value at each new grid point with a weighted average from the four nearest neighbors. This method is widely used in climate data (Hofstra *et al.*, 2008). After the interpolation process was completed, the precipitation unit ($kgm^{-2}s^{-1}$) of MPI-ESM model data was converted to mm/day. As a result of these transformations, the model data became comparable to the ERA5 datasets.

Interpolation allowed for more accurate modelling of climate variables at local scales in the analysis of economic impacts of extreme precipitation. This process is a critical step for estimating economic losses and for more detailed analysis of the impacts of climate change (Miller *et al.*, 2025). However, as with all interpolation methods, linear interpolation has its limitations in this context. These should be taken into consideration when evaluating the results.

2.3. Determining the Optimum Scale

In the first phase of the study, resolution analysis was performed on the 5 flood events that had the greatest impact in terms of economic damage. In this analysis, it was attempted to determine at which resolution the flood events could be observed more clearly, in which region the maximum precipitation fell, and the size of this region.

For this purpose, the grid point with the maximum daily total precipitation amount for each event was determined. These coordinates were used as a flood point in the analyses. Grid clusters of 3x3 and 5x5 sizes were created around the maximum grid, respectively. Daily total precipitation amounts were collected for all cells in the 3x3 and 5x5 grid clusters, and their averages were calculated. The ratio of the precipitation amount in the maximum grid, which is determined as the flood point, to the average precipitation amount of the surrounding grid clusters was compared. If the average precipitation in the environmental grid clusters is equal to 95% or more of the maximum precipitation in the flood point, then it is accepted that the flood occurred in a larger area than the flood point, so in the grid cluster. However, as a result of the analyses, it was observed that the precipitation in the maximum grid was higher in all events compared to the environmental grid clusters. In none of the 3x3 and 5x5 grid clusters did the precipitation amount reach 95% of the maximum grid. Therefore, the $0.25^\circ \times 0.25^\circ$ resolution of ERA5 data continued to be used in the analyses. To show this result, Figure 2.1 can be an example that the grid point has a maximum daily total precipitation amount that explains more the flood area than the larger area.

2.4. Grid-Based Extreme Precipitation Analysis of Flood Events

2.4.1. Determination of Flood Point

The grid points with the maximum daily total precipitation value were defined as the flood point by examining the ERA5 Daily Total Precipitation maps. If extreme precipitation values are observed in two different grid points determined on the map,

the daily precipitation amounts in both grids are examined separately, and these values are evaluated as the amount of precipitation that causes the flood event. This approach is especially important for analysing spatial differences in flood events that spread over large areas or affect more than one region since there is only a single economic damage amount for such events in the EM-DAT database. Some special cases have been taken into account in the economic damage analysis.

- (i) Data on Flood Disaster Containing Single-Day and Single-Region If EM-DAT data covers only a single day or a region, the economic damage is directly related to the grid point with maximum precipitation on that day. In this case, the grid with maximum precipitation is determined, and the economic damage is associated with this grid.
- (ii) Data on Flood Disasters that Last More Than One Day and Cover More Than One Region The regions affected by the flood event specified in the EM-DAT database were determined using Google Earth, and these regions were delimited by the ERA5 grid system. Thus, it was clarified which regions the grid points used in the study represented. Depending on time, the daily total rainfall amounts for each grid point in the affected regions were visualized on maps. These maps determined the grid points that received rainfall that could cause flooding. Grid points with extreme rainfall values that could cause flooding were determined by examining the daily rainfall amounts. These grid points were used as the basis for distributing economic damage. The total rainfall in each grid point was used as a weighting factor in distributing the economic damage. For example, if the total rainfall in a grid point was higher than in other cells, more economic damage was assigned to that cell.

Figure 2.1 shows the grid points analysed in the study area and the areas defined as flood points. The red dots on the map represent the flood points used in the study and where the effects of extreme rainfall events were evaluated.

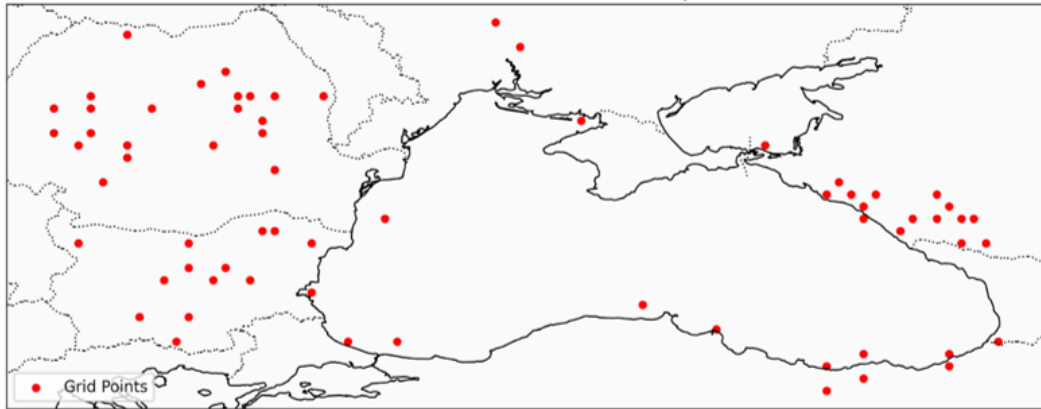


Figure 2.1. Selected flood points on the study area.

2.4.2. Correlating Flood Events with Economic Damage Data

For each flood event, the daily total rainfall amounts on the date(s) of the event were visualized on a grid basis. These visualizations also allowed us to see the spatial distribution of precipitation in the region where the flood occurred. After the determination of flood point(s) that were considered a critical area that could lead to flooding, economic damage data from the EM-DAT database due to flood events on those dates were associated with the amount of precipitation.

In this step, it is aimed to understand the spatial distribution of economic losses by correlating them with rainfall amounts and distributing them to flood areas. It is based on the regional distribution of economic damage based on the amount of precipitation on the date of the flood.

The dates of flood events and the affected regions obtained from the EM-DAT database are combined with the daily precipitation data obtained from the ERA5 reanalysis data. This step provides a clearer regional understanding of the economic growth created by rainfall amounts.

2.5. Analysis of Reference Period Data and Determination of the Return Period of Flood Points

2.5.1. Statistical Analysis

The mean, 95th, and 99th percentile values of daily precipitation were calculated for each grid point, and these statistical characteristics have been saved. These calculations were performed by using ERA5 reanalysis data for the reference period (1971–2000) and filtering the month data in which the flood occurred.

With this method, climatological values, thresholds, and extreme values for the selected grids are determined regionally. This approach is frequently used in the literature. It provides compatibility and is consistent with the standard extreme precipitation approaches in the literature. This analysis enables us to identify whether precipitation events associated with floods can be evaluated as extreme. We can assess the rarity and intensity of such events by comparing observed precipitation values during flood events with the calculated percentiles. The 95th percentile values were also used as threshold values to filter data in future model projections. Results for all grid points have been presented in Attachment A.

2.5.2. Return Period Analysis

The return periods of the determined precipitation amounts were calculated in line with the scope of the study. The aim here is to establish the relationship between the determined return periods and economic losses. The return period is a statistical concept that expresses the average number of years in which an event of a certain magnitude (for example, heavy rainfall, flood, storm, or earthquake) occurs. In other words, return periods indicate how rare or extreme a rainfall event is. For example, a flood event with a 50-year return period is expected to occur once every 50 years. However, this does not mean that the flood will occur only once in 50 years; it can occur more than once in a 50-year period. Determination of return period is important

in terms of long-term effects in determining the magnitude of economic damages. This concept is frequently used and very important in other sectors such as infrastructure design and finance (Hu *et al.*, 2021).

Within the scope of the study, the return periods corresponding to each amount of precipitation were calculated with the GEV distribution, which is used as a reliable method in modelling extreme precipitation events (Santos *et al.*, 2015). The GEV distribution has three basic parameters:

- Location Parameter (μ): Determines the centre of extreme values. This parameter represents the central location where the data is concentrated.
- Scale Parameter (σ): Shows the spread of the data. This parameter expresses the distribution width of extreme events.
- Shape Parameter (ζ): Determines the shape of the tail of the distribution. This parameter plays a role in modelling the behaviour of different types of extreme values, such as Gumbel, Fréchet, or inverse Weibull.

The precipitation amounts determined at flood points were converted to daily total precipitation, and the maximum values were selected from the daily total precipitation values of each year. This process allowed the creation of annual maximum precipitation series at each grid point. When creating these series, only the data of the month in which the selected flood event occurred between 1971 and 2000 was used. In this way, it was aimed to minimise temporal differences. The GEV distribution was applied to the annual maximum precipitation series for each grid point. This process involves estimating three parameters of the distribution (shape, location, and scale).

Extreme precipitation values were calculated for different return periods (e.g., 5, 10, 50, 100, 500, and 1000 years). The return period-extreme precipitation relationship for each grid point is shown in the graphs. In these graphs, the effect of the return periods is emphasised using the log-log scale.

After this analysis, the return periods of the precipitation on the flood day were calculated using the GEV distribution parameters to understand the link between the return period and economic losses. Only selected flood points were used. This process was carried out with the help of the cumulative distribution function (CDF) of the GEV distribution. The CDF of the GEV distribution is used to model the probabilities of extreme precipitation events. This distribution is a powerful tool to predict maximum precipitation amounts for different durations and regions (Wagesho and Claire, 2016). The CDF represents the total probability of all possible outcomes of a random variable up to a certain value. As a result of all these analyses, the return period of the precipitation amount on the flood day was determined. The above all analyses were applied to all flood events, and the results of all were recorded in Table 2.2.

Table 2.2. Precipitation, return periods, and economic losses of flood points.

Country	Date (MM/ DD/ YYYY)	Grid Point (Lat, Lon)	Precip- itation (mm/ day)	Return Period (years)	Total Economic Loss (\$)
Türkiye	5/27/2000	40.50°N, 38.25°E	38.9	31	102.848.700,70
Türkiye	5/27/2000	40.75°N, 39.00°E	40.4	33.6	93.109.291,98
Russia	1/10/2002	44.25°N, 39.00°E	15.8	1.1	684.055.960,80
Russia	1/21/2002	43.75°N, 39.75°E	31.1	2	289.351.784,80
Russia	8/8/2002	45.50°N, 37.00°E	50.5	22.4	201.336.321,20
Russia	8/9/2002	44.75°N, 38.50°E	24.8	6.6	195.882.215,20
Russia	8/29/2004	44.50°N, 39.25°E	42.3	12.6	165.319.090,20
Bulgaria	7/2/2005	43.50°N, 25.25°E	86.1	1236.9	145.869.785,50
Bulgaria	7/3/2005	43.00°N, 25.25°E	76.5	1000	141.547.717,80
Bulgaria	7/4/2005	42.25°N, 27.75°E	51.8	17.4	141.187.545,50
Romania	7/12/2005	45.75°N, 26.75°E	162	354.6	13.143.491,80
Romania	7/16/2005	46.25°N, 23.25°E	21.2	1.4	12.719.508,20
Romania	7/17/2005	46.25°N, 24.50°E	26	4.3	12.134.000,00
Romania	7/21/2005	45.50°N, 25.75°E	21.2	1.5	8.005.000,00
Romania	7/23/2005	45.50°N, 24.00°E	26	1.4	6.659.670,69

Table 2.2 Precipitation, return periods, and economic losses of flood points. (cont.)

Country	Date (MM/ DD/ YYYY)	Grid Point (Lat, Lon)	Precip- itation (mm/ day)	Return Period (years)	Total Economic Loss (\$)
Romania	7/24/2005	46.50°N, 26.50°E	19.9	1.5	3.749.801,17
Romania	7/24/2005	46.50°N, 28.00°E	19.3	3.1	3.706.198,83
Ukraine	7/1/2006	44.50°N, 34.00°E	13.1	2.5	3.391.336,74
Türkiye	9/8/2009	41.50°N, 28.50°E	48.8	164.8	92.226.000,00
Romania	6/21/2010	45.75°N, 22.50°E	39.3	10.6	72.980.228,14
Romania	6/21/2010	44.75°N, 23.50°E	40.5	7.8	64.110.671,15
Romania	6/22/2010	45.75°N, 23.25°E	55.9	15.7	36.353.964,14
Romania	6/22/2010	46.50°N, 26.25°E	53.2	132.8	36.058.910,47
Romania	6/22/2010	46.00°N, 26.75°E	51.5	8.9	36.056.000,00
Romania	6/25/2010	46.50°N, 27.00°E	38.7	7.1	34.720.089,53
Romania	6/26/2010	47.00°N, 26.00°E	45.9	21.4	20.807.329,31
Romania	6/28/2010	46.50°N, 26.25°E	39.2	15	17.853.035,86
Romania	7/2/2010	46.25°N, 23.25°E	17.8	1.6	14.678.296,88
Romania	7/3/2010	45.25°N, 24.00°E	24.7	2.2	14.388.000,00
Romania	7/3/2010	46.25°N, 26.25°E	24.5	3.5	13.788.703,13
Russia	10/16/2010	44.00°N, 40.00°E	19	1.1	781.152.000,00
Russia	5/25/2011	44.50°N, 38.25°E	21.7	4.2	191.611.668,80
Russia	5/26/2011	44.00°N, 40.50°E	23.1	1.6	185.488.739,60
Russia	7/6/2012	44.50°N, 37.50°E	50.6	232.9	796.280.000,00
Romania	9/14/2013	45.00°N, 27.00°E	37.6	14.5	3.705.620,10
Ukraine	9/14/2013	47.50°N, 32.00°E	62.8	26.1	3.011.273,14
Ukraine	9/15/2013	46.00°N, 33.25°E	20.1	6	2.762.770,02
Bulgaria	6/19/2014	43.75°N, 26.75°E	100.3	2083.8	154.762.742,10
Bulgaria	6/19/2014	42.50°N, 27.75°E	67.9	23083	150.017.099,50
Bulgaria	9/4/2014	43.00°N, 26.00°E	37.8	13.9	139.386.683,90
Bulgaria	9/4/2014	43.50°N, 23.00°E	41.2	19.6	137.506.966,00
Bulgaria	9/5/2014	42.00°N, 24.25°E	50.7	132.5	118.504.872,10

Table 2.2 Precipitation, return periods, and economic losses of flood points. (cont.)

Country	Date (MM/ DD/ YYYY)	Grid Point (Lat, Lon)	Precip- itation (mm/ day)	Return Period (years)	Total Economic Loss (\$)
Bulgaria	9/6/2014	41.75°N, 24.25°E	46.4	83.5	113.346.177,90
Bulgaria	2/1/2015	42.75°N, 26.50°E	42.5	24.4	109.786.759,10
Bulgaria	2/1/2015	42.00°N, 24.25°E	43	28.6	109.786.759,10
Russia	10/24/2018	44.00°N, 39.00°E	150.4	46.3	176.083.900,50
Türkiye	8/22/2020	41.25°N, 39.00°E	58.8	24.9	89.518.434,37
Türkiye	8/22/2020	41.25°N, 40.75°E	77.4	72.2	89.518.434,37
Türkiye	8/23/2020	41.50°N, 41.75°E	85.3	13.4	88.962.560,53
Türkiye	7/21/2021	41.00°N, 40.75°E	21	1.2	88.242.215,91
Türkiye	7/21/2021	41.50°N, 41.75°E	21.7	1.1	84.029.096,41
Türkiye	8/10/2021	42.25°N, 34.50°E	99.3	93.5	81.495.555,82
Türkiye	8/11/2021	41.75°N, 36.00°E	84.6	78.3	78.133.121,44

2.6. Log-Log Regression Analysis: Relationship between Return Period and Economic Loss

The relationship between the return period (calculated for each flood event) and economic losses has been examined to understand the economic effects of flood events. In this analysis, the data was transformed to a log-log scale, and a linear regression model was applied. This mathematically expressed how economic loss changed as the return period increased.

Flood events data shown in Table 4.1 included precipitation amounts, return periods, and economic losses for each flood point. Missing or erroneous values in the data were cleaned and prepared for analysis. Specifically, columns such as return period and economic losses were converted to numerical values. Following the removal of missing data, a logarithmic transformation was applied to allow analysis of return periods and economic losses over a wider range.

This analysis provides an equation that mathematically expresses the relationship between the return period and total economic loss on a logarithmic scale,

$$\log(E) = \beta \cdot \log(R) + \alpha, \quad (2.1)$$

where E Total economic loss, R Return period (years), β Slope coefficient, representing the effect of the return period on the economic loss, α Intercept, representing the baseline economic loss when $R = 1$ (i.e., when $\log(R) = 0$).

The corresponding regression equation on the original scale is expressed as:

The regression equation on the original scale is,

$$E = 10^\alpha \cdot (R)^\beta. \quad (2.2)$$

The regression model was implemented using the Python programming language via the SciPy library, and some statistical parameters, which are the correlation coefficient (R), explanatory ratio (R^2), and P-value, were obtained. The correlation coefficient (R) measures the linear relationship between two variables. Its value changes between -1 and 1. A positive and strong relationship is represented by +1, while -1 indicates a strong negative relationship. If there is no relationship, the value of 0 indicates this lack of relationship.

The explanatory ratio (R^2) is a measure of how much the independent variables (return period) explain the change in the dependent variable (economic loss). Its value changes between 0 and 1. When the value is closer to 0, it means that the model can explain the relationship between variables well (Kutner *et al.*, 2005; Fahrmeir *et al.*, 2022).

P-value is used to determine whether the effect of independent variables on the dependent variable is statistically significant. Generally, if the P-value is less than 0.05, the effect of the variable is considered significant.

After the regression analysis was completed in line with the values determined within the scope of the study, the analysis was repeated on a country basis. As a result of this process, regression equations representing the relationship between economic losses and return periods for the Black Sea coastal region and the relevant countries were derived.

The analysis results were visualised, and the relationship between the return period and economic losses was expressed more clearly. The graph was prepared on a log-log scale and included the data points, which are the values for each flood event, and a regression line that represents the relationship predicted.

2.7. Future Projections

In this part of the study, regulated CMIP6 projections were used to project extreme precipitation events according to ERA5 reference period climate norms and to calculate return periods. For the determination of extreme precipitation events in the period 2030-2060, 95th percentile values were used according to climate norms (1971-2000 period). These climate norms were used as a reference for the distribution of extreme precipitation events and the change in return periods. The threshold value for determining extreme precipitation events were determined as the 95th percentile according to the reference period (1971-2000). Events exceeding this value were filtered. Return periods were calculated using the GEV distribution of projected precipitation amounts in the future according to the reference period. As a result of these processes, extreme values were determined for the grid points determined in the future.

In order to estimate the economic impacts of extreme precipitation events, previously developed regression models were used for each country. In these models, the determined return periods were used as independent variables, and economic loss estimates were made specific to the relevant country. Thus, it was aimed at contributing to the development of climate change adaptation policies by predicting the potential financial impacts of future extreme precipitation events (Kron *et al.*, 2019). In order to

estimate the economic impacts of extreme precipitation events, previously developed regression models were used for each country. In these models, the determined return periods were used as independent variables, and economic loss estimates were made specific to the relevant country. Thus, it was aimed at contributing to the development of climate change adaptation policies by predicting the potential financial impacts of future extreme precipitation events (Kron *et al.*, 2019).

In conclusion, the data sources and methods used in the study provide a comprehensive framework for analysing historical trends and future projections of extreme precipitation events and their anticipated impacts in the Black Sea basin. ERA5 re-analysis data play a critical role in determining climate norms, CMIP6 climate projections in assessing future changes, and the EM-DAT database in analysing disasters and economic losses caused by extreme precipitation events.

3. RESULTS AND DISCUSSION

3.1. Study Period (2000-2024) Precipitation Analysis and Economic Losses

Extreme precipitation, one of the important results of climate change, can result in major disasters. The frequency of these disasters is also increasing due to climate change. Economic losses are generally inevitable after these disasters.

In this study, in order to explain the relationship between the frequency of return of extreme precipitation and economic damage, the days and regions of flood events involving cities on the Black Sea coast in the EMDAT database were examined using ERA5 reanalysis data. As a result of the analyses carried out by taking economic damage data from the EMDAT database, Georgia cannot include the study because of the lack of economic damage data.

3.1.1. General Assessment of Flood Events on the Black Sea Coast

Within the scope of the study, flood events that occurred between 2000 and 2024 were examined in detail, and analyses were carried out in detail. Only flood disasters with economic damage data were included in the study. In this context, economic damage results were not specified in all flood events obtained from the EMDAT database.

After geographical area filtering, 63 flood events were determined. Although there were 23 flood events with economic data, only 22 of these events were used in the study, as a flood disaster that occurred in Russia in 2000, for which the start and end dates were not given, was excluded from the analysis.

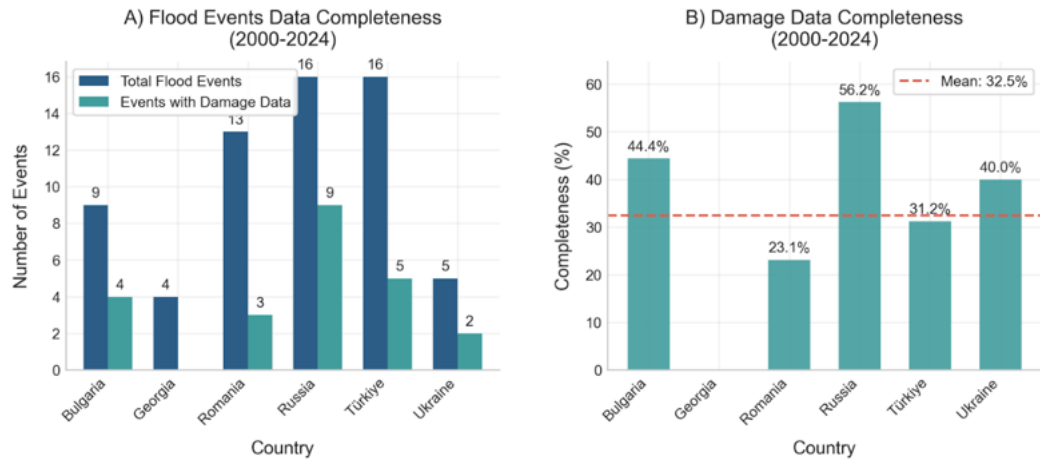


Figure 3.1. Data completeness of flood events in the black sea countries (2000-2024).

a) Comparison of reporting with total flood status and economic damage data, b) Damage data completion percentages by country. Source: EM-DAT, the international disaster database (2024).

The number of flood disasters in the Black Sea countries and their completeness in terms of economic damage vary greatly (Figure 3.1). When examined on a country basis, the records of the economic results of the 4 flood disasters that occurred in Georgia were not included in the EMDAT database. Therefore, they could not be included in the study. There are 16 flood disaster records in Türkiye and Russia in the 24-year period. However, the total number of data is the same, though the rates of including economic damage data differ. Russia was the country that provided the most data among the 6 countries, with a completeness of 56.2%. The deficiencies in the flood disaster criteria and economic loss data of the EMDAT database are among the important limitations of this study, and also common problems for this study (Jones *et al.*, 2023). Some regional extreme precipitation does not meet the criteria required for EMDAT may have economic consequences. Especially in cases where extreme precipitation events are repeated frequently but the intensity is low, the fact that they can have large effects is ignored, preventing the understanding of disaster effects.

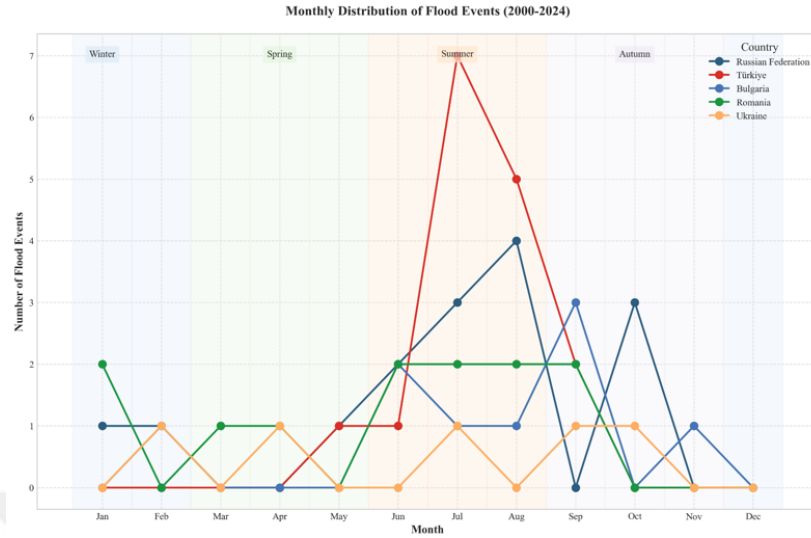


Figure 3.2. Monthly distribution of flood events in the study area.

The distribution of flood events in the Black Sea countries over time between 2000 and 2024 shows that the probability of extreme precipitation has been changing seasonally and monthly. The data we examined show that these events increase significantly in the summer months and reach their peak, especially between June and August. Seasonally, summer represents the period with the highest flood events, followed by autumn and spring. The analyses conducted by country show that Türkiye and Russia experience more flood events in the summer months without depending on the number of grid points. Flood events occur at the lowest levels in the winter months (Figure 3.2).

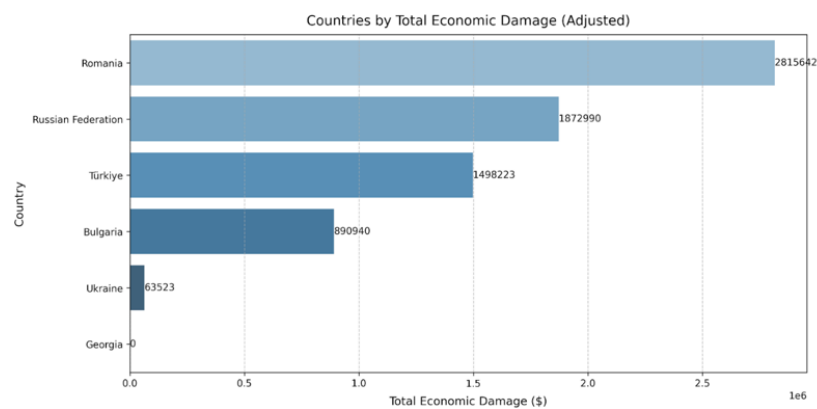


Figure 3.3. Countries by total economic damage (Adjusted).

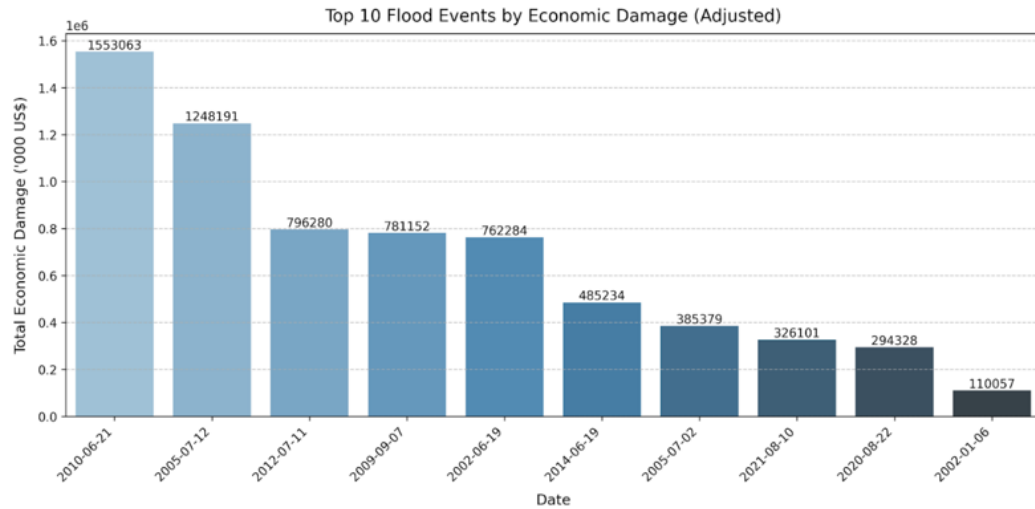


Figure 3.4. Top 10 flood events by economic damage.

When evaluated in terms of economic damage caused by flood disasters recorded in 24 years for these 5 countries, an economic loss of approximately 7.14 billion dollars was experienced. Although Russia was the country that experienced the most flood disasters (Figure 3.1), Romania stands out as the country with the highest total economic damage, with a total damage of 2.815.642.000 USD (Figure 3.3).

According to the EM-DAT database, the greatest economic damage was the flood disasters that occurred in Romania in 2010 and greatly affected the inner parts of Romania (Figure 3.4). 11 different flood points were determined using ERA5 data on the dates specified in the EMDAT database. There was a grid point with a return period of 132 years among the selected points, revealing the severity of this disaster. The reasons for the very high economic losses are shown as the flow rate in the Bistrita River exceeding the maximum flow rate (2850 m³/s) in history, major damage to the infrastructure, flooding of agricultural areas, halting of production in industrial areas, epidemics, and the establishment of camps to meet the shelter needs of citizens (Romanescu *et al.*, 2018; Minea *et al.*, 2022). In addition, prolonged heavy rainfall events and resulting river flooding also caused the Romania flood disaster of 2005. This event also occurred during the summer months. Four flood points were identified in the 2005 flood, but the return periods of these extreme rainfalls are not long. Extreme

precipitation and its long duration and lack of infrastructure increased the severity of the floods, causing economic losses of \$1.2 billion and at least 24 deaths. Also, river flow reached the record amount. It is one of the reasons for the high economic impact of the flood. The establishment of settlements in flood areas also increased the loss of life and property (Romanescu, 2013). Romania is followed by the Russian Federation, which recorded a total damage of 1,872,990,000 US dollars. The disaster, which occurred particularly in July 2012, was caused by sudden heavy rainfall. The incident took place in a region close to the Black Sea coast, which was warming due to climate change. During the summer season, the increased moisture transport contributed to excessive precipitation (Kostianaia and Kostianoy, 2021). In Romania, floods are spread out over longer days, while the incident in Russia occurred within a day or even shorter. The sudden floods in mountainous regions and the flood periods of up to 30 days in the Siretnehir basin show that the Black Sea coastal countries should be evaluated separately on a regional basis. Türkiye comes third, with damage of 1,498,223,000 US dollars. Bulgaria ranks fourth, with a total flood damage of 890,940,000 US dollars (Figure 3.3). However, it should be noted that this study only includes flood events with economic data. To understand and analyse these disasters, flood points were determined by using ERA5 reanalysis data.

3.1.2. Flood Points Statistics

In this section, extreme precipitation, which was related to flooding, was determined, and percentile analysis was performed. The coordinates of the flood points were determined as a result of more detailed examination of the flood events specified in the EM-DAT database. 53 grid points were determined as a flood point. The precipitation amounts observed in the determined coordinates is well above the mean daily total precipitation amounts in the month when the floods occurred, compared to the reference period. The majority of events are above the 99th percentile values. However, precipitation amounts and threshold values vary greatly between countries.

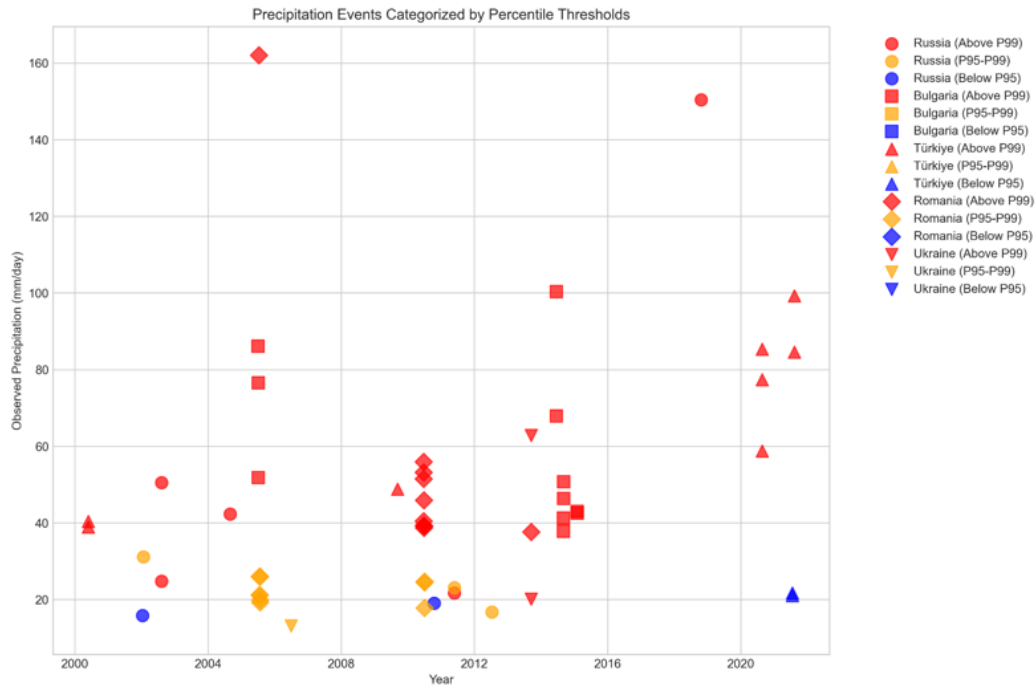


Figure 3.5. Precipitation events categorised by percentile thresholds.

The highest number of flood points was determined in Romania. The analyses show that 10 out of 19 flood points exceeded the 99th percentile. The other events occurred in the P95-P99 range. Among all the selected points, the highest daily total rainfall was measured in Romania as 162.0 mm/day. Rainfall exceeded the P99 threshold at 8 different points determined in a one-week period in June 2010. 11 flood points were determined in Bulgaria, and all the rainfall amounts observed at these points are above the P99 threshold. In June and September 2014, 6 different flood points were determined. The 100.3 mm/day rainfall observed in June is the highest rainfall amount measured in Bulgaria. In Türkiye, the rainfall amount at the two flood points determined was measured below the 95th and 99th percentile values. The precipitation amount at the other 8 flood points also exceeded the P99 threshold. The rainfall amounts measured in Russia and the percentile analyses have a wide range. While 150.4 mm/day rainfall caused flooding in October 2018, 15.8 mm/day rainfall caused flooding in the very close coordinates in January 2002. Rainfall at 2 different points is below the P95 and P99 thresholds. The country with the fewest flood points is Ukraine. The lowest rainfall (13.1 mm/day) among the determined coordinates was

measured there (Figure 3.5). This clearly reveals the impact of regional climatic and geographical differences on flood events.

3.2. Relationship between Return Period and Economic Loss

The analysis was carried out on a logarithmic scale by examining the relationship between return periods and economic losses, since the Black Sea coastal countries have different precipitation trends.

3.2.1. Black Sea Coasts

In this study, a regression analysis was performed on a logarithmic scale in order to examine the relationship between the return period and economic losses. The regression line obtained as a result of the analysis reveals the direction and magnitude of the relationship between the variables in question. As shown in Figure 3.6, the slope of the regression line ($\beta=0.16$) was determined to be positive but a low value. This situation shows that economic losses increase only to a limited extent with the increase in the return period.

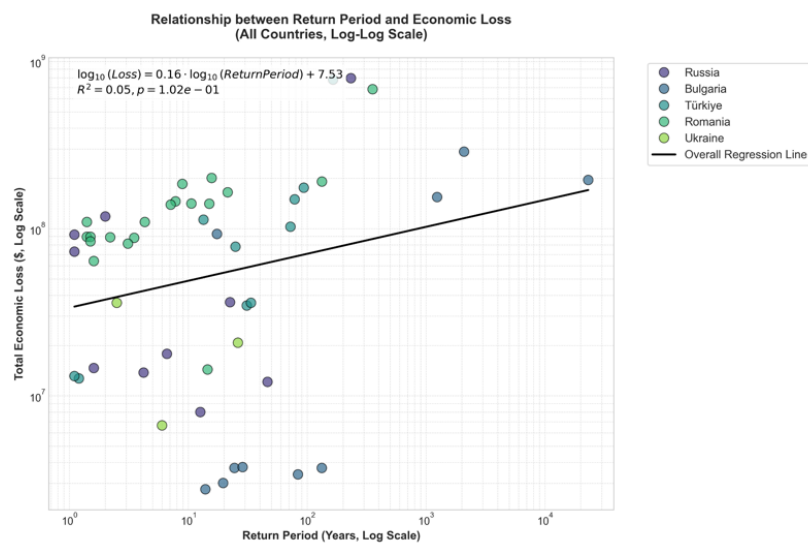


Figure 3.6. Black sea basin relationship between return period and economic loss.

The explanatory power of the model was evaluated using the coefficient of determination (R^2). The obtained value of $R^2 = 0.027$ reveals that the model explains only 2.7% of the change in economic losses. This is a very low value and shows that the effect of the independent variable (return period) on the dependent variable (economic loss) is weak. The constant term in the regression model represents the logarithmic value of the economic loss when the return period is zero. However, since the p-value is greater than 0.005, it was determined that the relationship between the logarithmic values of the return period and the economic loss is not statistically significant.

There are several main reasons why the analysis results cannot adequately explain the relationship between the variables. First of all, the high disaster threshold value in the EMDAT database used led to the analysis of only a certain part of the events evaluated in the study. In addition, the proportion of events with economic loss information in the data set is limited to approximately 32%. These deficiencies may have contributed to the low explanatory power of the model in general.

In addition, the effect of extreme precipitation on economic losses may vary depending on regional factors. The Black Sea coastal countries focused on in the study exhibit significant differences in terms of their climatic and socioeconomic structures. These differences have caused the economic impacts created by floods and inundations not to be evaluated homogeneously. In order to conduct a more in-depth analysis, the data were analysed on a country basis, and the effects of regional dynamics were evaluated in more detail.

3.2.2. Bulgaria

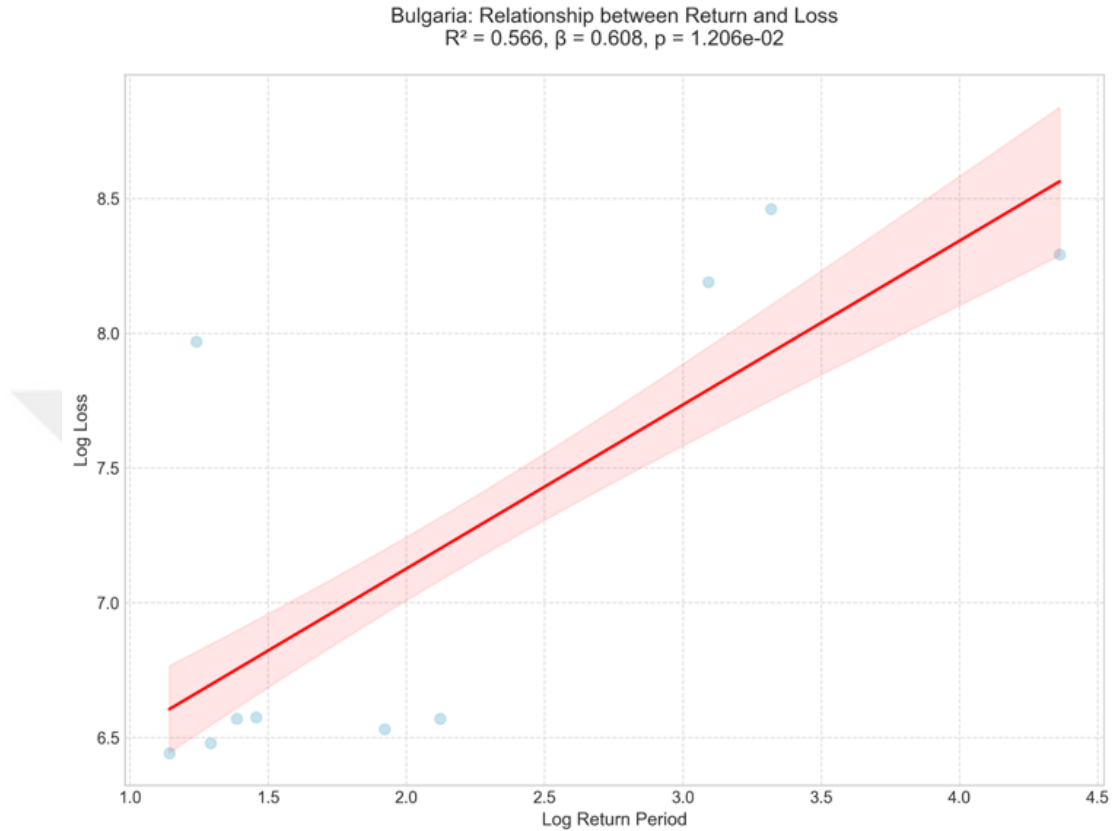


Figure 3.7. Relationship between return period and economic loss in Bulgaria.

When Bulgarian data was analyzed to understand the relationship between return periods and economic losses, a positive relationship was found between LogReturnPeriod and LogLoss, and the regression coefficient (R^2) was calculated as 0.566 shown in the Figure 3.7. The return period of extreme rainfalls experienced in Bulgaria explains approximately 57% of the economic losses. It is reasonable to determine the economic losses according to the return period of the rainfalls experienced. The slope of the graph shows that each logarithmic increase in the return period causes a logarithmic increase of 0.61 units in economic losses. A wider confidence interval is observed in the increasing return periods. This interval shows the uncertainty level of the model's predictions and represents the range within which the true regression line can be found with a given probability (usually 95%). On a logarithmic scale, a narrower confidence interval is observed in 1-2 return periods. The predictive power of the model is higher

in this range. The P-value of 0.01206 indicates that the results are not random and are statistically significant. Return periods are one of the important factors in explaining economic losses in Bulgaria.

3.2.3. Romania

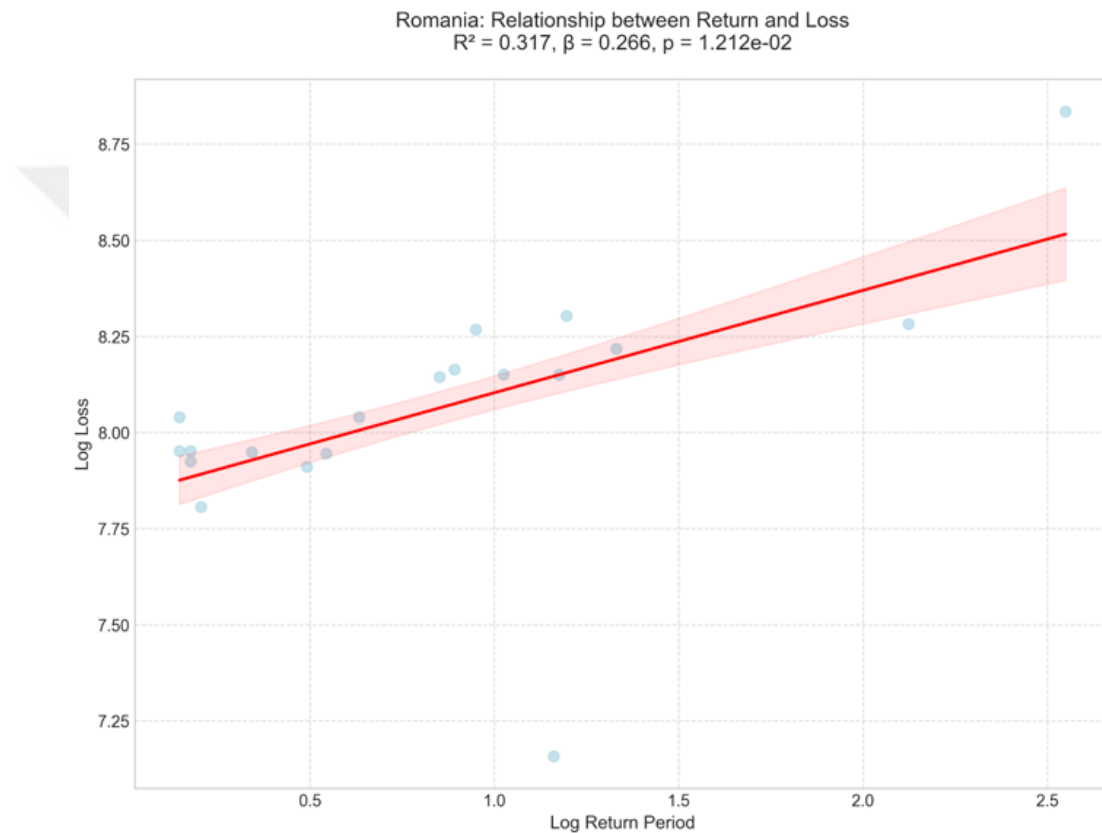


Figure 3.8. Relationship between return period and economic loss in Romania.

In Romania, a positive correlation was found between LogReturnPeriod and LogEconomicLoss, and the regression coefficient (R^2) was calculated as 0.317 shown in the Figure 3.8. The return period of extreme precipitation experienced in Romania explains approximately 31% of the economic losses. It is reasonable to determine the economic losses according to the return period of the rainfalls experienced. The slope of the graph shows that each logarithmic increase in the return period causes a logarithmic increase of 0.27 units in economic losses. A wider confidence interval is observed in the increasing return periods. This interval shows the uncertainty level of the model's

predictions and represents the range within which the true regression line can be found with a given probability (usually 95%). The P-value of 0.01212 indicates that the results are not random and are statistically significant. Return periods are one of the important factors in explaining economic losses in Bulgaria.

3.2.4. Russia

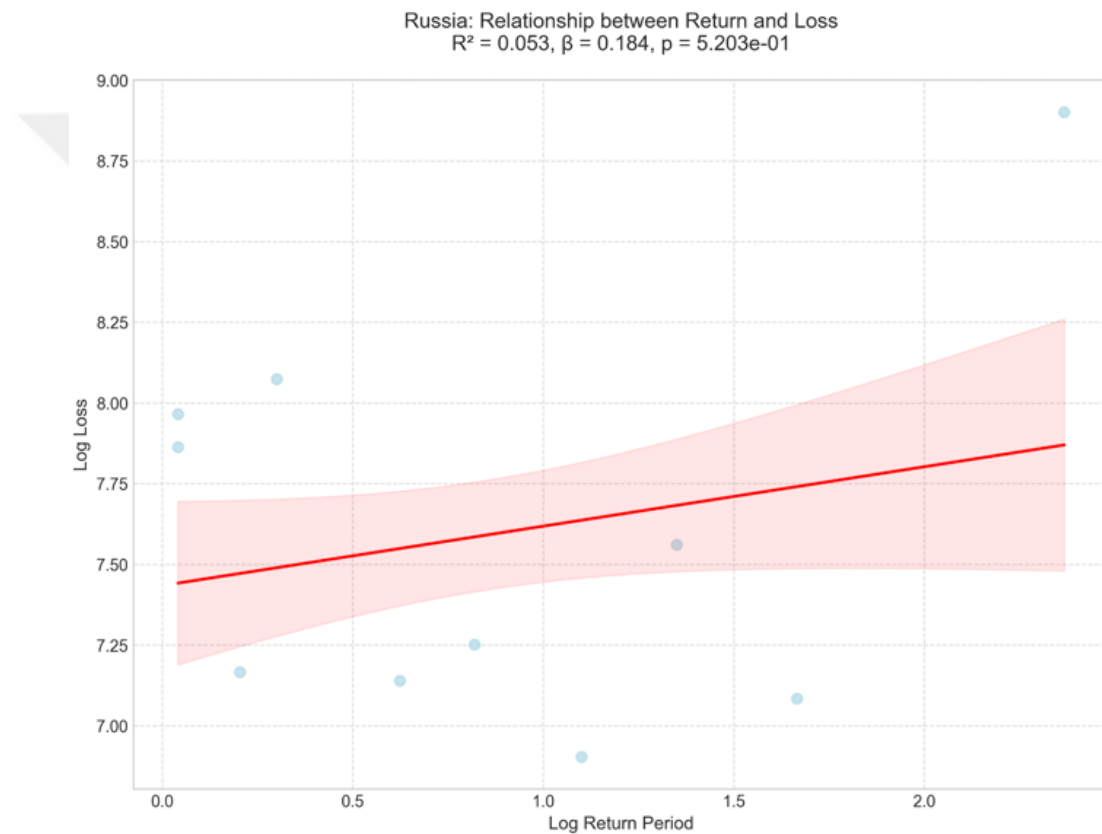


Figure 3.9. Relationship between return period and economic loss in Russia.

In Russia, with a regression coefficient of 0.053, log return period and log economic loss have a positive relation. The return period has a minimal impact on explaining economic losses, as seen by this low R^2 value. However, the regression slope (β) was shown to be 0.184, indicating that economic losses rise by 0.184 units for every logarithmic increase in the return period. A larger confidence interval is seen in the graph as return periods increase. Return periods of 1-2 show a lower confidence interval on a logarithmic scale, suggesting that the model's predictive power is higher in this range.

However, the P value of 0.520 shows that the return period is not a significant factor in explaining economic losses and that the results are not statistically significant. This situation shows that return periods alone are not a sufficient factor in understanding the economic impacts of extreme precipitation in Russia. Compared to other nations, Russia experiences less economic damage from excessive rainfall (Figure 3.9). This situation may require a more detailed examination of the dynamics specific to this country.

3.2.5. Türkiye

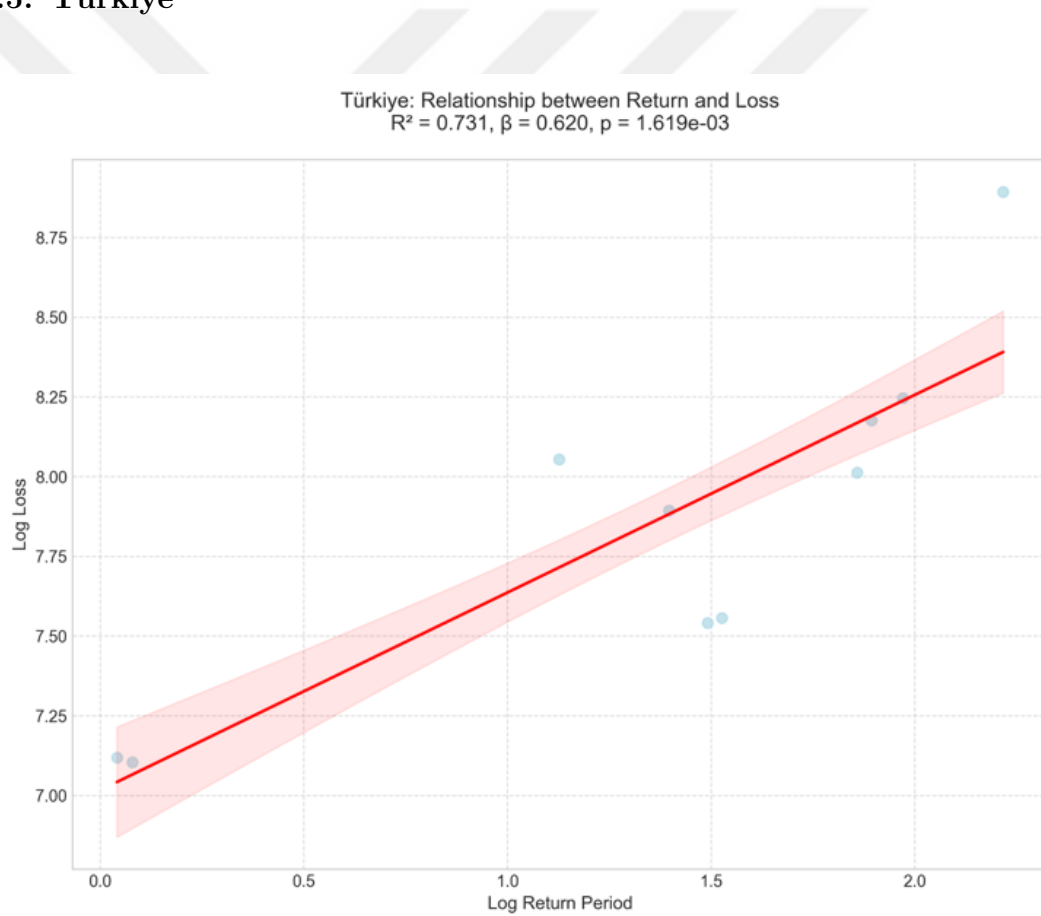


Figure 3.10. Relationship between return period and economic loss in Türkiye.

In Türkiye, the β value shows that economic losses have a positive and strong relationship with the return periods of precipitation. The model can explain 73% of the change in economic losses in relation to the change in the return period. The separate p value proves that the relationship between economic losses and the return period is

statistically non-random. This graph shows that when the return period increases, also economic loss increases in Türkiye.

For Türkiye, this methodology produced reliable and significant results. Extreme events and their economic effects that could happen on the same grids for Türkiye have been evaluated using the model's projected precipitation data for future periods. The strong impact of return periods on economic losses in Türkiye reveals the country's vulnerability to extreme weather events. This situation emphasises the importance of infrastructure investments, disaster management and climate change adaptation strategies. At the same time, Türkiye's geographical location and climatic diversity may be a factor that can increase the frequency and severity of such events. Therefore, it would be useful to conduct such analyses in a broader perspective, including socioeconomic and environmental factors.

3.2.6. Ukraine

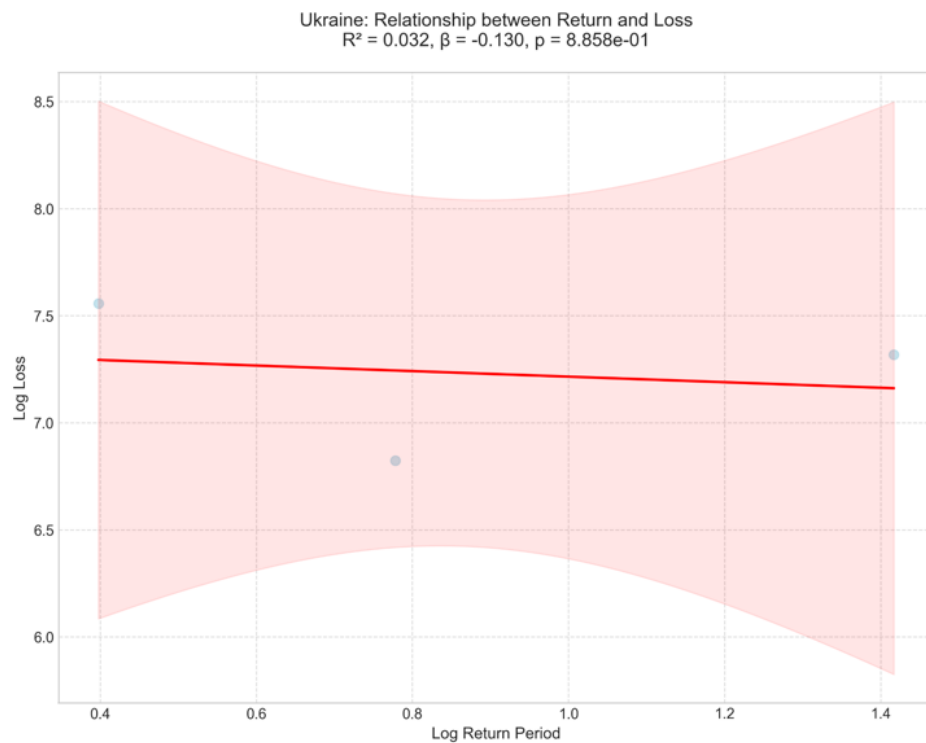


Figure 3.11. Relationship between return period and economic loss in Ukraine.

Since only 3 of the data from Ukraine included economic loss data, this model was not statistically significant; the p-value was too high (Figure 3.11). The relationship between the return period and economic losses was not understood. Loss analysis based on future data was not performed for this country. In order to obtain more consistent results for Ukraine in the future, more data needs to be recorded. In this way, clearer models and conclusions about economic losses can emerge.

3.3. Anticipated Economic Impacts of Future Extreme Precipitation on the Flood Points

In this section, to estimate the economic impacts of future extreme precipitation events by using the before-determined regression parameters and future precipitation projections, the focus is on precipitation estimates between the 2030 and 2060 time periods. The SSP5-8.5 climate scenario and data obtained from the projections of MPI-ESM-LR were used for precipitation data. Within the scope of the study, the future precipitation behaviour of the determined flood points and the impact of these events on economic losses were evaluated with both statistical and spatial analyses. This study provides valuable information on the economic impacts of extreme precipitation due to climate change. The frequency, intensity and economic impacts of extreme precipitation events were analysed using ERA5 Reanalysis data, EM-DAT database and MPI-ESM-LR model data. Return periods were calculated with log-log GEV (Generalised Extreme Value) modelling, and economic losses were estimated with regression analysis. The study was designed to model the economic impacts of future extreme precipitation events under the SSP5-8.5 scenario for the period 2030-2060.

3.3.1. Estimation of Future Extreme Precipitation Projections of Flood Points under SSP5-8.5 Scenario

In this study, extreme precipitation events for the selected flood points during the period 2030-2060 were determined based on values exceeding the 95th percentile threshold value. Data obtained from MPI-ESM (Max Planck Institute Earth System

Model) projections were used. In the literature, the 95th percentile value is accepted as a widely used threshold value in defining extreme precipitation events (An *et al.*, 2015; Fischer and Knutti, 2015). This threshold value is recommended as a reliable criterion for evaluating the hydrometeorological and socio-economic impacts of extreme precipitation. It was determined that a large portion of the flood events recorded in the EM-DAT database between 2000 and 2024, which was selected as the reference period of the study, were compatible with this threshold value. This confirms the capacity of the selected threshold value to represent extreme precipitation events in the region (Fischer and Knutti, 2015).

The spatial and temporal distribution of extreme precipitation events for the period 2030-2060 in Bulgaria, Russia, Türkiye, Romania and Ukraine under the SSP5-8.5 scenario was analysed. The frequency of extreme precipitation events, average and maximum precipitation amounts, return periods and the riskiest years were evaluated for each country. The findings reveal that extreme precipitation events show regional differences and provide important clues about the future impacts of these events. A total of 387 different extreme precipitation events were identified according to the 95th percentile threshold value for 28 flood points selected within the scope of the study.

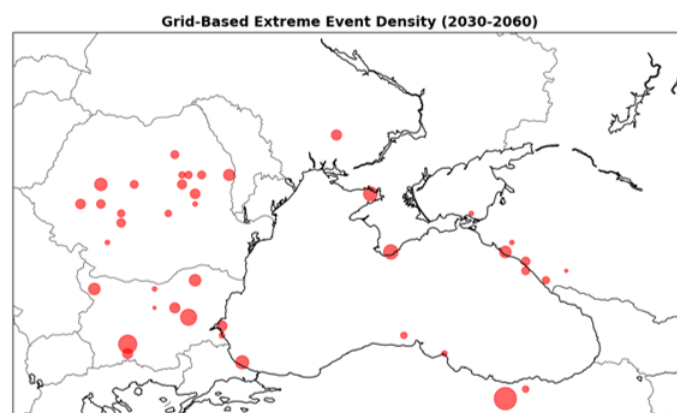


Figure 3.12. Spatial distribution: intensity of extreme rainfall events (2030-2060).

Figure 3.12 shows the intensity and spatial distribution of extreme precipitation events for the period 2030-2060 under the SSP5-8.5 scenario. On the map, larger red

dots represent higher intensity extreme precipitation events. That is, larger red areas show that more extreme precipitation events occur. Extreme precipitation events are particularly concentrated in parts of Bulgaria, Romania and Türkiye.

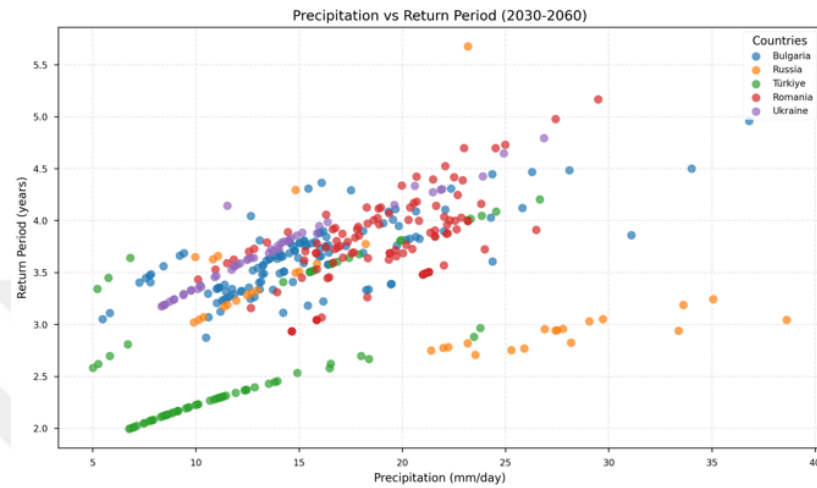


Figure 3.13. Precipitation vs return period (2030-2060).

Figure 3.13 shows the intensity and frequency of extreme precipitation events by country under the SSP5-8.5 scenario.

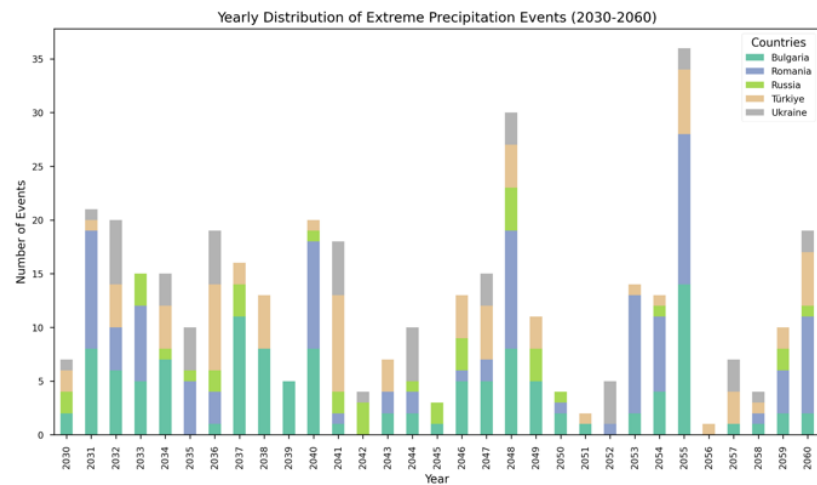


Figure 3.14. Yearly distribution of extreme precipitation events (2030-2060).

Figure 3.14 compares the changes in extreme precipitation events over the years by country under the SSP5-8.5 scenario.

Bulgaria stands out as the country where extreme rainfall events are observed most frequently. A total of 119 extreme rainfall events were recorded, indicating that the country is highly sensitive to extreme rainfall under the SSP5-8.5 scenario. The mean precipitation amount was calculated as 14.7 mm/day, and the maximum precipitation was calculated as 36.79 mm/day. Since the inner parts of Bulgaria are also included in the EMDAT database, when determining the flood points in Bulgaria, the highest precipitation among the selected points is predicted in Pazardžik district as a result of the analyses. The amount of precipitation varies between 5.47 mm/day and 36.79 mm/day. The average return period was determined as 3.65 years, and the highest return period was determined as 4.96 years. February stands out as the risky month, while the riskiest year was determined as 2055. The fact that high rainfall amounts in Bulgaria have shorter return periods indicates that such severe events are frequent (Figure 3.13 and Figure 3.14). This situation reveals that the country is more vulnerable to extreme rainfall events and that these events can have greater economic and social impacts.

Russia, although the country with the least frequent extreme precipitation events, has higher values than other countries in terms of precipitation amounts. A total of 36 extreme precipitation events were recorded, and the average precipitation amount of these events was 20.50 mm/day, which is the highest value among the analysed countries. The maximum precipitation amount was measured at the highest level with 38.62 mm/day. The average return period was determined as 3.23 years, while the highest return period was 5.68 years, which is longer than other countries (Figure 3.13 and Figure 3.14). The risky month was determined as May, and the riskiest year was determined as 2048. Despite the rarity of extreme precipitation events in Russia; their intensity is quite high. This suggests that the effects of rare extreme precipitation events can be much more devastating. It is estimated that they can have serious effects, especially on agriculture and infrastructure systems.

Türkiye is in the middle level in terms of the frequency of extreme precipitation events, with a total of 76 events recorded. The average precipitation amount is 12.30

mm/day, which is the lowest among the analysed countries. The maximum precipitation amount is calculated as 26.66 mm/day. The average return period is the shortest, 2.67 years, which shows that extreme precipitation events occur more frequently than in other countries. The highest return period is determined as 4.20 years. While May stands out as the risky month, the riskiest year is determined as 2041. The fact that extreme rainfall events occur more frequently in Türkiye indicates that these events are repeated more regularly (Figure 3.13 and Figure 3.14). Extreme rainfalls have also created economic impacts in the Marmara and Black Sea regions of Türkiye in the study period (2000-2024). The literature emphasises the effects of floods on infrastructure and the energy sector in these regions. This situation reveals the necessity of taking preventive measures, especially in water management and city infrastructure. In addition, it is evaluated that the economic and social effects of frequently recurring events may be more widespread.

Romania ranks second among the analysed countries with a total of 107 extreme precipitation events. The average rainfall amount was calculated as 18.98 mm/day, and the maximum rainfall amount was calculated as 29.49 mm/day. The average return period was 3.81 years, which is the longest among the analysed countries. The highest return period was determined as 5.17 years. The risky month was July, and the riskiest year was 2055. Although Romania has a high frequency of extreme precipitation events, the long return periods indicate that these events occur less frequently but with greater intensity (Figure 3.13 and Figure 3.14). This situation highlights the need for Romania to prepare for extreme precipitation events and the importance of developing adaptation strategies, especially in agricultural activities and rural areas.

Ukraine ranks second lowest among the analysed countries with a total of 49 extreme rainfall events. The average rainfall amount was calculated as 12.73 mm/day, and the maximum rainfall amount is 26.85 mm/day. The average return period was determined as 3.71 years, and the highest return period was determined as 4.79 years. The risky month will be September, and the riskiest year will be 2032. The fact that extreme precipitation events are observed less frequently in Ukraine indicates that

these events, although they are less frequent, can have serious effects. Especially the extreme precipitation events that may occur in 2032 require the country to prepare for this period. In addition, the determination of September as a risky month emphasises the importance of taking preventive measures in terms of agriculture and water management during this period (Figure 3.13 and Figure 3.14).

These results show that extreme precipitation events under the SSP5-8.5 scenario show significant differences among countries. There are significant differences, especially in terms of event frequency, precipitation amounts and return periods. While frequent severe events are remarkable in Bulgaria, rare but intense events are prominent in Russia. Rainfall amounts in Russia show a higher variation compared to other countries, while Türkiye has the lowest average rainfall. The highest median precipitation amount was calculated at 19.3 mm/day in Russia. The distribution of extreme precipitation events by month varies among the Black Sea Coast countries. In particular, there is a concentration in Bulgaria and Türkiye in the 9th and 2nd months. In September, 110 extreme precipitation events were recorded in Bulgaria, Türkiye and Ukraine. In Russia, rare but intense rainfall events indicate that their effects can be more devastating. In Türkiye, heavy rainfall events are more frequent but less intense. In Romania and Ukraine, differences were observed according to risky years and months.

3.3.2. Estimation of Anticipated Economic Impacts of Future Extreme Precipitation

This thesis focuses on examining the relationship between the return periods of extreme precipitation events and economic losses in the Black Sea coastal regions. In the last part of the study, countries that provide statistically significant results, such as Türkiye, Romania and Bulgaria, are examined in detail (Table 4.1); economic loss estimates are made only for these countries, and suggestions are developed for future models.

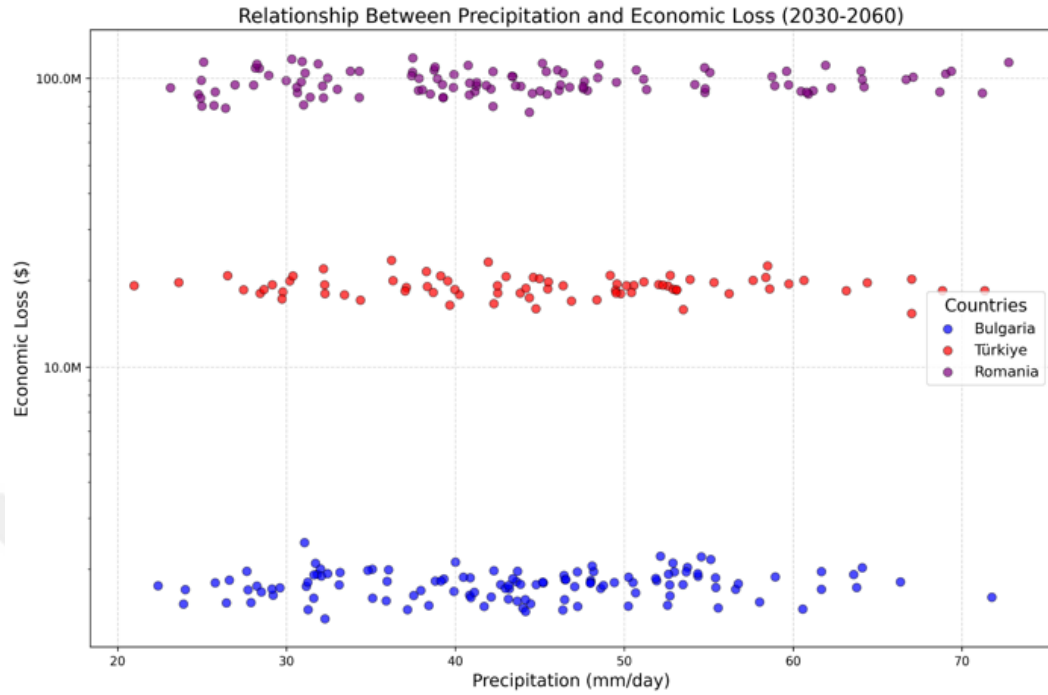


Figure 3.15. Relationship between return period and economic loss (2030–2060).

In addition, Figure 3.15 illustrates the relationship between return periods (years) and economic losses (\$) for three countries—Türkiye, Bulgaria, and Romania—during the projected period of 2030–2060 under SSP5-8.5 scenarios. The data highlights significant differences in economic loss patterns across the countries. Projected economic losses vary significantly across countries, with Türkiye showing relatively stable impacts across return periods, Romania experiencing sharp increases, and Bulgaria demonstrating lower overall losses. Romania’s vulnerability, particularly in agricultural regions, becomes evident as return periods increase. Bulgaria, while less affected overall, demonstrates a more consistent economic impact across return periods.

3.3.2.1. Bulgaria. The analysis results in Bulgaria show that the frequency and intensity of extreme precipitation events vary regionally across the country. It is observed that extreme precipitation is concentrated in certain regions in February, June, July and September. For example, in the southeast of the country (42.75°N, 26.5°E), the economic losses of the extreme precipitation events that occurred in February exceeded approximately 2 million USD in 2038 with a maximum daily precipitation of 24.35 mm.

The return period of this event was calculated as approximately 4.45 years. Similarly, the daily precipitation of 22.35 mm in the same region in 2047 would increase the economic losses to approximately 1.98 million USD. This situation shows that even small increases in precipitation lead to significant increases in economic losses. It is also understood that economic losses in this region tend to increase in the long term and that the infrastructure remains vulnerable to such extreme events.

In the central part of Bulgaria, especially in the coordinates 42°N, 24.25°E, the extreme events that occurred in February caused a significant increase in economic losses. For example, in 2047, the maximum daily precipitation in this region reached 36.79 mm, causing an economic loss of approximately 2.15 million USD. The fact that the return period of this event is approximately 4.96 years indicates that the region is at risk in terms of extreme precipitation events and that similar events may occur in the future. The increasing trend in economic losses in this region creates significant risks, especially for the agricultural and infrastructure sectors.

Extreme rainfall events that occurred in the northeast of the country (43.75°N, 26.75°E) in June are also noteworthy. The economic losses of extreme events in this region have reached approximately 1.85 million USD, especially in 2031 and 2037, when daily rainfall exceeds 16 mm. The return periods of these events are calculated as approximately 3.9 years. Considering the intensity of agricultural activities in the region, it is thought that the economic impact of such extreme events may be more extensive.

Rainfall events that occurred in the western and southern regions of the country in September (at coordinates 42°N, 24.25°E and 41.75°N, 24.25°E) caused dramatic increases in economic losses. In particular, 34.01 mm of daily rainfall in 2031 caused an economic loss of approximately 2.03 million USD. This situation shows the sensitivity of the infrastructure and urbanisation structure of the region to extreme rainfall events. In addition, the return periods of extreme rainfall in this region exceed 4 years, increasing the probability of similar events in the future.

It has been observed that there is a logarithmic relationship between the increase in precipitation amounts and economic losses (Figure 3.15). This situation emphasises the determining role of precipitation amounts on economic effects. Especially the economic effects of large flood events show that precipitation amounts are an important determinant.

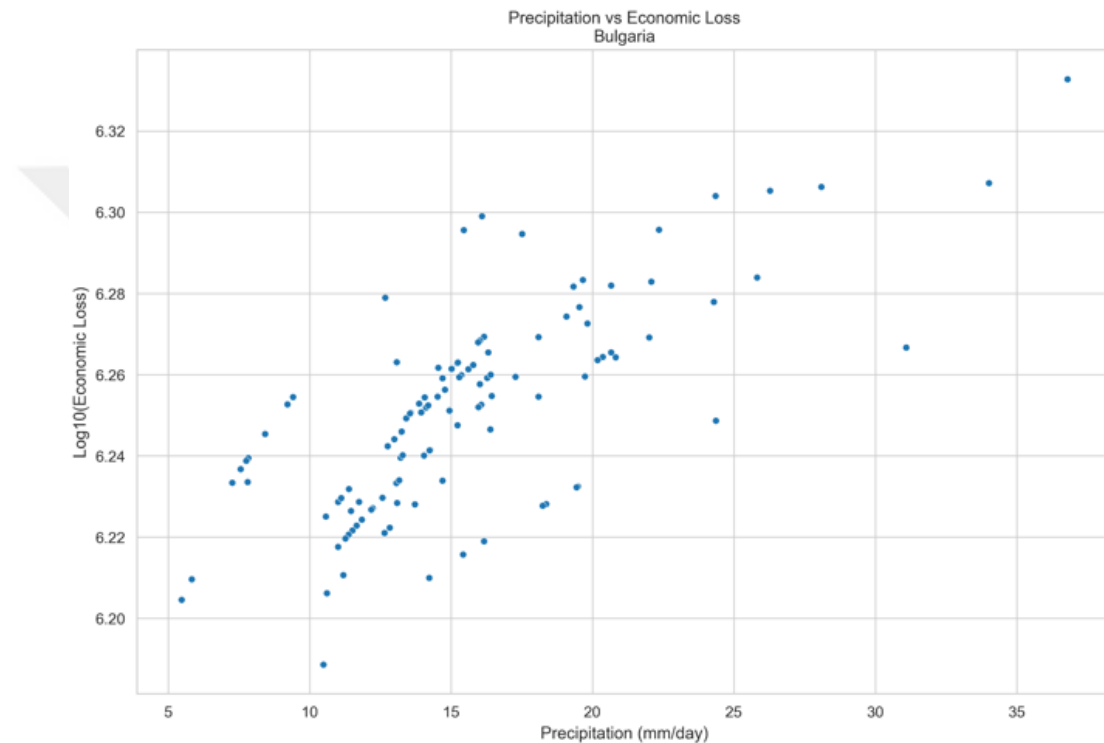


Figure 3.16. Precipitation vs economic loss in Bulgaria.

When economic losses are examined annually, Figure 3.16 shows that annual economic losses generally tend to decrease. However, sudden peaks were observed in some years due to the severity of extreme events. The year 2055 is the year in which the highest economic loss was experienced in the analysed period, with 25,204,696 USD. This situation shows that the economic impact of the extreme events that occurred in that year was very large. The highest number of extreme precipitation events was also observed in this year.

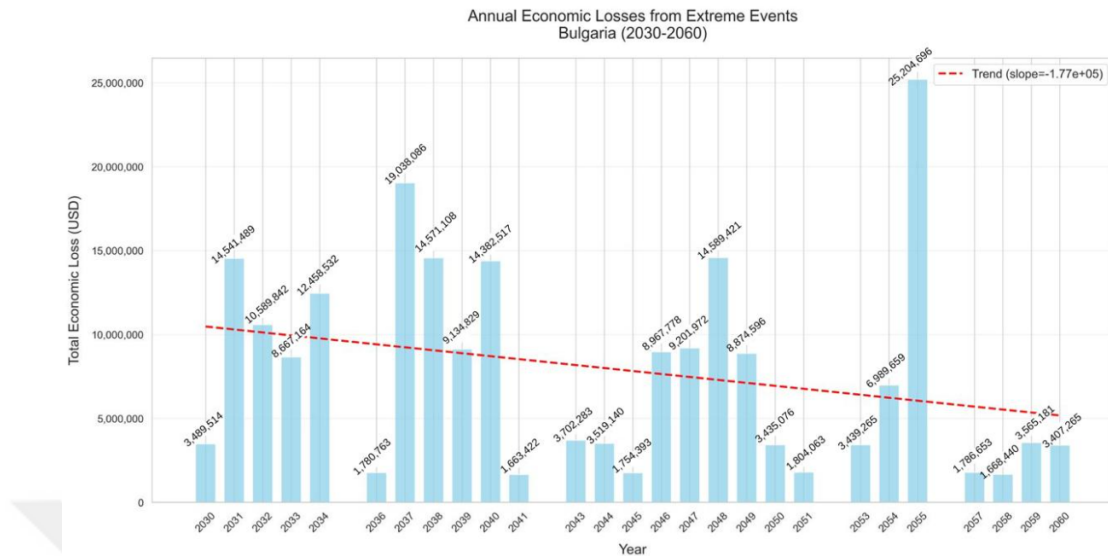


Figure 3.17. Annual economic losses from extreme events in Bulgaria (2030-2060).

As a result, the economic impacts of extreme precipitation events in Bulgaria show regional differences and are particularly concentrated in certain regions and months. The strong relationship between precipitation and economic losses suggests that risks may increase further in future climate change scenarios.

3.3.2.2. Romania. Extreme precipitation events in Romania are predicted to cause significant economic losses according to future climate projections. Analyses based on CMIP6 projections and ERA5 reference period climate norms reveal in detail the distribution and economic impacts of extreme precipitation events in the 2030-2060 period.

The analysis results in Romania show that the frequency and intensity of extreme precipitation events vary regionally across the country. In the northwest of the country (46.25°N, 24.5°E), the economic losses of extreme precipitation events occurring in July will exceed approximately 106.35 million USD in 2040 with a maximum daily precipitation of 29.49 mm. The return period of this event is calculated as approximately 5.17 years. Similarly, in the same region, a daily precipitation of 27.41 mm in 2053 would cause economic losses to approximately 105.29 million USD. This shows that

even small increases in precipitation lead to significant increases in economic losses. It is also understood that economic losses in this region tend to increase in the long term, making the infrastructure vulnerable to such extreme events.

In eastern Romania, especially at 46.5°N , 28°E , extreme events that occurred in September caused a significant increase in economic losses. For example, in 2044, the maximum daily precipitation in this region reached 24.98 mm, causing an economic loss of approximately 103.87 million USD. The return period of this event is approximately 4.73 years, indicating that the region is at risk of extreme precipitation events and that similar events may occur in the future. The increasing trend in economic losses in this region creates significant risks, especially for the agricultural and infrastructure sectors.

Extreme precipitation events that occurred in the central part of the country in June (45.75°N , 22.5°E) are also noteworthy. The economic losses of extreme events in this region reached approximately 99 million USD, especially in 2033 and 2048, when daily precipitation exceeded 22 mm. The return periods of these events are calculated as approximately 4 years. Considering the intensity of agricultural activities in the region, it is thought that the economic impact of such extreme events may be more extensive.

The rainfall events that occurred in the southwest of the country in July (45.5°N , 24°E) caused serious economic losses. In particular, 26.48 mm of daily rainfall in 2040 would cause an economic loss of approximately 98.75 million USD. In addition, the return period of extreme rainfall in this region is 3.9 years, showing that the probability of similar events in the future does not take a long time.

A logarithmic relationship was observed between the increase in rainfall amounts and economic losses. This situation emphasises the important role of rainfall amounts on economic impacts. In particular, the economic impacts of major flood events show that rainfall amounts are an important determinant.

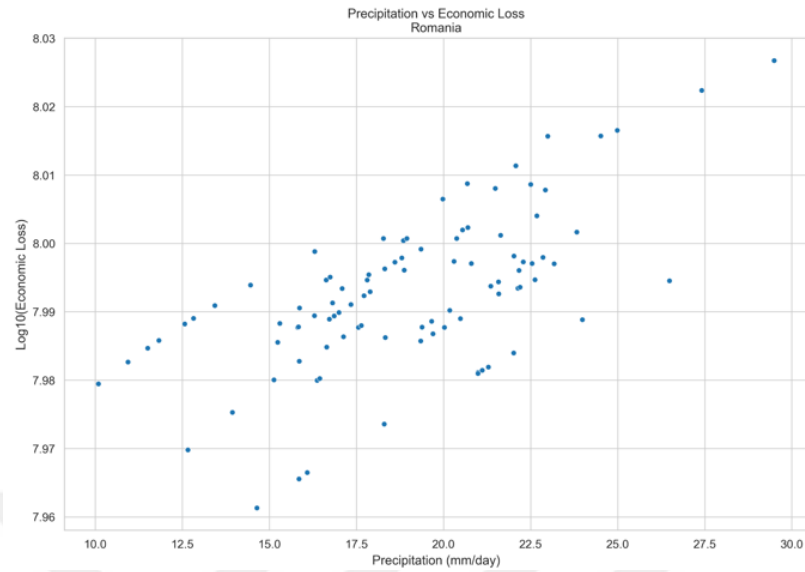


Figure 3.18. Precipitation and economic loss in Romania.

Figure 3.18, which shows the relationship between precipitation and economic losses, shows the distribution of daily precipitation values and economic losses on logarithmic scales. The graph clearly shows that even small increases in precipitation can cause large changes in economic losses. Especially when the rainfall exceeds 20 mm/day, the logarithmic value of economic losses increases up to 8.02. In the lower rainfall range of 10-15 mm/day, the logarithmic value of economic losses varies between 7.96 and 7.99.

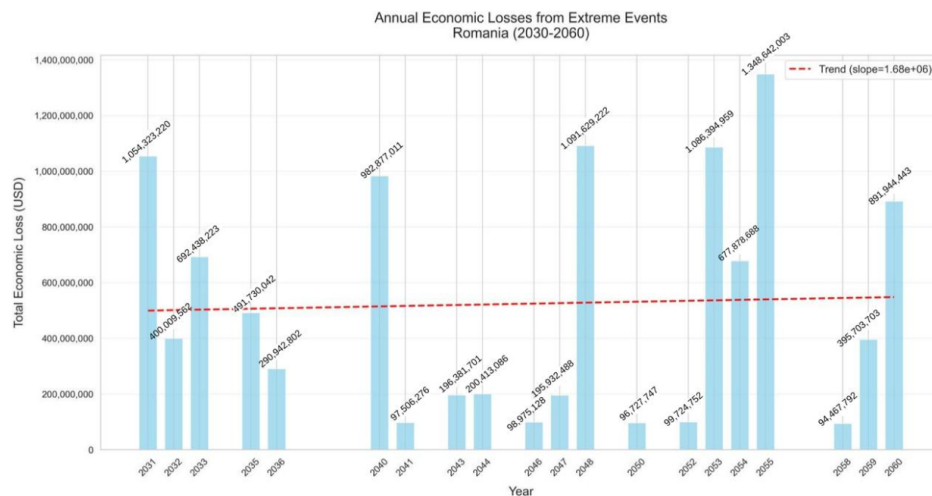


Figure 3.19. Annual economic losses from extreme events in Romania (2030-2060).

Figure 3.19 shows that there are large fluctuations in annual economic losses in Romania. The highest economic loss was in 2055, with USD 1,348,642,003, while the other peak years were USD 1,086,394,959 in 2053 and USD 1,091,629,222 in 2048. The lowest economic loss among the years that extreme events were determined was recorded in 2052, at USD 94,467,792. The red dashed trend line shows the general trend of economic losses. In the long term, a slight increasing trend in economic losses was observed. However, this trend has a rather low slope, and economic losses generally follow a fluctuating course. These fluctuations are due to changes in the frequency and intensity of extreme precipitation events.

The fluctuating course of economic losses is due to regional and temporal differences in extreme precipitation events. The reasons for the losses experienced, especially in the peak years such as 2055, 2053, and 2048, should be analysed in detail. The effects of the events experienced in these years on infrastructure, agriculture, and settlement areas should be examined. The general trend line shows that economic losses tend to increase slightly. Taking this trend into account, long-term adaptation policies and disaster management plans should be developed.

3.3.2.3. Türkiye. In Türkiye, analyses estimate the regional distribution and economic impacts of extreme precipitation events. Below, the projections for the Central Black Sea, Western Black Sea and Eastern Black Sea regions are summarised.

It is estimated that the frequency and intensity of extreme precipitation events will increase in the Western Black Sea Region. The extreme precipitation expected to occur in May at the coordinates of 40.5°N, 38.25°E is noteworthy. It is estimated that the daily precipitation amount will increase to 23.47 mm, and the economic losses will reach 19.99 million USD.

The minimum daily precipitation amount of extreme precipitation will be 6.77 mm in May 2038, which will cause an economic loss of approximately 15.92 million USD. It is also estimated that long-term extreme precipitation events will increase.

Especially in the Western Black Sea region, at the coordinates of 40.5°N, 38.25°E, long-term extreme precipitation is observed throughout May. The economic impacts of these events reach serious dimensions, and the return periods emphasise the frequency of such events.

Excessive rainfall at coordinates 41.75°N, 36°E in August in the Central Black Sea Region can significantly affect the region economically. It is estimated that daily rainfall will reach 6.83 mm in August 2041 and economic losses will reach 23.11 million USD. It is expected that daily rainfall will reach 5.76 mm in August 2055 and economic losses will be 22.35 million USD. The return periods vary between 3.44 and 3.64 years, indicating that excessive rainfall events can occur at regular intervals in this region.

The frequency and intensity of extreme precipitation in the Eastern Black Sea Region increase the economic and infrastructural risks of the region. The events expected to occur in the coordinates of 42.25°N, 34.5°E are particularly noteworthy. In August 2041, it is estimated that the daily precipitation will reach 6.69 mm and the economic losses will be 19.68 million USD. Projection shows that followed by 2 days, extreme precipitation will continue. In August 2055, it is expected that the daily precipitation will reach 5.82 mm and the economic losses will increase to 19.18 million USD. The return periods ranging from 2.58 to 2.80 years indicate that extreme precipitation will occur more frequently in this region.

The economic effects of extreme precipitation in the coordinates of 41.5°N, 28.5°E in and around Istanbul are remarkable in September. It is estimated that the daily precipitation amount will reach 26.66 mm and the economic losses will be 25.27 million USD in 2048. The fact that the return periods vary between 3.41 and 4.20 years indicates that extreme precipitation events can occur regularly in and around Istanbul.

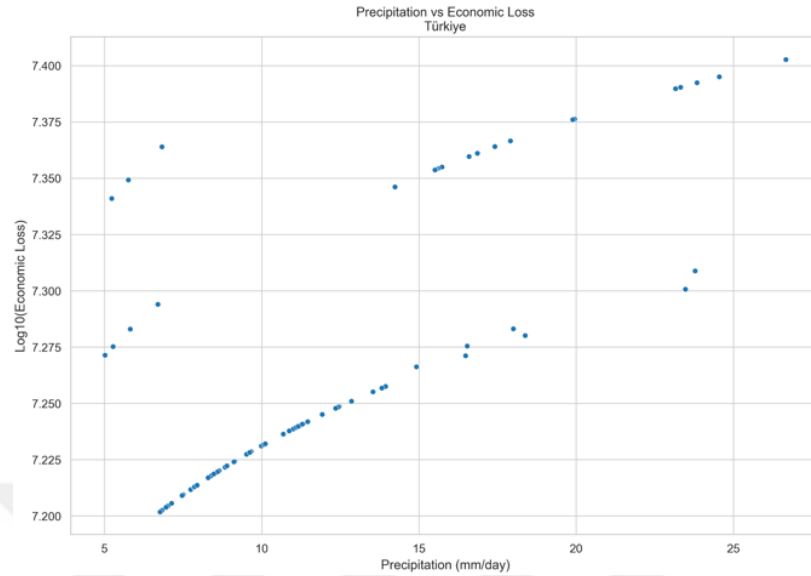


Figure 3.20. Precipitation and economic loss in Türkiye.

Figure 3.20 shows that the relationship between rainfall amounts and economic losses was analysed with a logarithmic model. These analyses clearly reveal the decisive role of rainfall amounts on economic impacts. Especially when daily rainfall exceeds 15 mm/day, it causes a rapid increase in economic losses. The fact that the conversion periods generally vary between 2-4 years emphasizes the frequency and impact of extreme weather events.

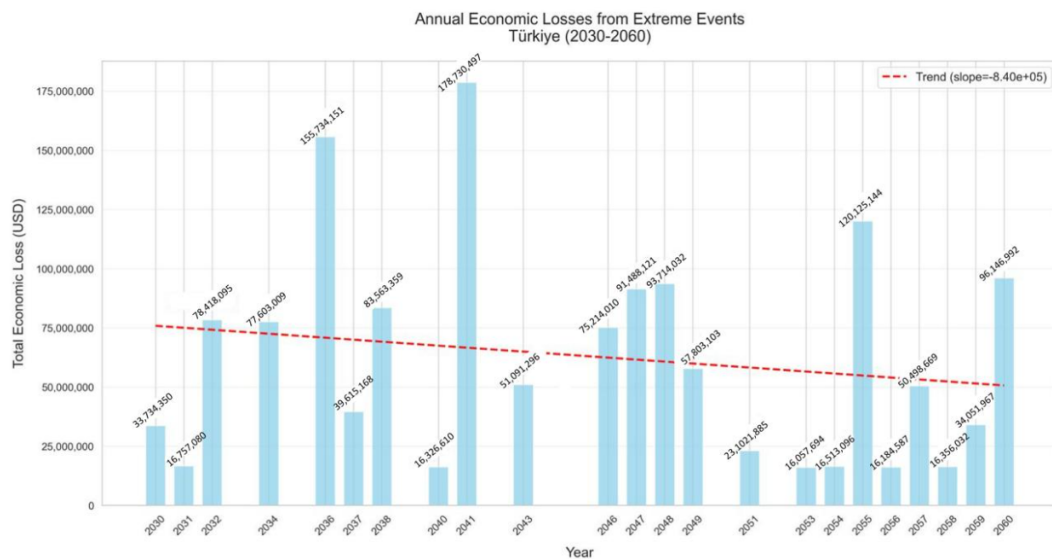


Figure 3.21. Annual economic losses from extreme events in Türkiye.

The estimates for annual economic losses in Türkiye in Figure 3.21 indicate that it will follow a fluctuating course. Figure 3.21 shows the annual economic loss estimates tend to decrease. However, severe economic impacts are projected in this period. It is predicted that the highest economic loss will be experienced in the analysed period in 2041, and the economic loss will reach 178.73 million USD. Similarly, it is predicted that the economic losses will reach 155.73 million USD in 2036 and 120.12 million USD in 2055. However, it is predicted that the economic losses will be at their lowest level in 2051 with 16.57 million USD.



4. CONCLUSION AND RECOMMENDATIONS

This study has revealed important findings by analysing the economic impacts and future projections of flood events caused by extreme rainfall in selected regions (2000-2024) in the Black Sea coastal countries. The return period of extreme rainfall, economic losses, and regional differences were examined in detail, and the economic impacts of future extreme precipitation events (2030-2060) were estimated.

The deficiencies in the EM-DAT database (32% completion rate) and the exclusion of Georgia from the analysis emphasise the urgent need for standardised data collection protocols in regional disaster assessments (Jones *et al.*, 2023). The fact that the EM-DAT database does not include small-scale but frequently recurring extreme rainfall events (Gall *et al.*, 2008; Joshi, 2024) limited the predictive ability of the model. In the study conducted by Joshi (2024), it was stated that reporting deficiencies in the EM-DAT database led to inadequate coverage, especially in low-fatality disasters. This situation shows that disaster databases need to be made more inclusive.

Flood events in the Black Sea coastal countries between 2000 and 2024 caused an economic loss of approximately 7.14 billion US dollars. These losses were reported by Romania (\$2.815 billion), Russia (\$1.872 billion), and Türkiye (\$1.498 billion), respectively. It has been determined that flood events are mostly concentrated in the summer months and are more frequent during this period, especially in Türkiye and Russia. Similarly, it is emphasised in the literature that heavy rainfall in the summer months causes floods and increases economic impacts (IPCC, 2021; Kundzewicz *et al.*, 2014). Flood effects are felt more dramatically, especially in countries with sensitive infrastructure and exposed to heavy rainfall, such as Romania (Romanescu, 2013).

4.1. Relationship Between Return Period and Economic Loss

In this study, the relationship between return time and economic losses was analysed using a logarithmic model. A statistically significant relationship was found between return time and economic losses in Türkiye, Bulgaria and Romania. However, this relationship remained weak in other countries due to lack of data and other regional characteristics. The findings show that economic losses increase as the return time of flood events increases.

Analyses conducted specifically for Bulgaria reveal that the return period explains 57% of economic losses. Flood events occurring with longer return periods caused greater economic losses. It is stated in the literature that flood events with longer return periods generally affect larger hydrological systems, and this situation increases infrastructure damage (Dobrovičová *et al.*, 2015). In Bulgaria, these results can be associated with infrastructure deficiencies and inadequate flood prevention systems, especially in rural areas.

In the analyses conducted for Romania, return periods explain 31% of economic losses. It was determined that high rainfall amounts in Romania caused serious economic losses. It is emphasised in the literature that heavy rainfall in the Black Sea coastal regions of Romania increases the risk of flooding, and the economic effects of this situation are felt largely in agricultural areas and residential areas. In particular, flood events with long return periods have caused major financial losses in Romania's agricultural production regions.

Türkiye shows the strongest relationship between return periods and economic losses. The analyses reveal that return periods explain 73% of economic losses. The frequency and economic effects of extreme rainfall in Türkiye have been observed more frequently compared to other countries. It is stated in the literature that extreme rainfall in the Black Sea coastal regions of Türkiye causes floods and that the economic effects of these floods are greater, especially in densely populated areas. In addition,

the magnitude of the economic effects of flood events in Türkiye is associated with increasing urbanisation, inadequate infrastructure, and the lack of flood prevention systems.

These findings reveal that flood events with longer return periods have greater economic impacts and that this relationship varies across countries. In line with studies in the literature, it is emphasised that flood events with longer return periods have more serious consequences in terms of both infrastructure damage and economic losses. The study suggests that return periods are an important parameter in flood risk management and that strategies to reduce economic losses should be developed by taking this parameter into account.

Table 4.1. Regression model parameters for regional extreme rainfall events.

Country/Region	β	Intercept (α)	R^2	p-value	statistical significance
Türkiye	0.62	7.02	0.73	0.0016	High
Bulgaria	0.61	5.91	0.57	0.012	Medium
Romania	0.27	7.84	0.32	0.012	Low
Russia	0.18	7.43	0.05	0.52	None
Ukraine	-0.13	7.34	0.03	0.89	None
Black Sea Coast	0.16	7.53	0.05	0.10	Marginal

Table 4.1 shows the regression model parameters for regional extreme precipitation events. Türkiye has the strongest effect on economic losses with a high regression coefficient.

4.2. Future Projections and Expected Economic Losses (2030–2060)

Future climate projections under the SSP5-8.5 scenario indicate significant regional differences in the relationship between extreme precipitation events and economic losses across the Black Sea countries. These projections emphasise the critical role of infrastructure resilience and sector-specific vulnerabilities, such as agriculture, in shaping future economic impacts.

A logarithmic relationship has been observed between the increase in rainfall in Bulgaria and economic losses. This situation emphasises the decisive role of rainfall on economic impacts. In particular, it is observed that the economic impacts of major flood events are associated with weaknesses in the infrastructure and agricultural sectors. Based on future projections, infrastructure improvement works and the development of preventive policies for the agricultural sector are recommended.

Analyses in Romania reveal that the frequency and intensity of extreme rainfall events show regional differences. The economic impacts of extreme rainfall events, especially in July and September, are striking. A logarithmic relationship has been observed between the increase in extreme rainfall and economic losses in Romania. Losses in the agricultural and infrastructure sectors increase depending on the regional intensity of extreme events. The reasons for the high economic losses caused by floods in Romania are based on both natural and human-induced factors. The geographical structure of the country, especially the deep valleys in mountainous and hilly regions and the riverbeds with high flood risk, are prone to floods and flash floods. In addition, infrastructure deficiencies, illegal deforestation, poor agricultural practices, inadequate urban planning, and deficiencies in flood prevention efforts significantly increase the effects of floods. The main reasons for this disaster include excessive rainfall, deforestation deteriorating soil stability, construction on riverbanks, inadequate drainage systems, and deficiencies in warning systems. The efforts to reduce the effects of floods in Romania are defined as complex processes that require time and financial resources (Constantin-Horia *et al.*, 2009). Based on future projections, it is recommended to improve water management systems in agricultural areas and strengthen urban infrastructure.

Projections made in Türkiye reveal the regional distribution and economic impacts of extreme precipitation events in detail. The frequency and intensity of extreme precipitation events are particularly striking in the Western Black Sea, Central Black Sea and Eastern Black Sea regions. It has been determined that there is a logarithmic relationship between the increase in extreme precipitation in Türkiye and economic

losses. Extreme events, especially in regions such as the Western Black Sea and Istanbul, show the sensitivity of infrastructure and urbanisation structures to extreme precipitation. Based on future projections, it is recommended to strengthen urban infrastructure, improve water management systems and develop early warning systems.

In particular, Türkiye and Russia experienced more flood events in the summer months. These results are consistent with the findings in the literature. For example, various studies have emphasised that flood events increase in the summer months and that heavy rainfall during this period causes floods. In addition, it is frequently stated in the literature that the countries with the highest economic losses are densely populated and have sensitive infrastructures. In addition, the fact that long flood events in Romania are caused by long-term extreme rainfalls also affects the country's resilience and increases economic losses. The fact that Romania, Russia, and Türkiye stand out in this context reveals that the economic effects of flood events may show regional differences. In line with the findings in the literature, it is recommended that preventive measures be taken against the increased flood risk in the summer months and policies to reduce economic losses be strengthened.

This study contributes to the development of strategies to manage flood risk in the Bulgaria, Romania, and Türkiye by examining both the economic effects of flood events. In line with the findings in the literature, it is recommended that preventive measures be taken against the increased flood risk in the summer months and policies to reduce economic losses be strengthened.

4.3. Recommendations

The analysis has revealed that there are significant differences in the frequency, intensity, and return periods of extreme precipitation events among the countries on the Black Sea coast. These differences necessitate the development of specific adaptation strategies according to the nature of the risks faced by each country.

Firstly, deficiencies in the EM-DAT database and exclusion of Georgia from the analysis may have limited the scope of the study. I recommend a more comprehensive and standardised data collection system for future studies. In particular, better reporting of small-scale but frequently occurring extreme precipitation events should be ensured. Data sharing and joint flood risk management projects should be developed among the countries bordering the Black Sea. Regional cooperation can enable the development of more effective strategies to reduce the economic impact of floods.

In addition, while the relationship between return periods and economic losses has been strongly demonstrated in countries such as Türkiye, Bulgaria and Romania, the weakness of this relationship in countries such as Russia and Ukraine indicates that regional differences should be examined in more detail. More specific analyses can be conducted by taking into account the infrastructure, economic structure, and climatic characteristics in these countries.

Bulgaria is seen to be the most vulnerable country to extreme precipitation with its high frequency of events and short return periods. This situation necessitates the expansion of early warning systems, the strengthening of rural and urban infrastructure, and the adoption of seasonal measures against risks that are particularly concentrated in February. In Romania, despite long return periods, high precipitation intensities are striking. In this country, where agricultural production is greatly affected, it is recommended to develop climate-adapted agricultural policies, modernise water management systems, and increase preparations for the particularly risky period of July.

In Türkiye, the fact that extreme rainfalls occur more frequently and have shorter return periods indicates that the economic effects of these events may be more widespread and permanent. Considering the effects of past floods on infrastructure, transportation, and energy systems in the Marmara and Black Sea regions, urban planning needs to be reorganized, and rainwater drainage systems, especially in densely populated areas such as Istanbul, need to be strengthened.

In Russia, extreme precipitation events are rare, but their intensity is high, which shows that even rare events can have devastating effects. Therefore, mitigation measures should be taken, especially in fragile areas such as agricultural lands and energy infrastructure, and the capacity to prepare for events with high return periods should be strengthened. In Ukraine, despite the relatively low frequency of events, early response plans based on long-term climate scenarios should be developed in advance of high-risk precipitation events that are likely to occur in 2032.

These findings reveal that flood events with longer return periods have greater economic impacts and that this relationship varies across countries. In line with studies in the literature, it is emphasised that flood events with longer return periods have more serious consequences in terms of both infrastructure damage and economic losses. The study suggests that return periods are an important parameter in flood risk management and that strategies to reduce economic losses should be developed by taking this parameter into account. Therefore, advanced analyses supported by more complex statistical models and projection methods will enable more precise predictions of future economic and social impacts. Common flood risk management strategies developed through regional cooperation and data sharing can provide more effective and sustainable solutions for the Black Sea coastal countries.

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APPENDIX A: ERA5 DAILY TOTAL PRECIPITATION MAPS FOR FLOOD EVENTS BY COUNTRY

This appendix presents maps of daily total precipitation amounts visualised to determine the location and amount of maximum pre-flood rainfall on the dates of flood events specified in the EM-DAT database.

The maps were created using ERA5 reanalysis data. The calculated total rainfall values are shown with a colour scale. Visualisations of rainfall amounts by country on dates associated with EM-DAT flood events are below.

A.1. Bulgaria

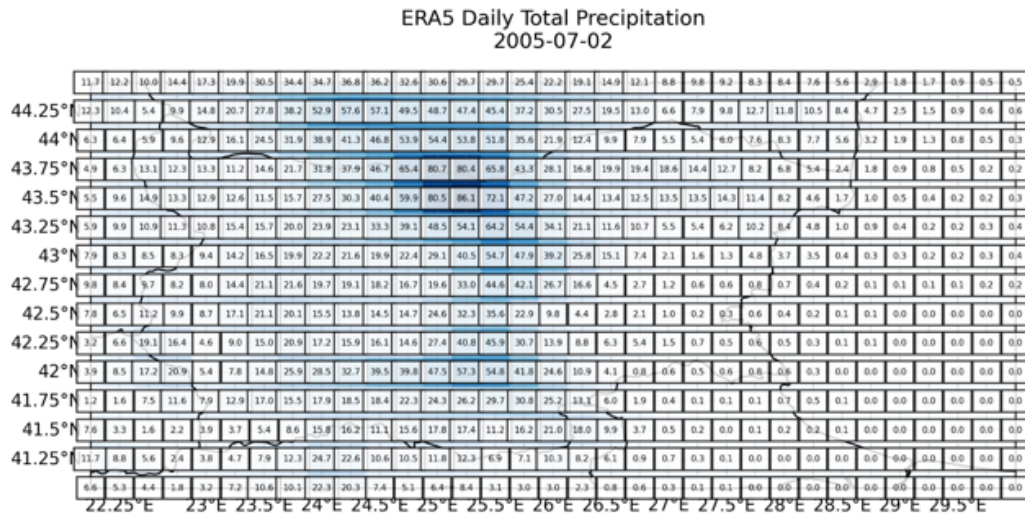


Figure A.1. ERA5 daily total precipitation on 2005-07-02.

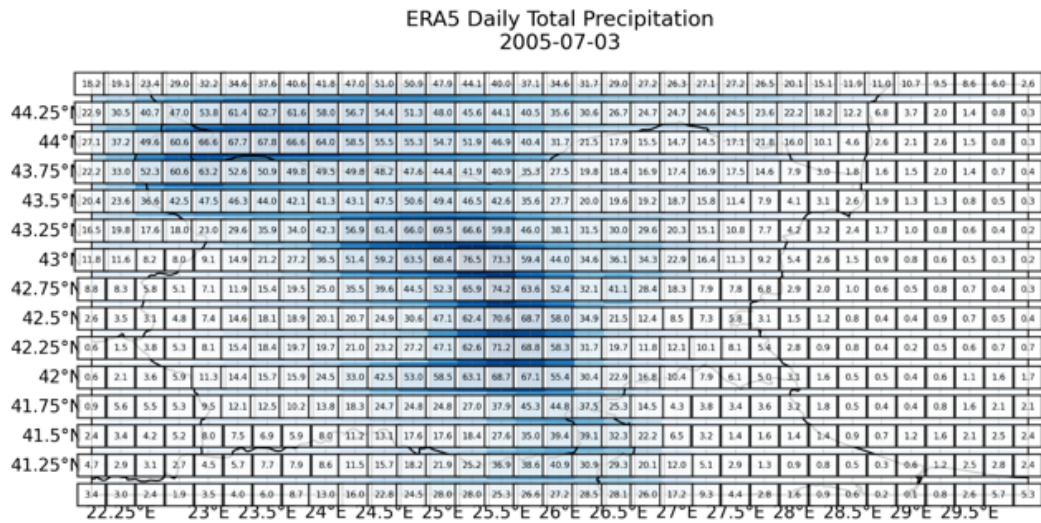


Figure A.2. ERA5 daily total precipitation on 2005-07-03.

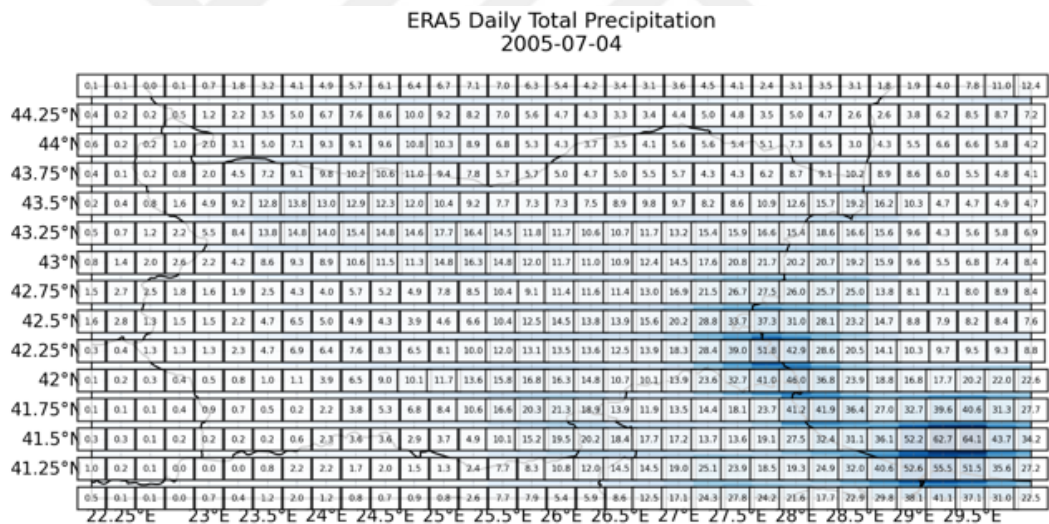


Figure A.3. ERA5 daily total precipitation on 2005-07-04.

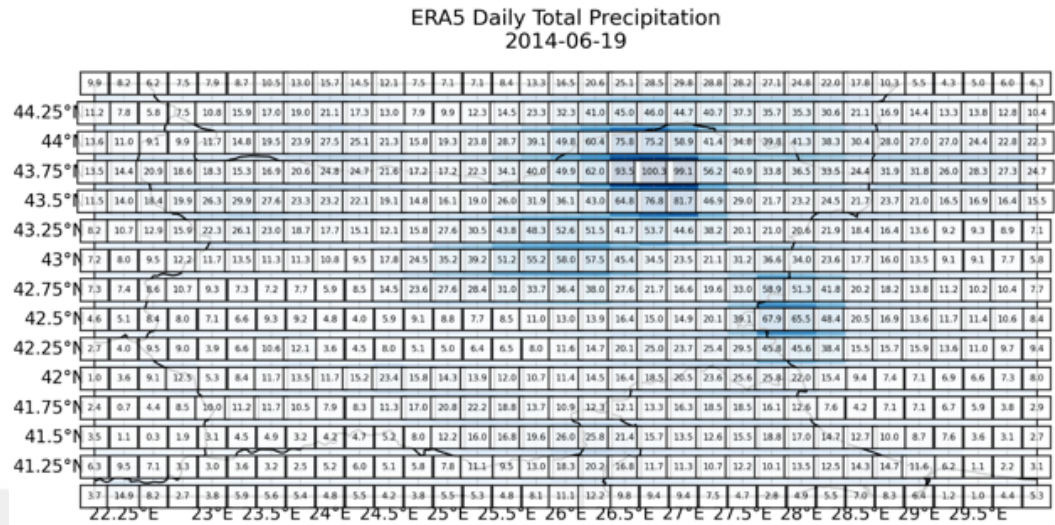


Figure A.4. ERA5 daily total precipitation on 2014-06-19.

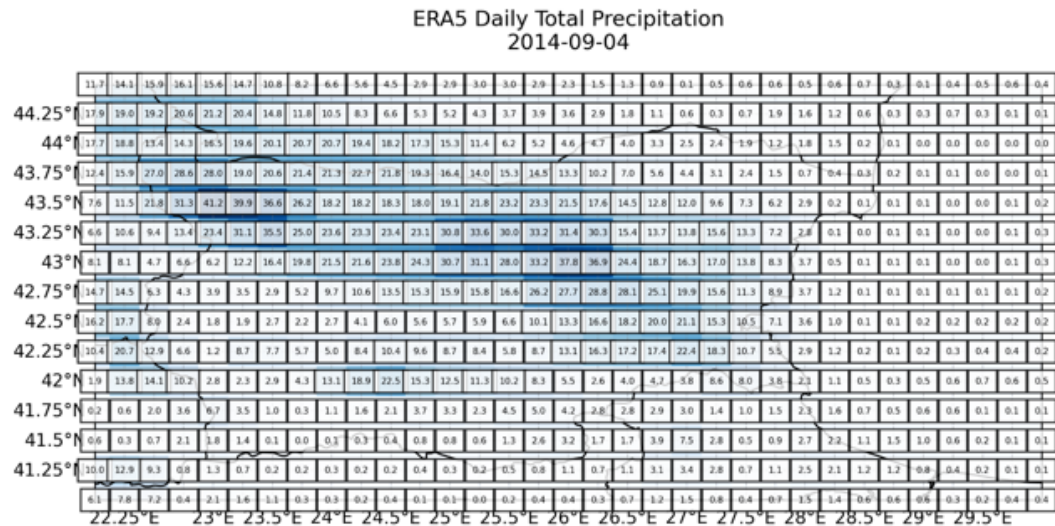


Figure A.5. ERA5 daily total precipitation on 2014-09-04.

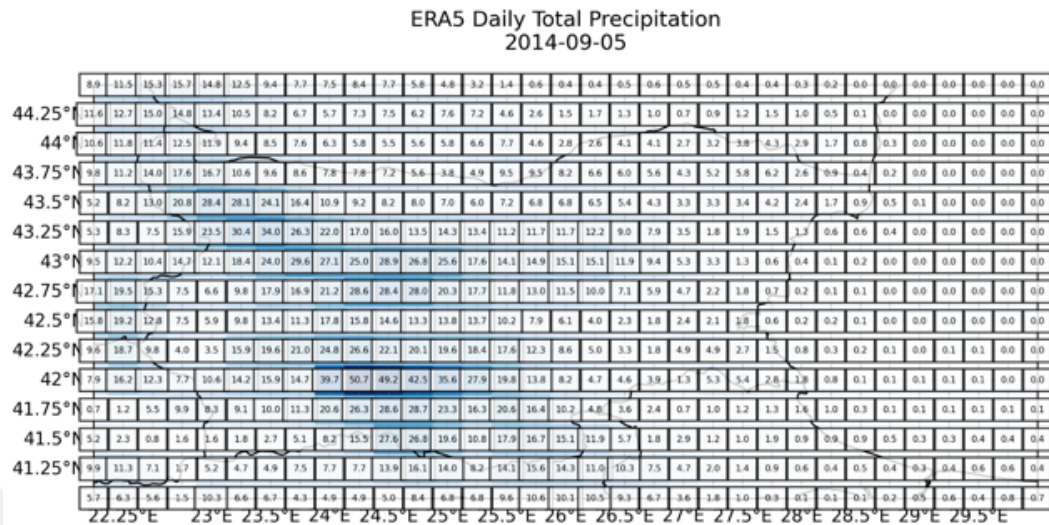


Figure A.6. ERA5 daily total precipitation on 2014-09-05.

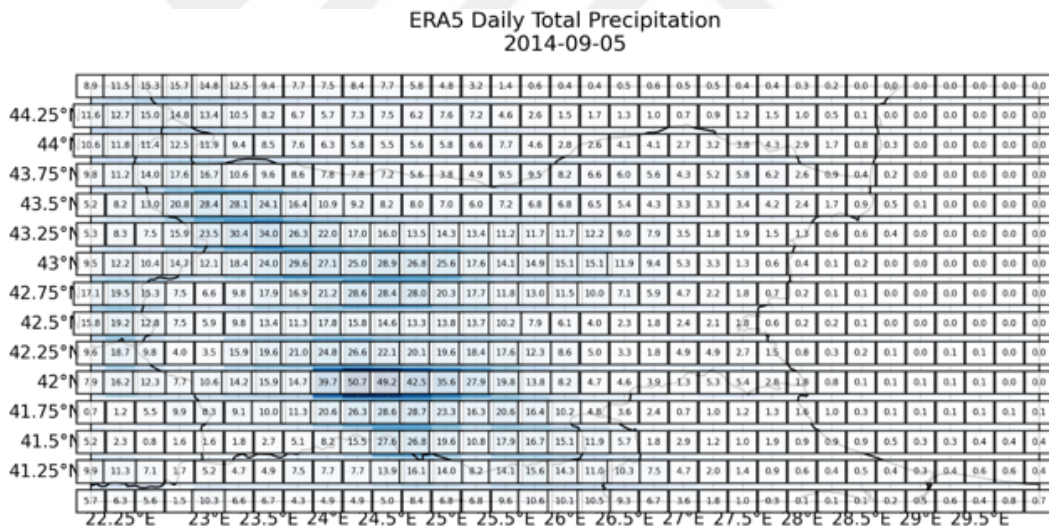


Figure A.7. ERA5 daily total precipitation on 2014-09-06.

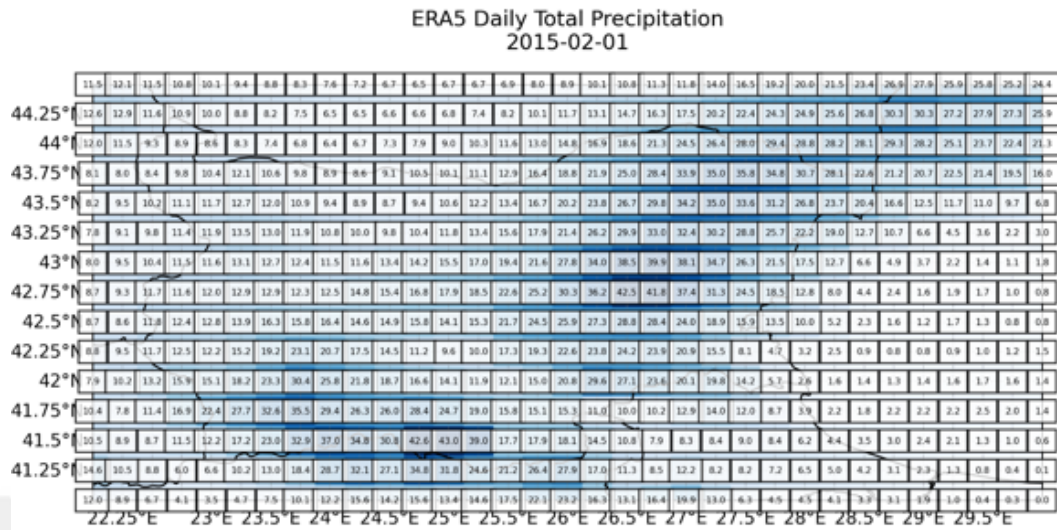


Figure A.8. ERA5 daily total precipitation on 2015-02-01.

A.2. Romania

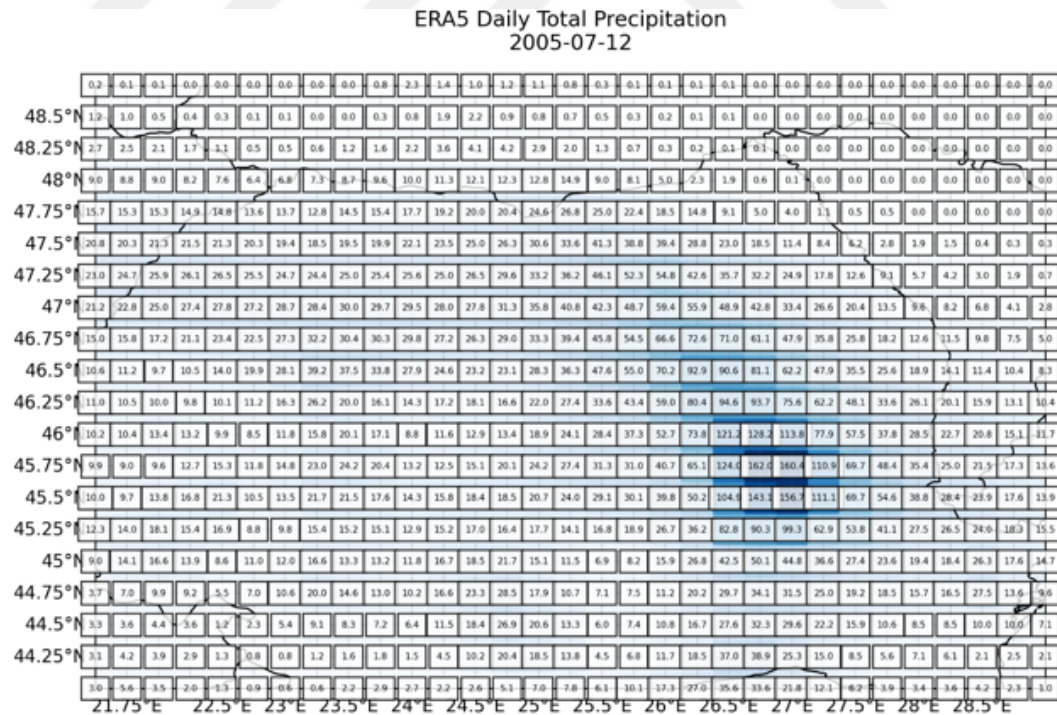


Figure A.9. ERA5 daily total precipitation on 2005-07-12.

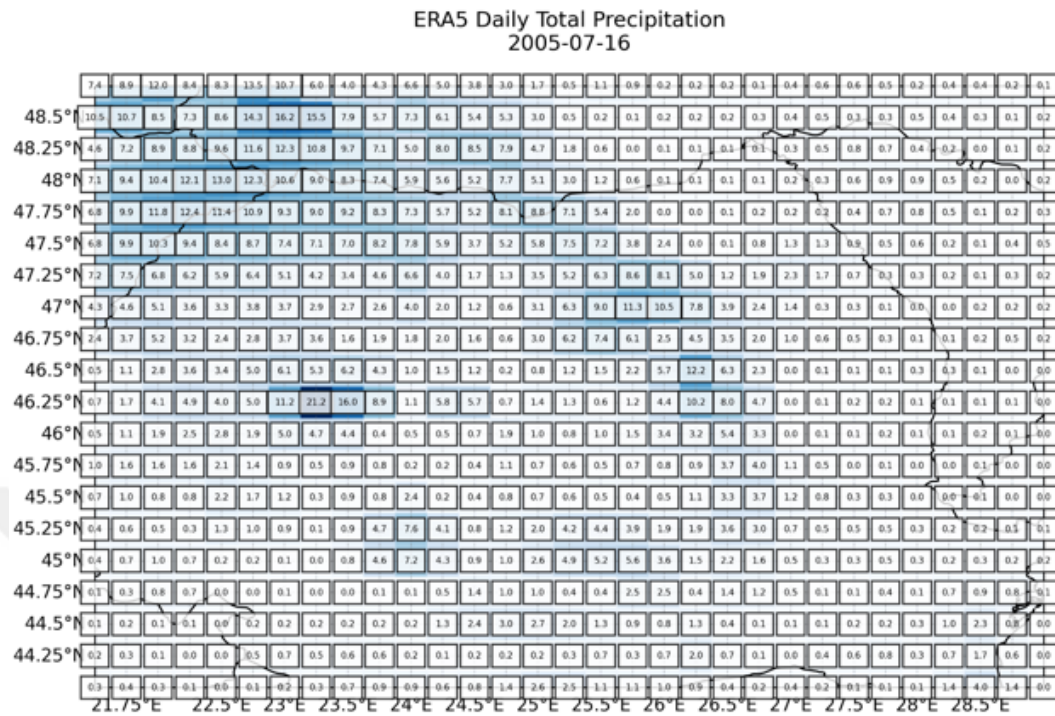


Figure A.10. ERA5 daily total precipitation on 2005-07-16.

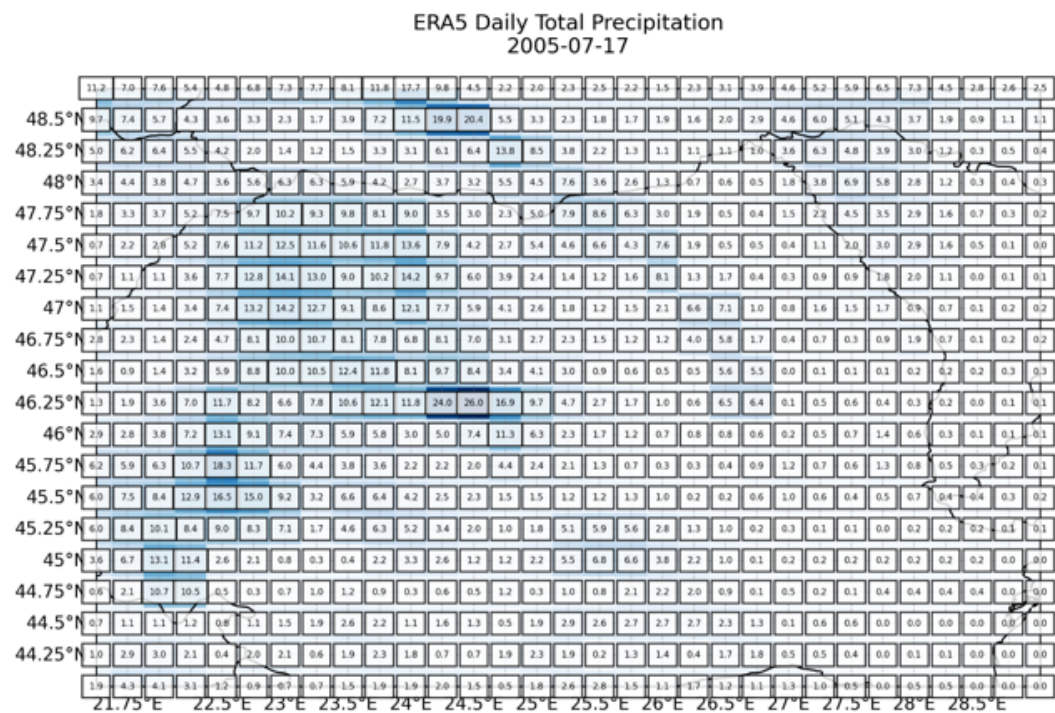


Figure A.11. ERA5 daily total precipitation on 2005-07-17.

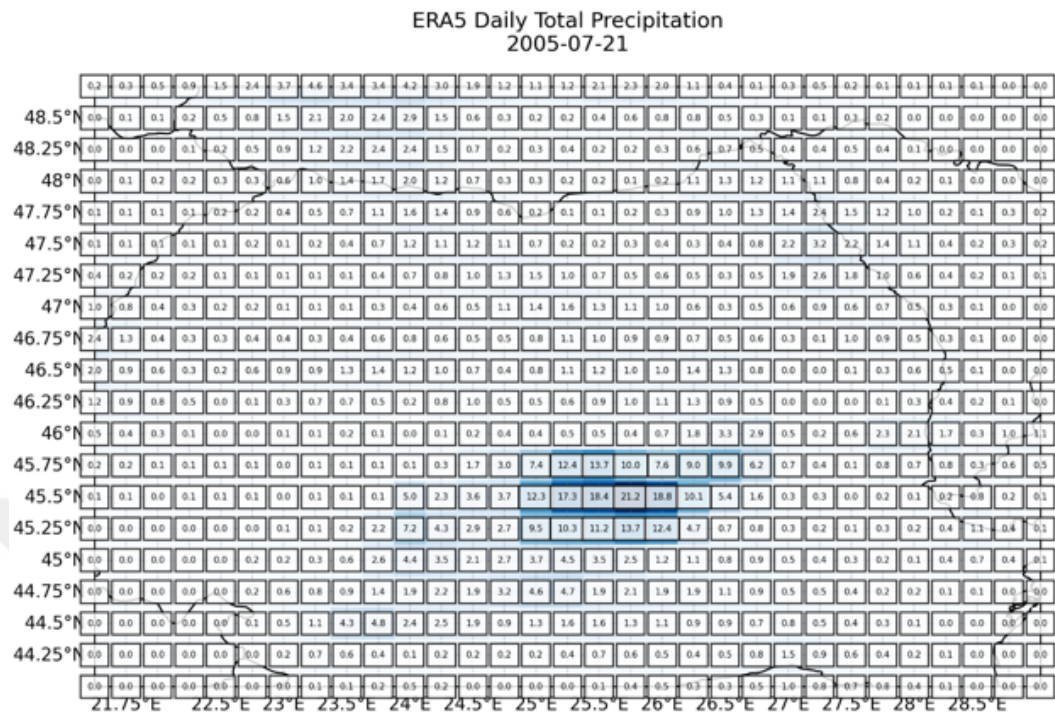


Figure A.12. ERA5 daily total precipitation on 2005-07-21.

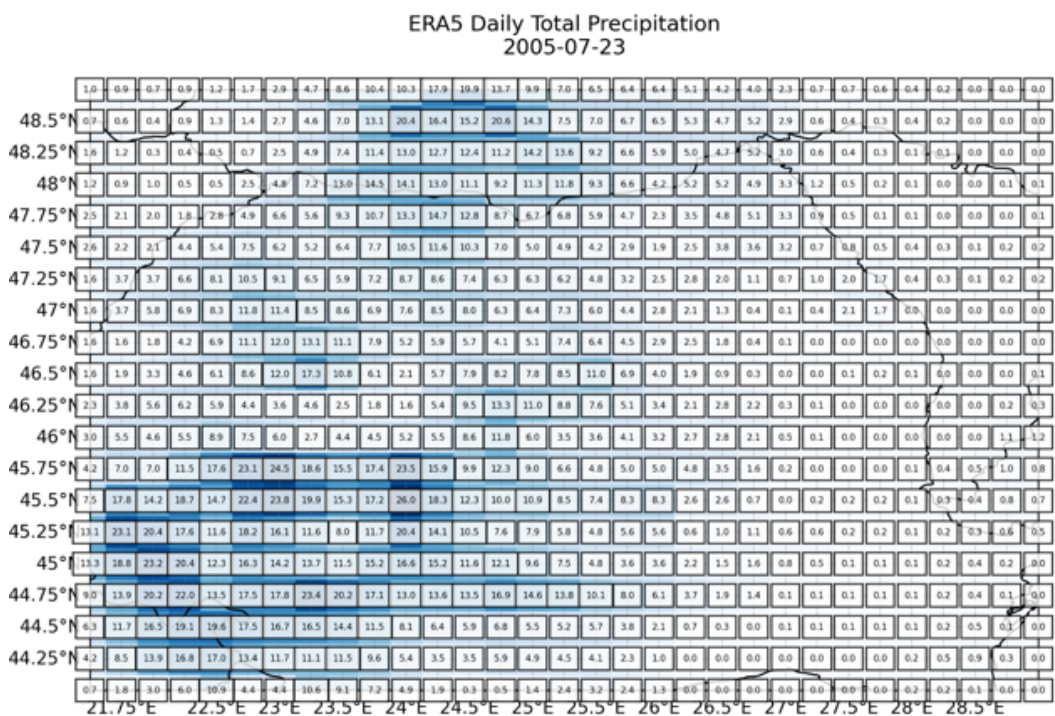


Figure A.13. ERA5 daily total precipitation on 2005-07-23.

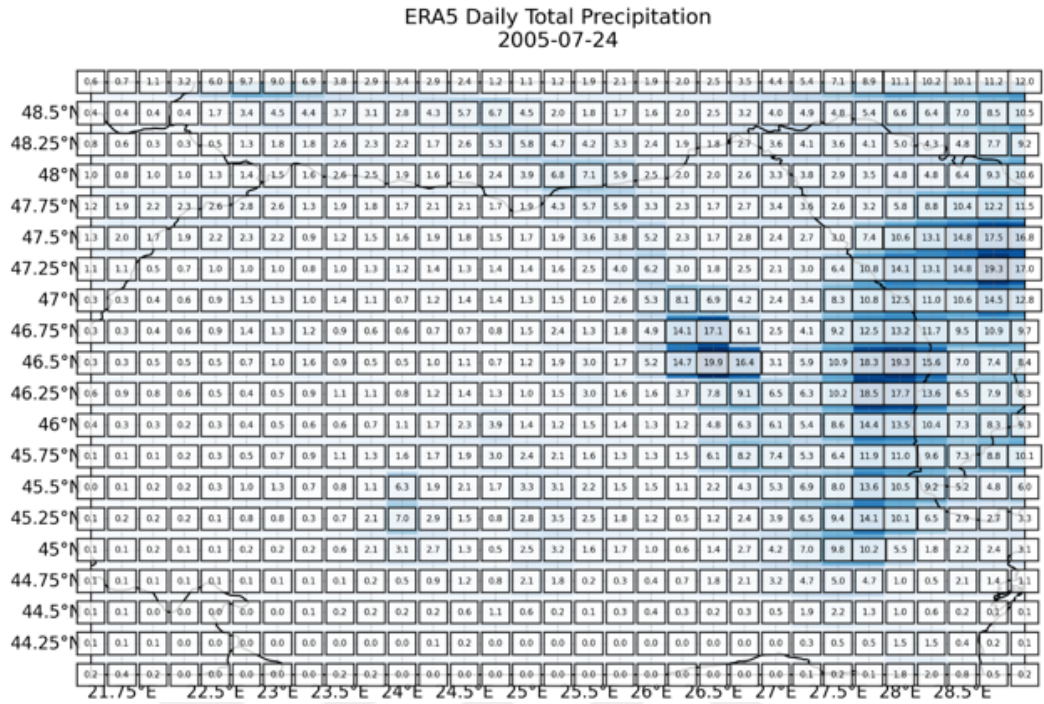


Figure A.14. ERA5 daily total precipitation on 2005-07-24.

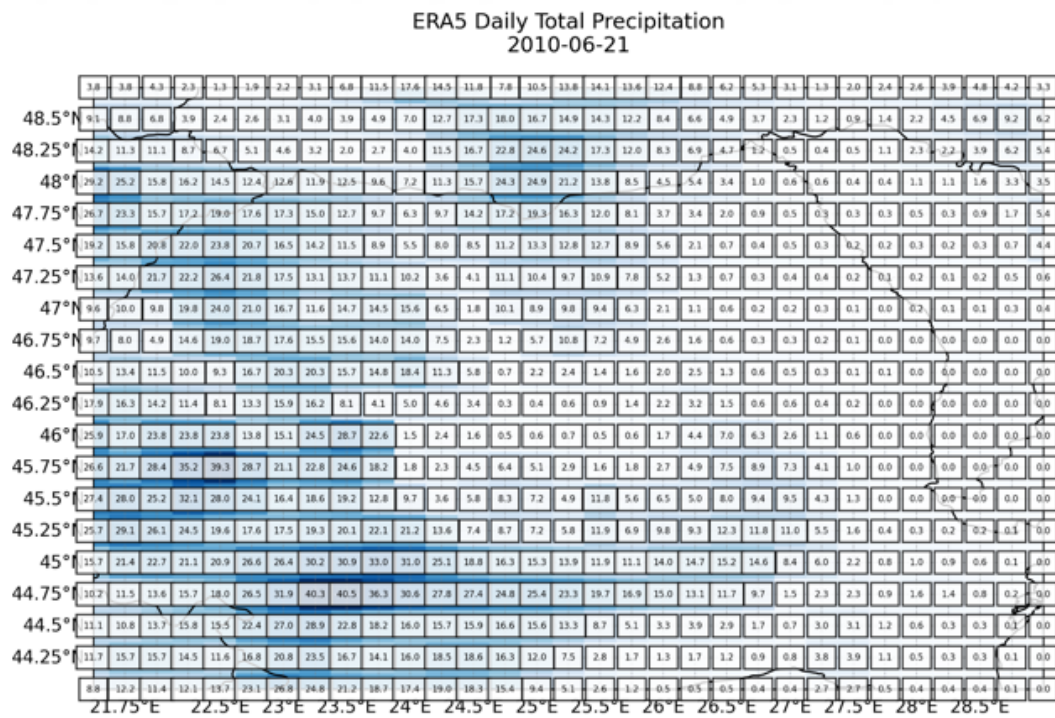


Figure A.15. ERA5 daily total precipitation on 2010-06-21.

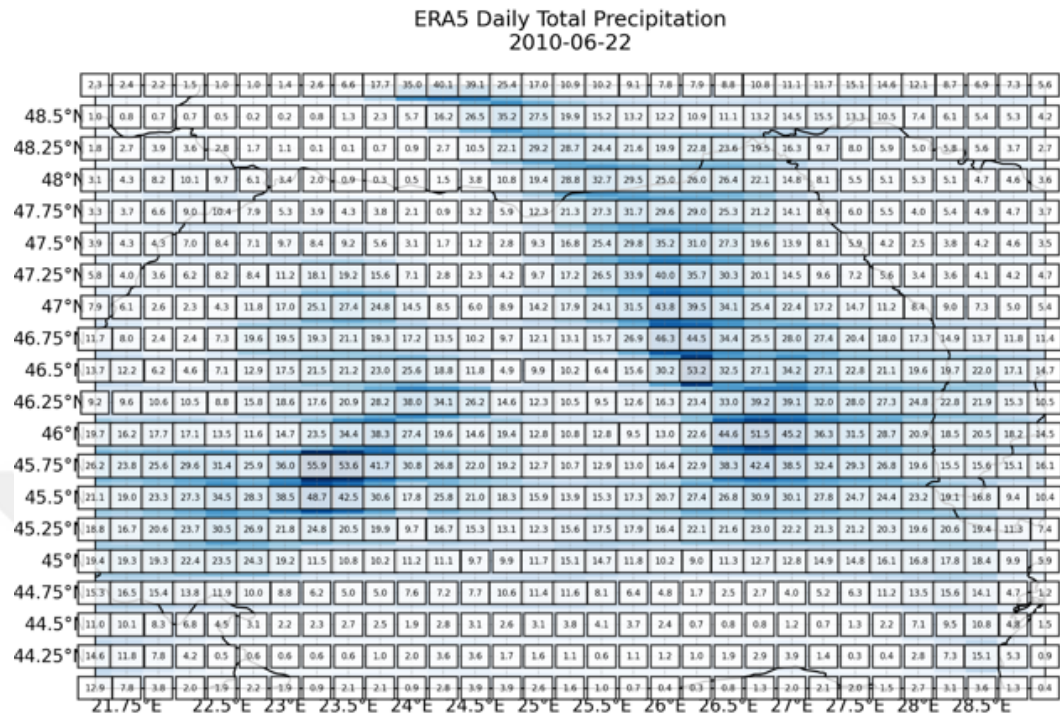


Figure A.16. ERA5 daily total precipitation on 2010-06-22.

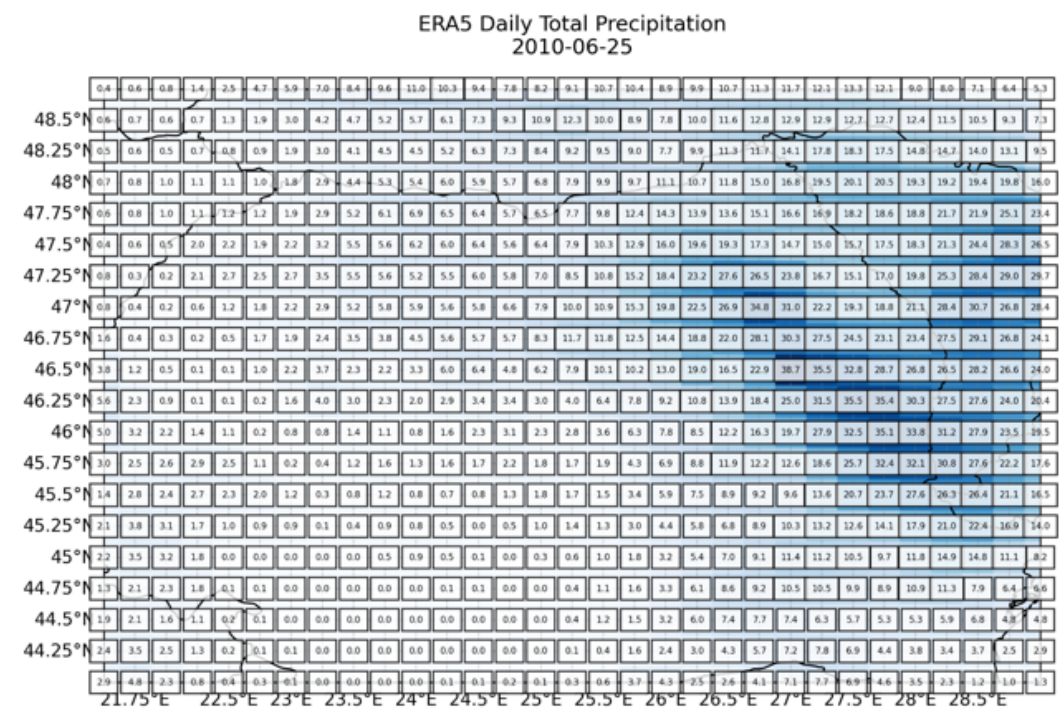


Figure A.17. ERA5 daily total precipitation on 2010-06-25.

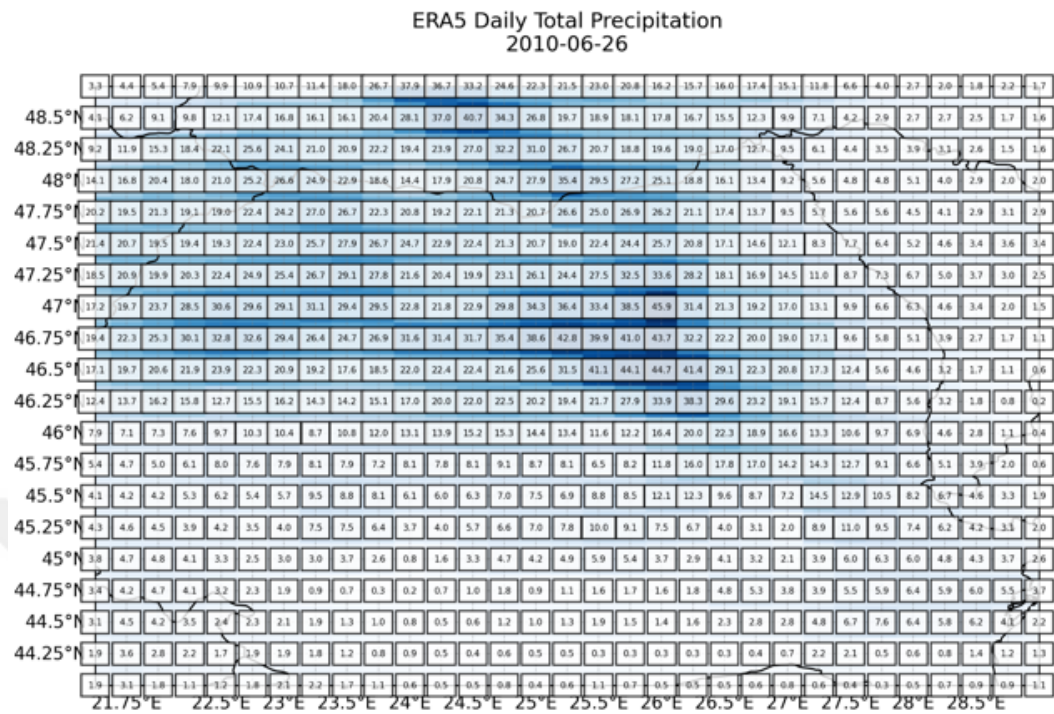


Figure A.18. ERA5 daily total precipitation on 2010-06-26.

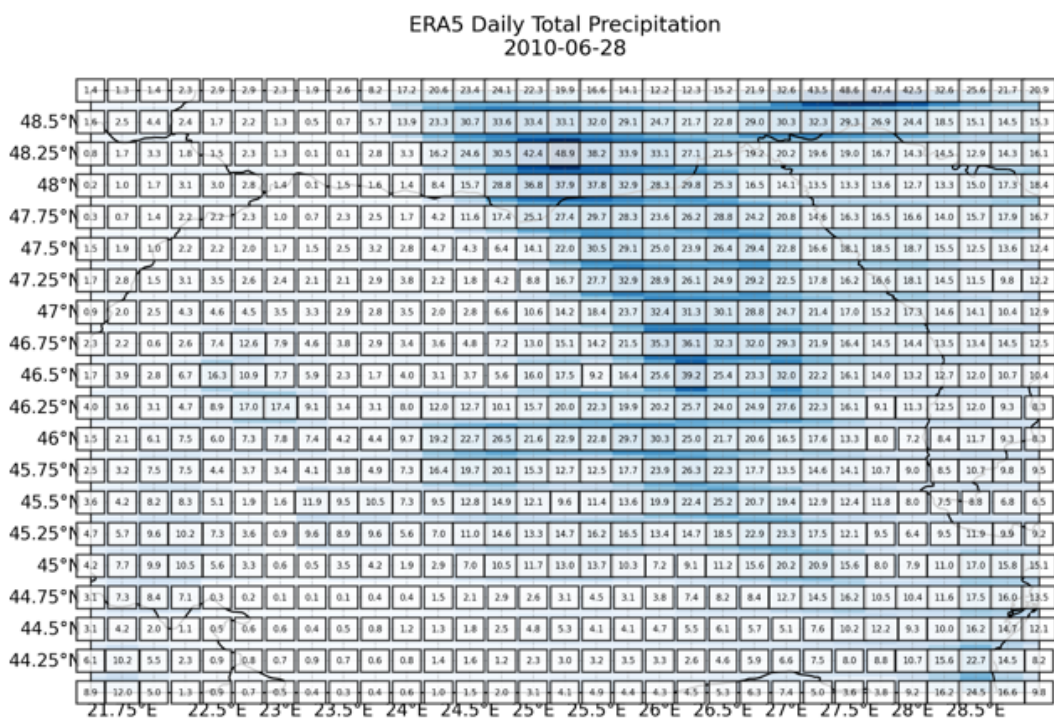


Figure A.19. ERA5 daily total precipitation on 2010-06-28.

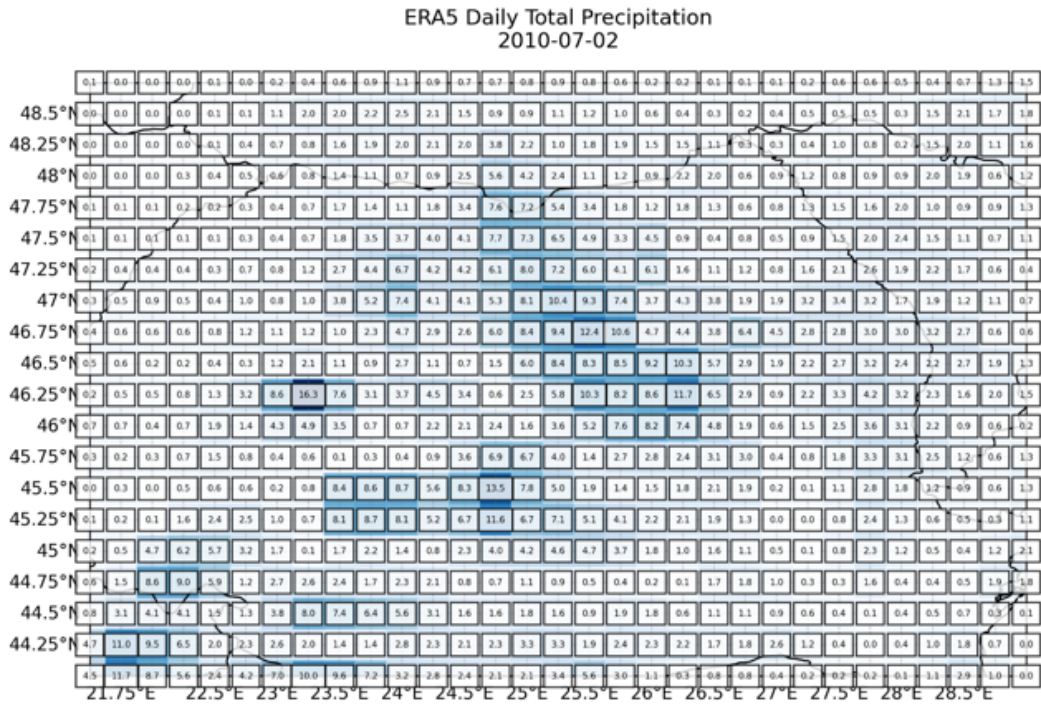


Figure A.20. ERA5 daily total precipitation on 2010-07-02.

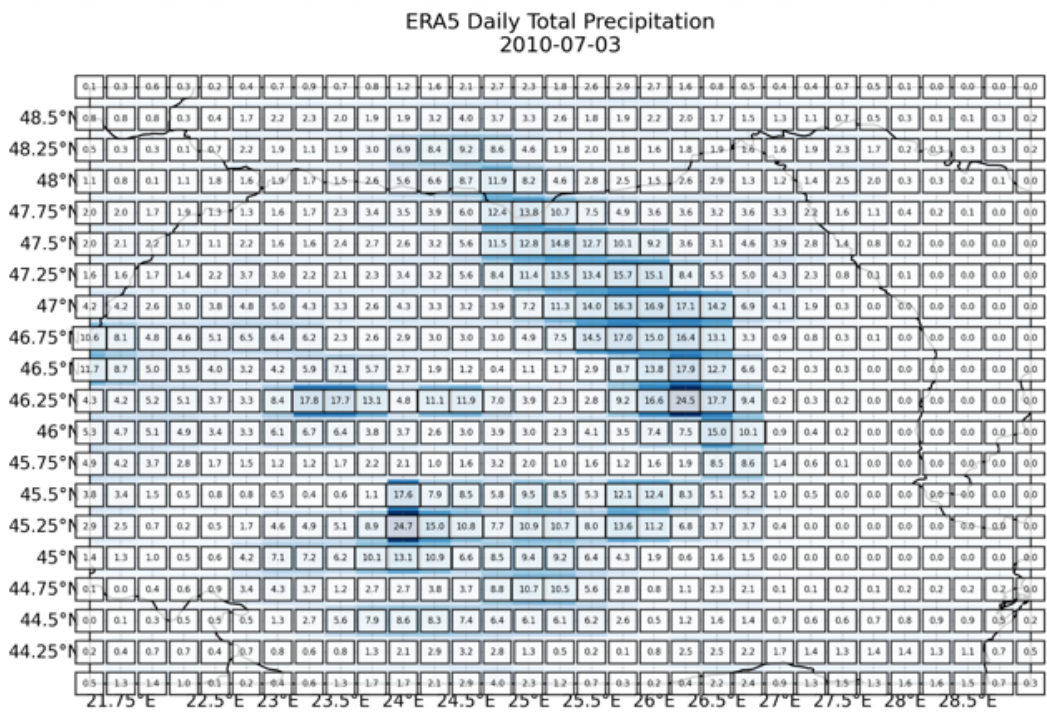


Figure A.21. ERA5 daily total precipitation on 2010-07-03.

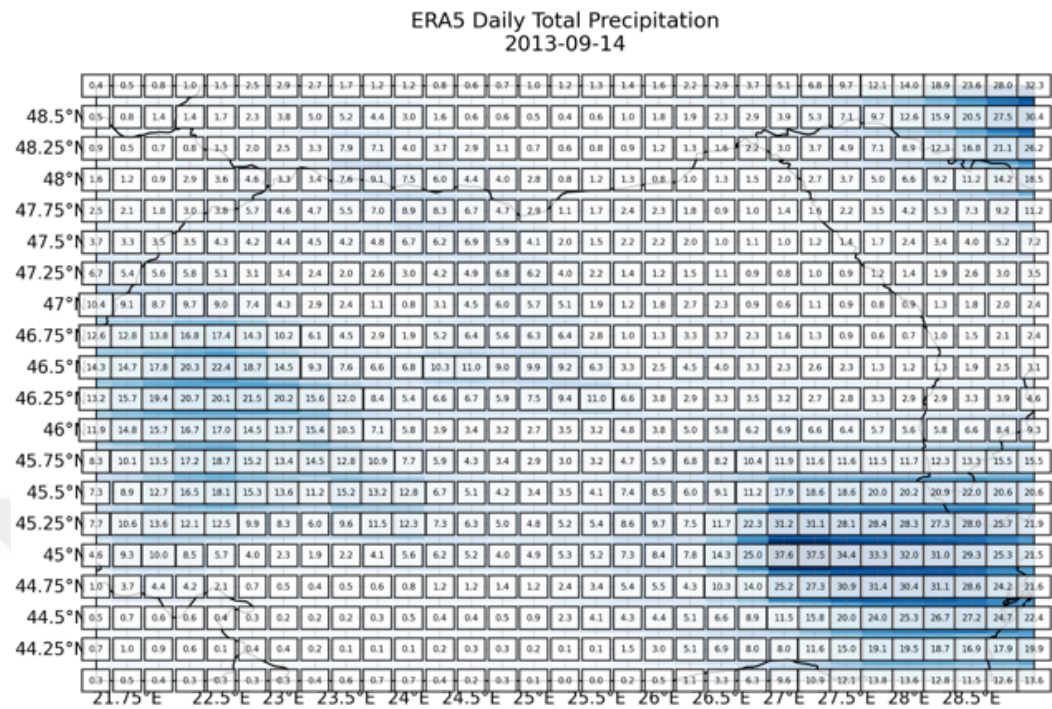


Figure A.22. ERA5 daily total precipitation on 2013-09-14.

A.3. Russia

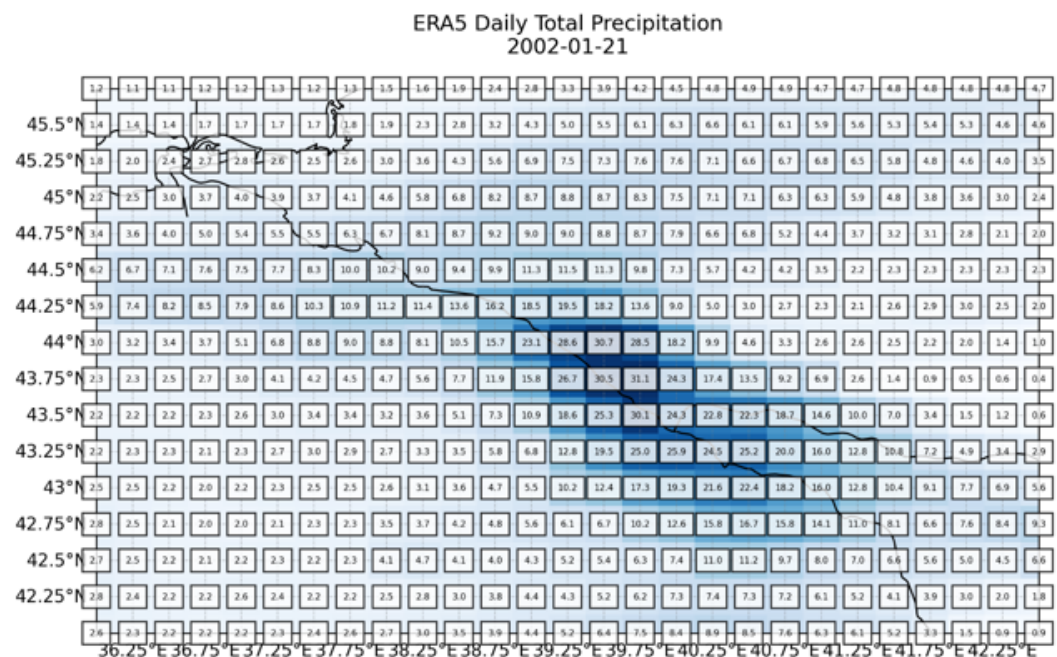


Figure A.23. ERA5 daily total precipitation on 2002-01-21.

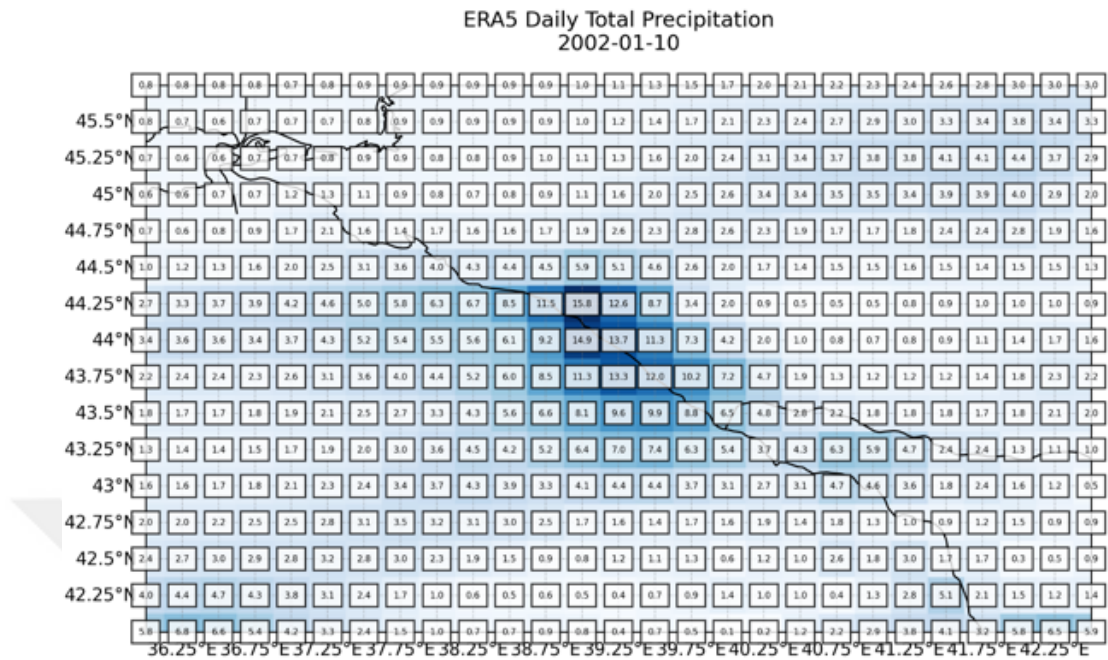


Figure A.24. ERA5 daily total precipitation on 2002-01-21.

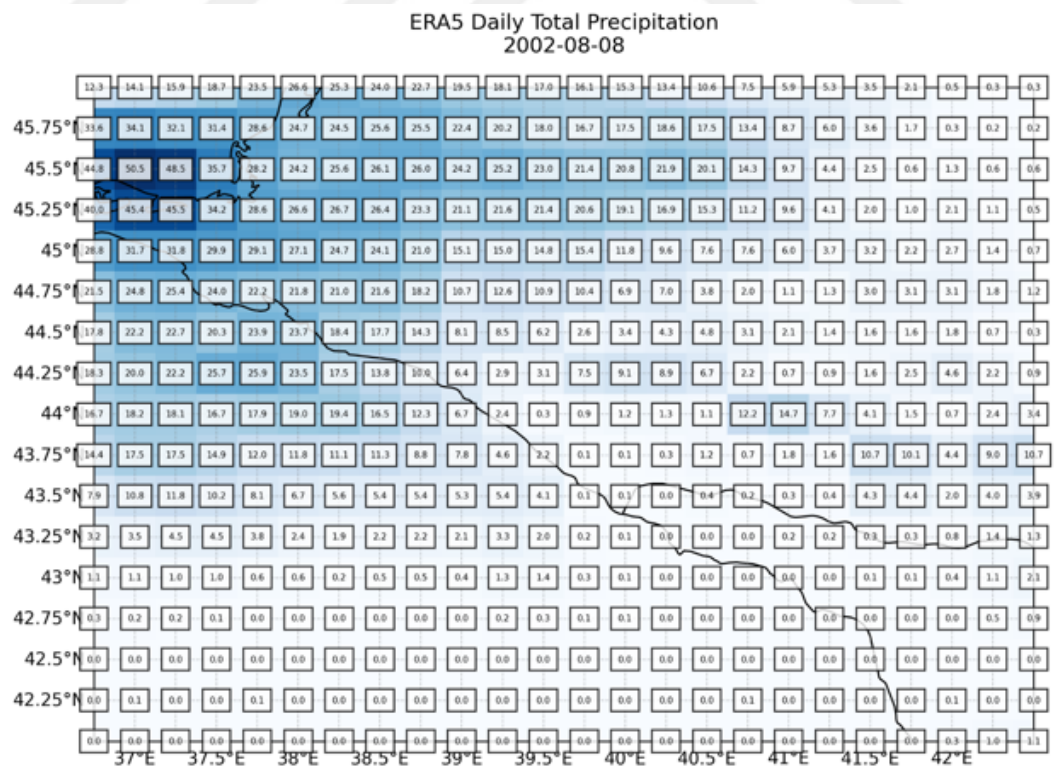


Figure A.25. ERA5 daily total precipitation on 2002-08-08.

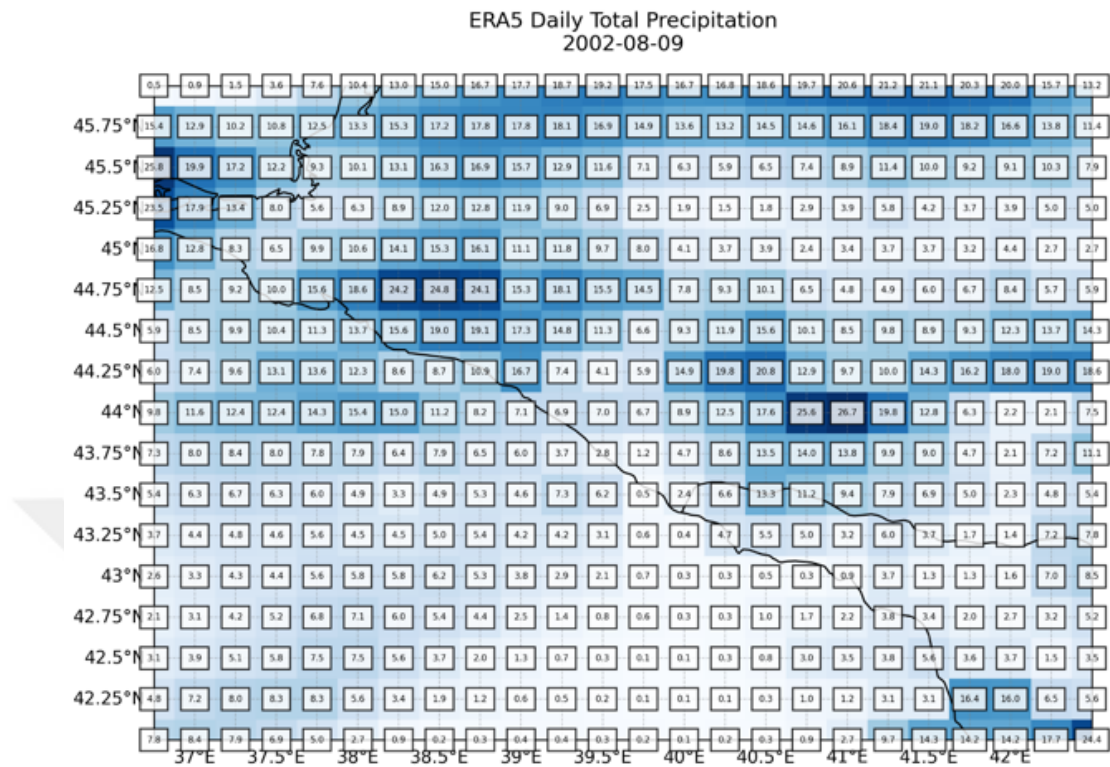


Figure A.26. ERA5 daily total precipitation on 2002-08-09.

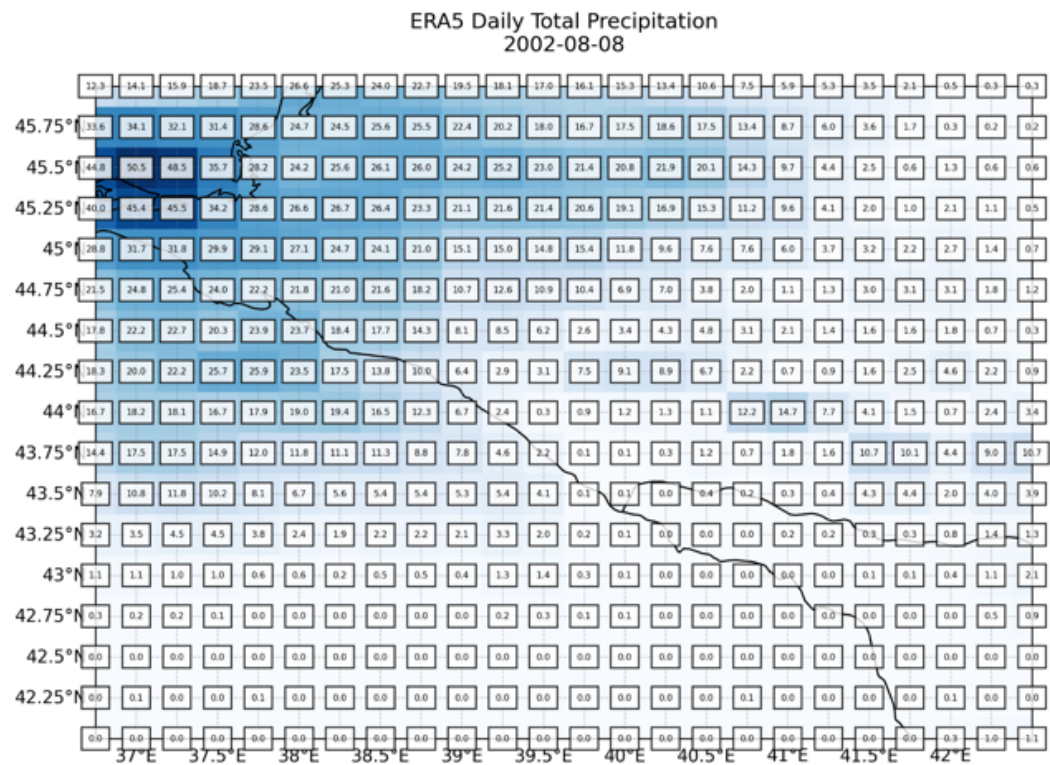


Figure A.27. ERA5 daily total precipitation on 2002-08-08.

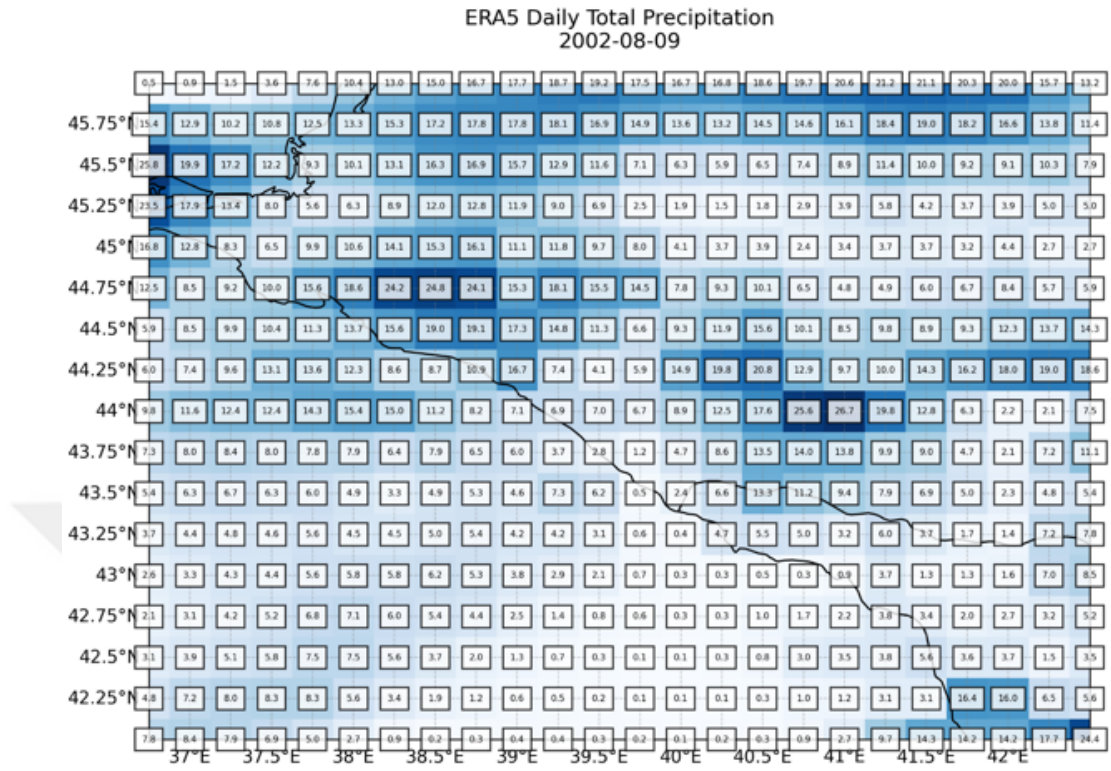


Figure A.28. ERA5 daily total precipitation on 2002-08-09.

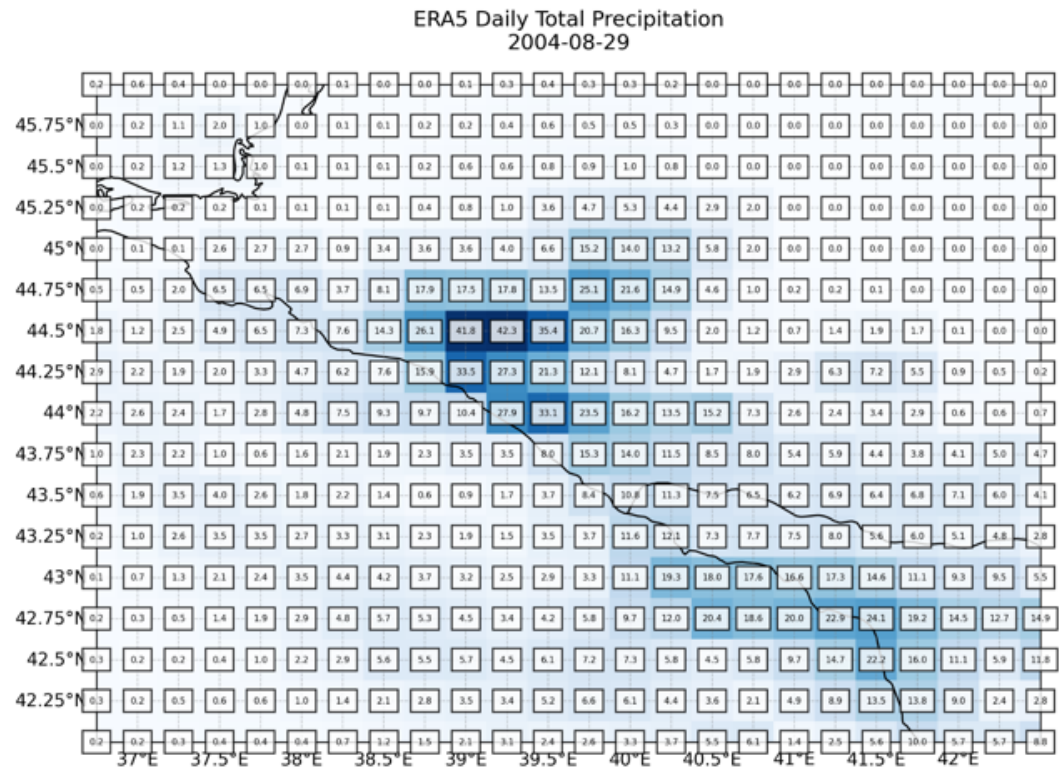


Figure A.29. ERA5 daily total precipitation on 2004-08-29.

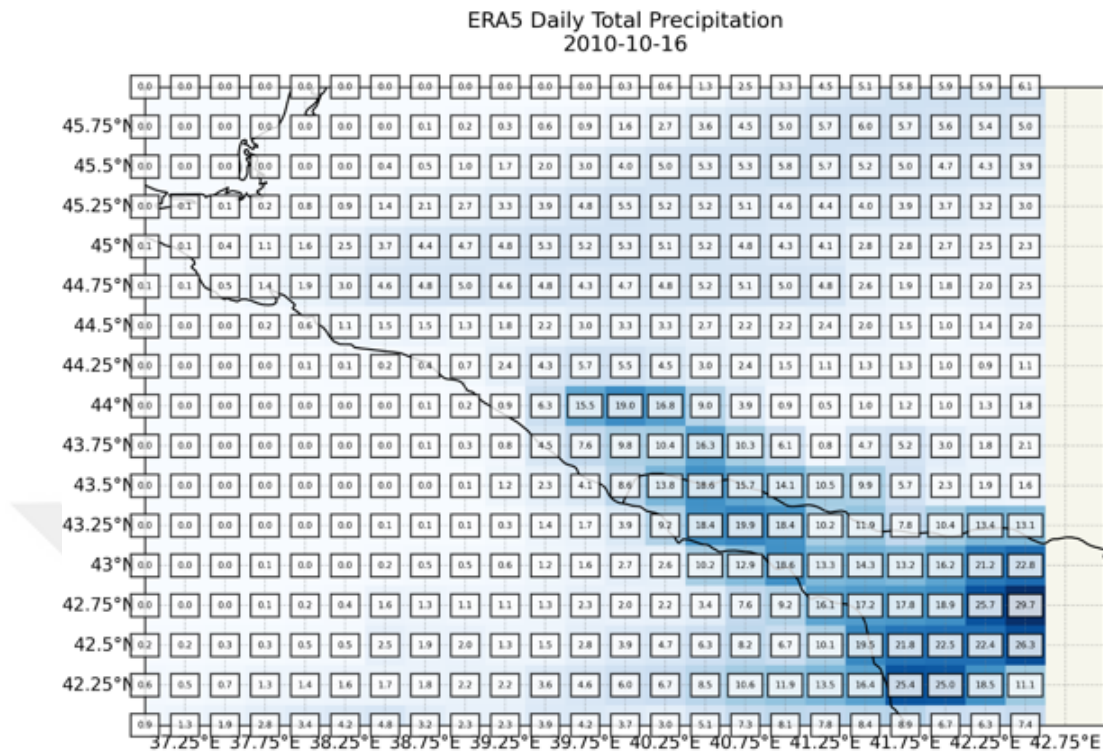


Figure A.30. ERA5 daily total precipitation on 2010-10-18.

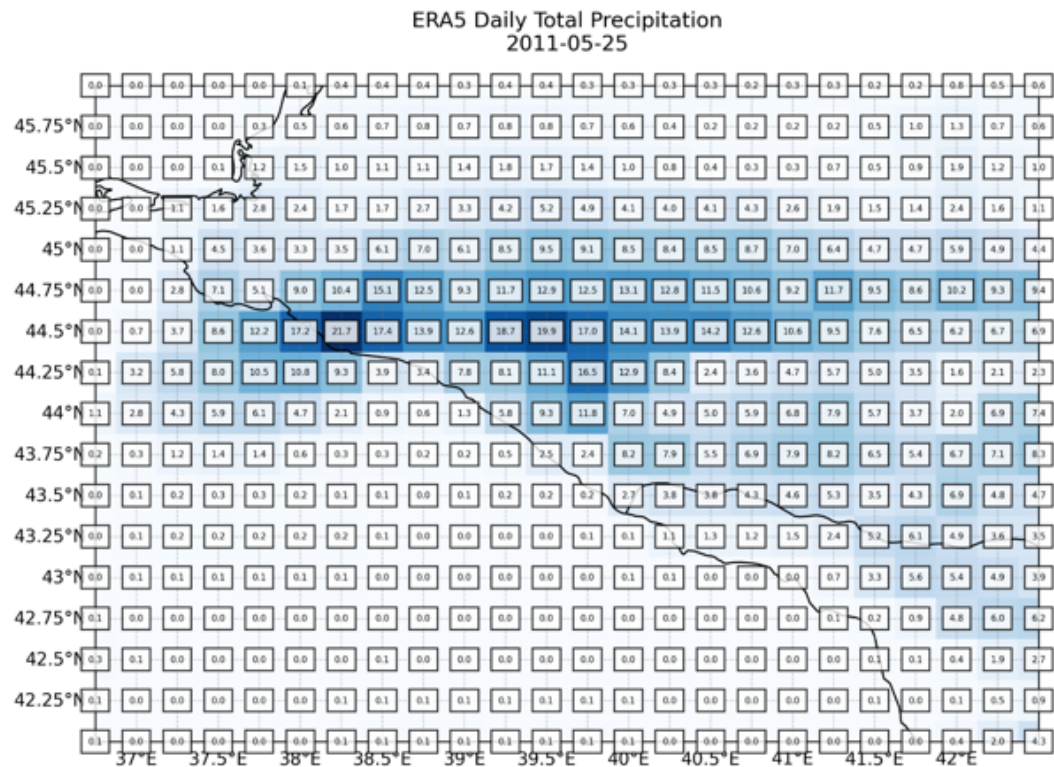


Figure A.31. ERA5 daily total precipitation on 2011-05-25.

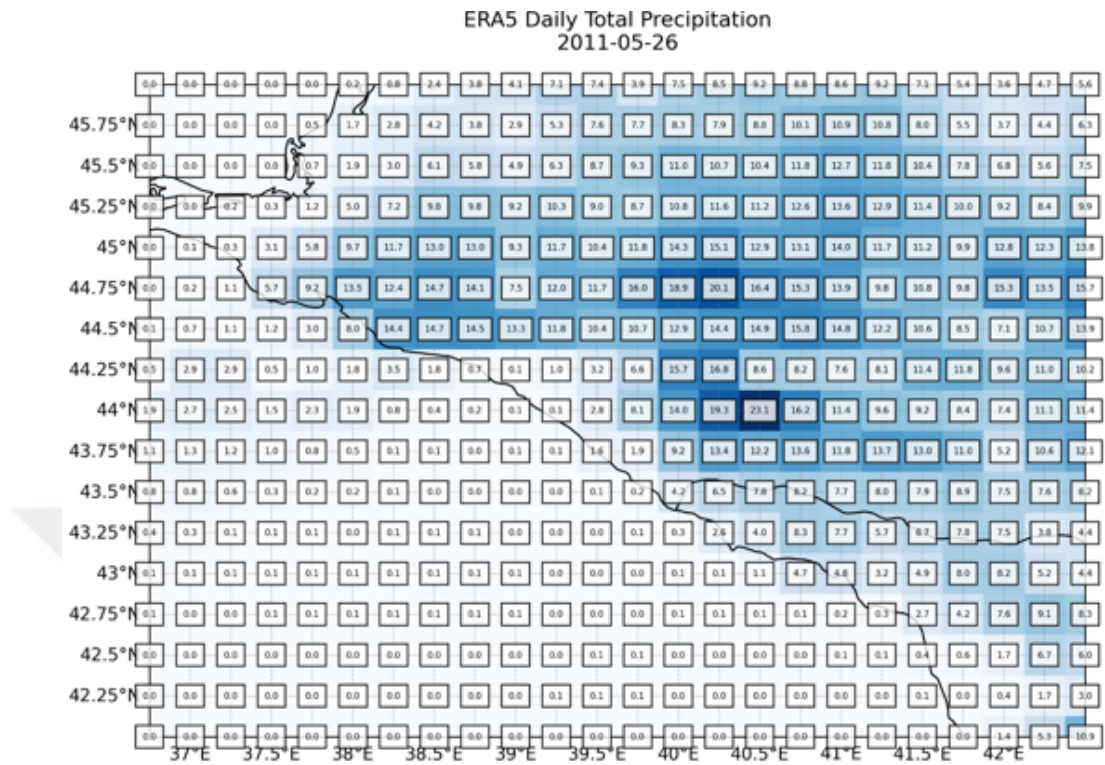


Figure A.32. ERA5 daily total precipitation on 2011-05-26.

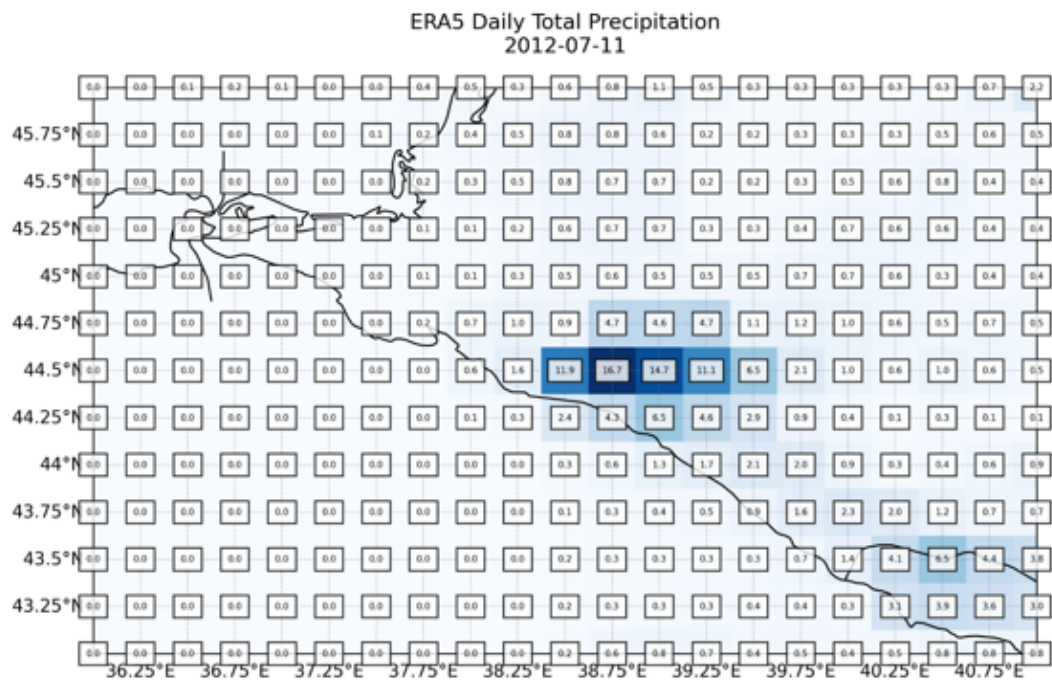


Figure A.33. ERA5 daily total precipitation on 2012-07-11.

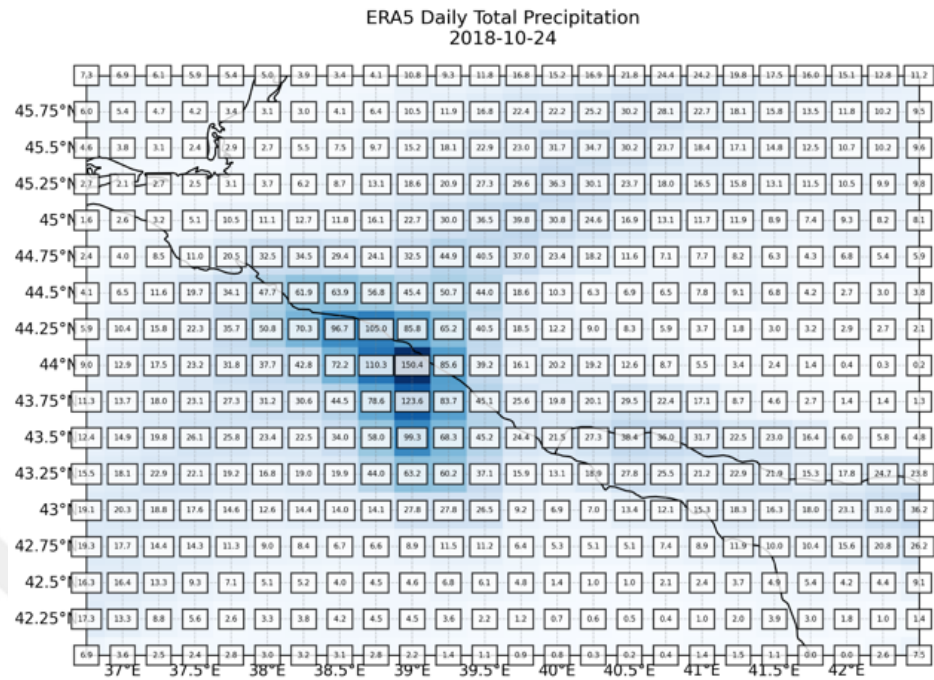


Figure A.34. ERA5 daily total precipitation on 2018-10-24.

A.4. Türkiye

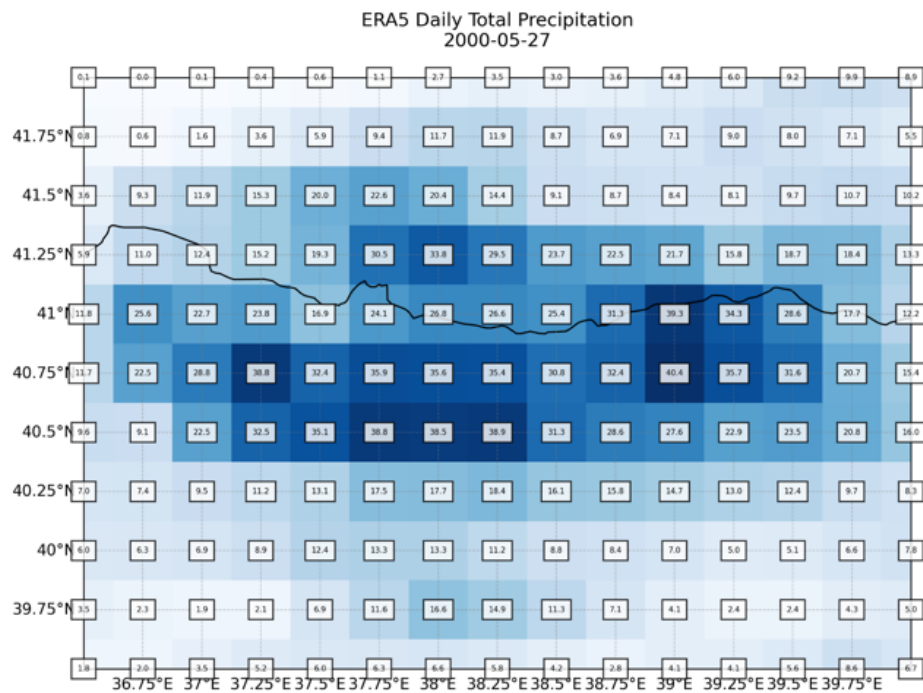


Figure A.35. ERA5 daily total precipitation on 2000-05-27.

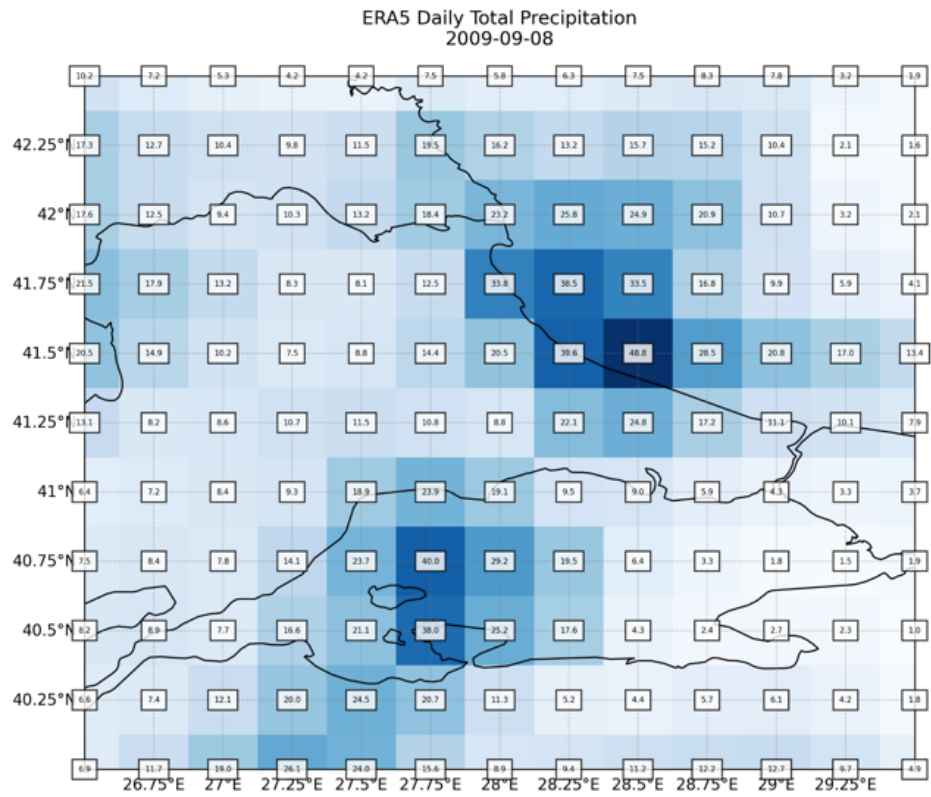


Figure A.36. ERA5 daily total precipitation on 2009-09-08.

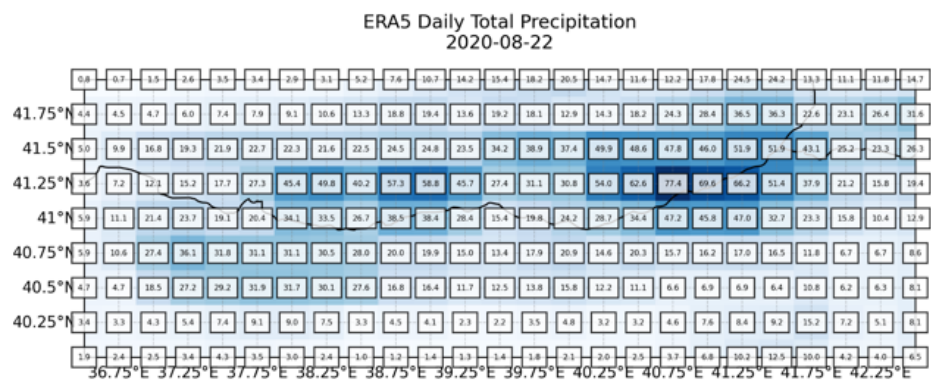


Figure A.37. ERA5 daily total precipitation on 2020-08-22.

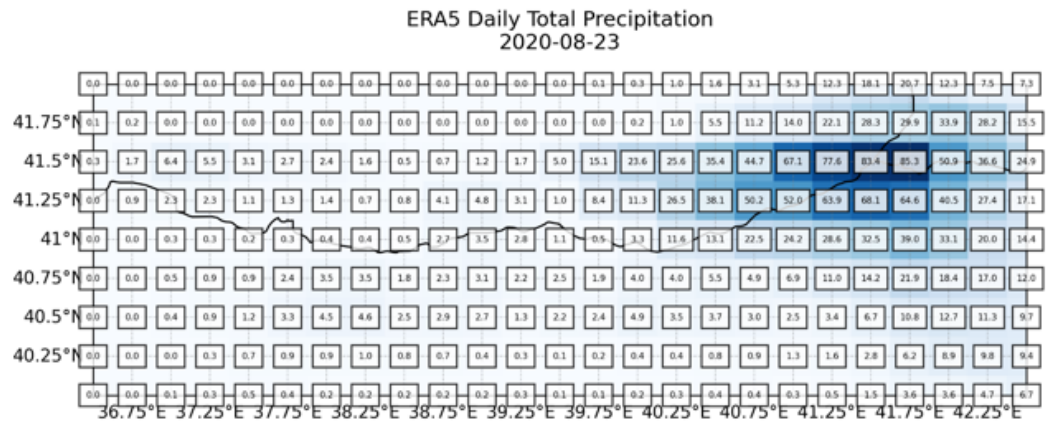


Figure A.38. ERA5 daily total precipitation on 2020-08-23.

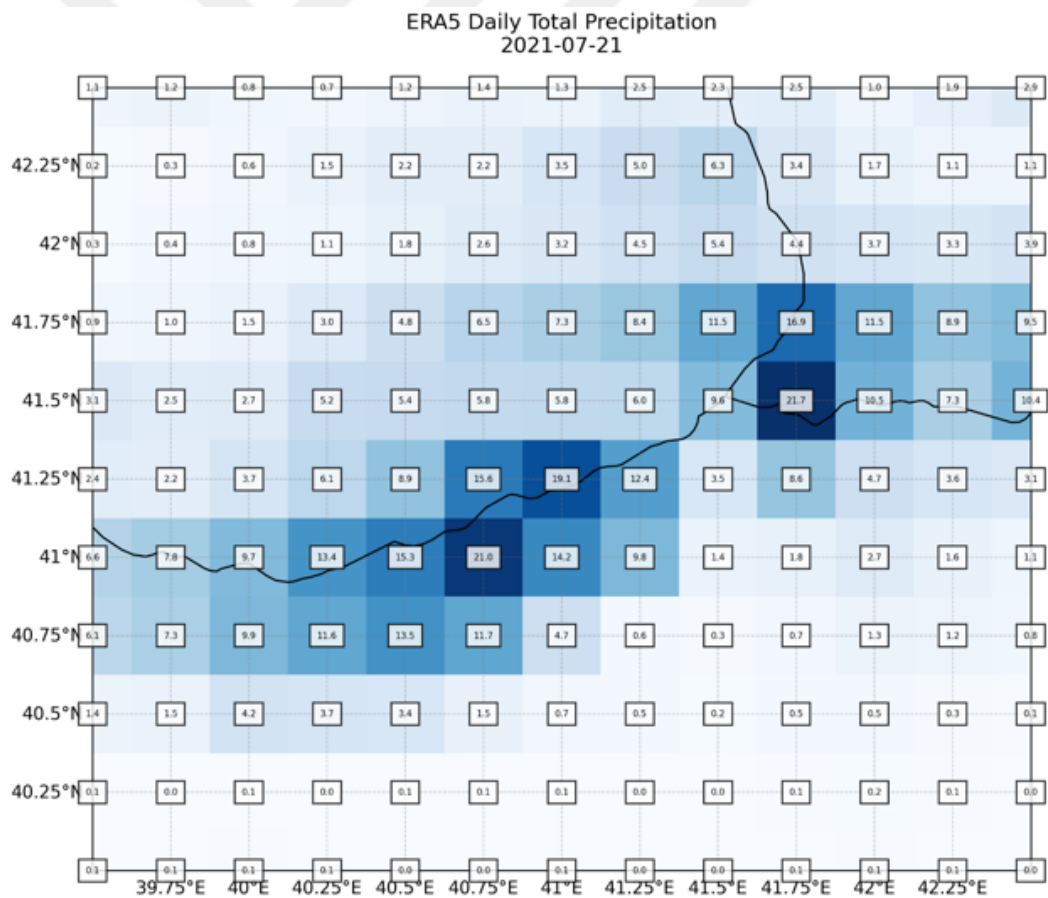


Figure A.39. ERA5 daily total precipitation on 2021-07-21.

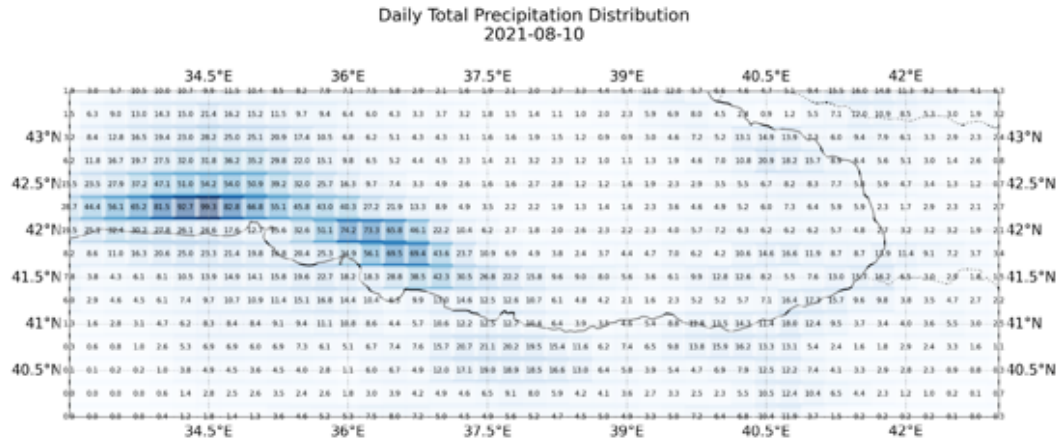


Figure A.40. ERA5 daily total precipitation on 2021-08-10.

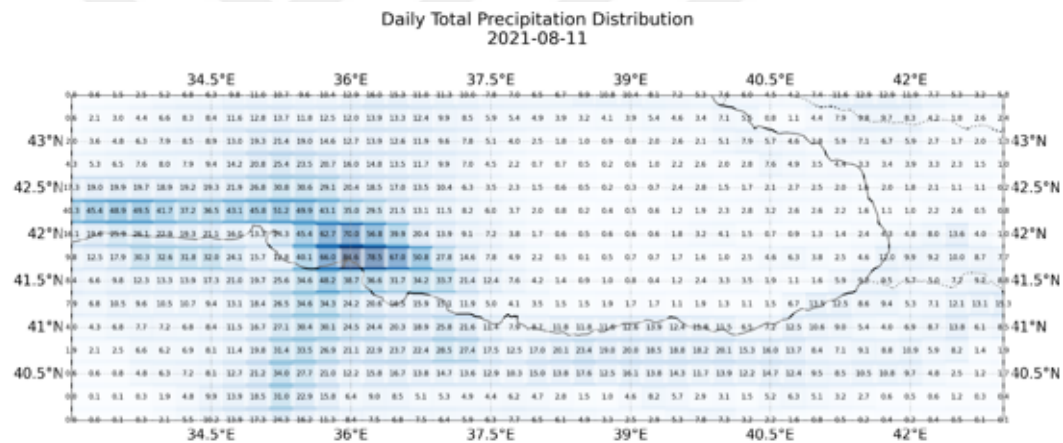


Figure A.41. ERA5 daily total precipitation on 2021-08-11.

A.5. Ukraine

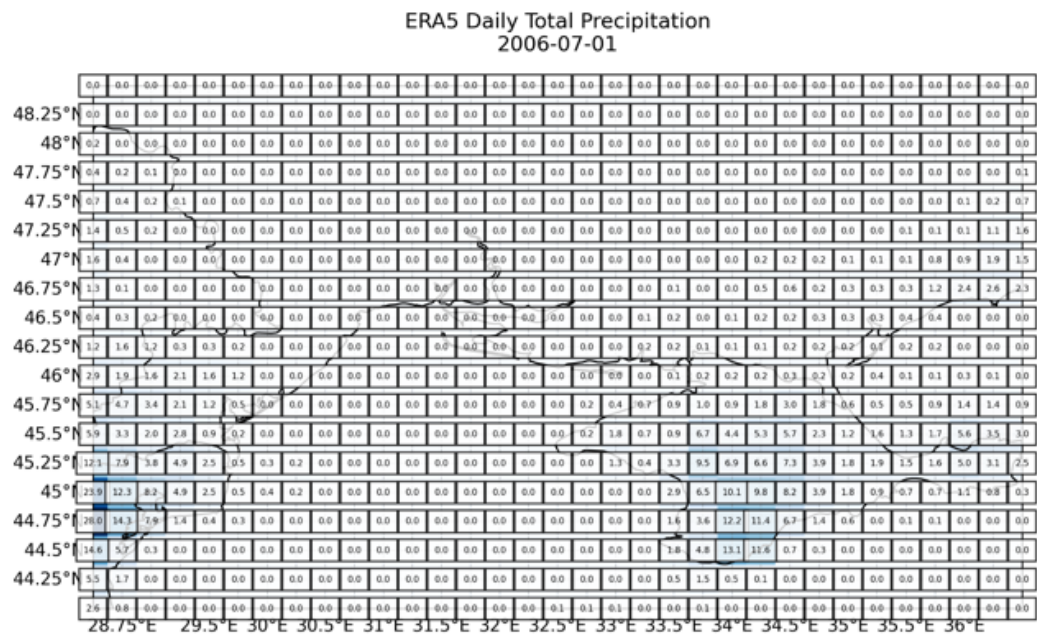


Figure A.42. ERA5 daily total precipitation on 2006-07-01.

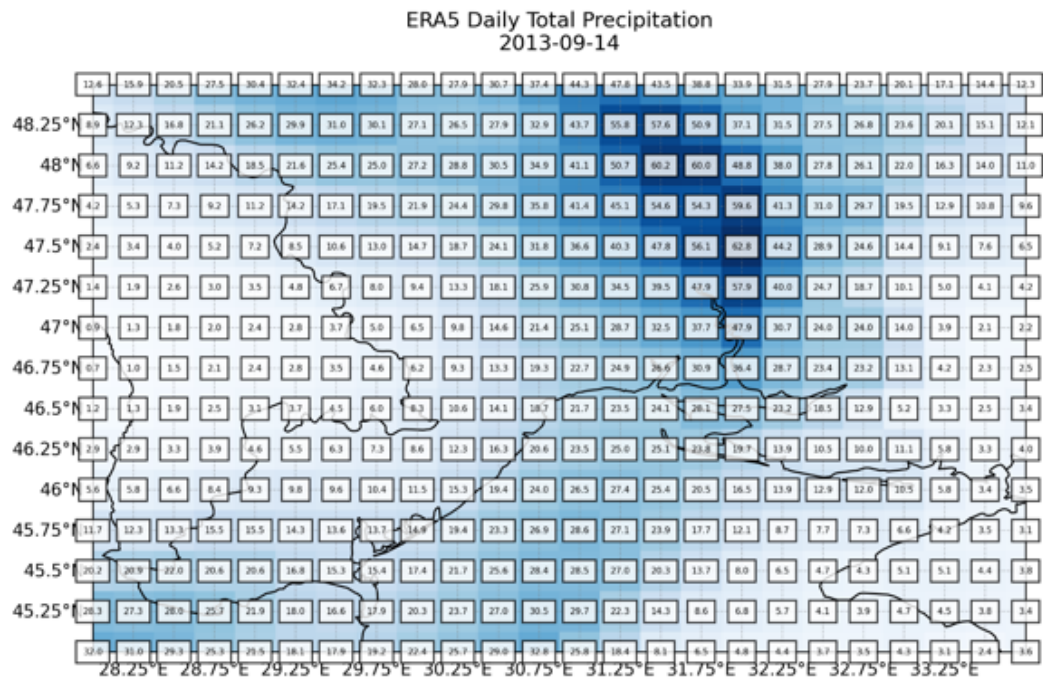


Figure A.43. ERA5 daily total precipitation on 2013-09-14.

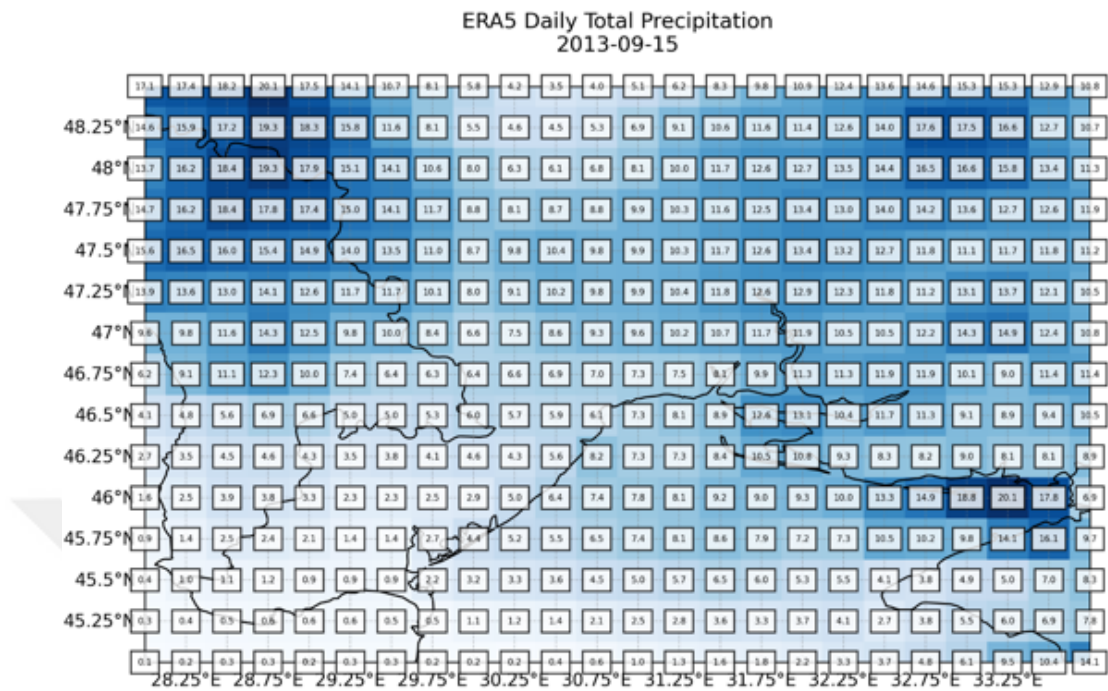


Figure A.44. ERA5 daily total precipitation on 2013-09-15.

APPENDIX B: EXTREME PRECIPITATION
THRESHOLD RESULTS

B.1. Observed Precipitation Events (2000–2024)

This section provides a statistical overview of extreme precipitation events recorded between 2000 and 2024 across five Black Sea coastal countries. Table B1 summarizes the total number of events, categorized by thresholds based on the 95th and 99th percentiles, along with the corresponding threshold values and the maximum observed daily precipitation for each country. These data support the return period calculations used in the core regression analyses.

Table B.1. Statistical distribution of extreme precipitation events (2000-2024).

Country	Total Events	Above P99	P95-P99	Below P95	P95 Value	P99 Value	Max Observed
Russia	10	5	3	2	16.34	29.87	150.4
Bulgaria	11	11	0	0	9.96	21.73	100.3
Türkiye	10	8	0	2	19.41	40.47	99.3
Romania	19	10	9	0	14.74	28.11	162.0
Ukraine	3	2	1	0	8.21	18.39	62.8

B.2. Future Projections (2030–2060)

Table B2 presents the monthly 95th and 99th percentile precipitation thresholds (in mm/day) for different geographic coordinates, derived from MPI-ESM1-2-LR projections (SSP5-8.5) for the 2030–2060 period.

Table B.2. Future precipitation threshold percentiles by location and month.

Month	Latitude	Longitude	95th Percentile (mm/day)	99th Percentile (mm/day)
2	42,75	26,5	10,51385403	25,00831127
2	42	24,25	10,86566448	21,87263489
5	44,5	38,25	9,809112549	20,94429016
5	44	40,5	20,08895874	31,26834869
5	40,5	38,25	6,721973419	17,20989227
5	40,75	39	13,23165894	31,63021088
6	43,75	26,75	13,27142715	22,3482132
6	42,5	27,75	7,033991814	16,84967995
6	45,75	22,5	19,25568581	31,00084305
6	44,75	23,5	18,95627975	37,46490002
6	45,75	23,25	18,44795942	29,4779563
6	46,5	26,25	20,41102648	31,63647652
6	46	26,75	16,55128002	35,7141161
6	46,5	27	14,66412544	27,49444485
6	47	26	16,41709805	29,58676815
6	46,5	26,25	20,41102648	31,63647652
7	44,5	38,75	12,95666695	21,90022945
7	43,5	25,25	12,87047863	22,4666357
7	43	25,25	13,30091953	25,69869995
7	42,25	27,75	5,405187607	17,79952049
7	46,25	23,25	14,40844536	26,05478287
7	46,25	23,25	14,40844536	26,05478287
7	45,25	24	12,2033596	26,81611538
7	46,25	26,25	14,40844536	26,05478287
7	45,75	26,75	16,55917168	30,26787758
7	46,25	23,25	14,40844536	26,05478287
7	46,25	24,5	14,40844536	26,05478287
7	45,5	25,75	13,69364262	27,98043728

Table B.2 Future precipitation threshold percentiles by location and month. (cont.)

Month	Latitude	Longitude	95th Percentile (mm/day)	99th Percentile (mm/day)
7	45,5	24	13,69364262	27,98043728
7	46,5	26,5	16,34126902	29,36861753
7	44,5	34	8,845806122	15,36840439
7	41	40,75	24,87661839	48,02649975
7	41,5	41,75	29,34794426	69,33984383
9	43	26	10,50510406	24,07287598
9	43,5	23	11,14621162	27,75699615
9	42	24,25	12,91344166	28,64864349
9	41,75	24,25	10,36641598	19,63655949
9	41,5	28,5	12,54957914	30,508461
9	46,5	28	10,01849174	26,31493568
9	44,5	34	9,319901466	22,62884617
9	47,5	32	9,585916996	22,80685902
9	46	33,25	7,800197601	21,66195393
10	44	39	22,55591154	48,48740101
1	44,25	39	19,94953156	34,3387413
1	43,75	39,75	26,65176392	40,1499939
8	45,5	37	8,876800537	23,43790054
8	44,75	38,5	8,32529068	17,00716972
8	41,25	39	12,93077469	34,24501419
8	41,25	40,75	25,45728683	41,21259506
8	41,5	41,75	15,18068314	25,46789169
8	42.25	34,5	3,905391693	11,89294815
8	41,75	36	3,905391693	11,89294815

These findings reveal that flood events with longer return periods have greater economic impacts and that this relationship varies across countries. In line with studies in the literature, it is emphasized that flood events with longer return periods have more serious consequences in terms of both infrastructure damage and economic losses. The study suggests that return periods are an important parameter in flood

risk management and that strategies to reduce economic losses should be developed by taking this parameter into account.

