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Temperature as a premium factor. Insurance incorporating climate change. A comparative case study between Europe and North America

Nomikou-Lazarou Irene

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Temperature as a premium factor. Insurance incorporating climate change. A comparative case study between Europe and North America.

Nomikou-Lazarou Irene

Fulbright Scholar and PhD Candidate on Climate Risk Management

Department of Economics, Athens University of Economics and Business

Email: nomikoulazeir@aueb.gr

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1 Abstract

This study explores the critical role of insurance in managing risks associated with climate change. By distributing risk among various entities, the typical insurance premium structure encompasses a systematic component (the expected loss) and an unsystematic component (low-probability events often uncharged). However, with increasing climate-related natural disasters, there is a shift from the unsystematic to the systematic part of premium calculations. Our findings reveal that while both North America and Europe face rising climate risks, Europe exhibits a systematically higher insurance gap due to varying levels of public welfare support and cultural attitudes, which introduce different levels of moral hazard in both regions. Historical data indicate a strong correlation between temperature anomalies and the frequency and severity of climate disasters; however, Europe shows a higher disaster response for each degree of warming. This creates considerable challenges for individuals seeking natural disaster coverage and threatens the financial stability of the European insurance market. Consequently, these findings underscore the urgent need for collaboration between insurers and policymakers. As climate risks extend beyond the private sector, it is critical to enhance resilience and ensure long-term economic stability for affected communities. Estimated projections indicate a steep increase in climate-related premiums until 2030, with North America showing higher premiums across all Shared Socioeconomic Pathways (SSP) scenarios. However, it is estimated that Europe is about to face mid-scenario hikes, which is the most probable one, as early as 2026-2027, reaching four times the premiums of 2024, posing significant challenges to the sustainability of disaster coverage.

2 Keywords

Insurance, extreme natural events, temperature anomaly, natural catastrophes, regional, expected losses, climate risk, premium, Europe, North America, total economic damages, insured damages, ssp, arrival factor.

3 Introduction

In an era where climate change is reshaping the landscape of risk management, the insurance industry is faced with unprecedented challenges in protecting businesses, households, and financial institutions against the potential losses associated with increasingly severe natural disasters. As climate-driven events continue to escalate, insurers must adapt their models and approaches to effectively respond to the evolving risk environment. Mechanisms such as Special Purpose Vehicles (SPVs) and Catastrophe bonds (CAT bonds) have become essential tools for isolating risks and mitigating financial exposure, while concepts like expected loss rate (EL) and expected excess return (EER) are integral in determining appropriate insurance premiums. This dynamic landscape necessitates continuous innovation and proactive strategies, underscoring the critical need for reliable risk assessment practices that can address both historical trends and future projections.

This paper delves into the intricate relationship between climate change and the insurance sector, with a specific focus on the comparative analysis of insurance premiums and risk management strategies between North America and Europe. By examining historical data and the impact of temperature anomalies on disaster frequency, our objective is to reveal how these factors influence market dynamics and insurance pricing. The findings highlight the importance of crafting adaptive and sustainable insurance frameworks that respond to regional disparities in risk perception and policy responses. Ultimately, this research aspires to contribute to the existing literature by integrating climate factors into traditional insurance pricing algorithms, providing a regional yet scalable framework for premium estimation. Ultimately, this research aims to provide crucial information for insurers and policymakers striving to increase resilience and stability amidst escalating climate risks.

The structure of the paper is as follows. In Chapter 4, we explore the vital role of insurance in managing climate change risks and the mechanisms of insurance and reinsurance that provide financial stability amidst unprecedented challenges. By examining the interplay between risk assessment, premium structures, and climate science, we aim to inform strategies for mitigating the impacts of climate change on the insurance sector and society. Chapter 4.1 investigates the compelling evidence linking natural catastrophes with climate change, emphasizing the urgent need to understand their interrelationship. Following this, Chapter 4.2 highlights the growing connection between global warming and the frequency of extreme weather events. Chapter 4.3 addresses how climate change fundamentally alters risk assessment and management practices, pressing insurers to adapt to new challenges. In Chapter 4.4, we discuss the establishment of coherent risk measures via alternative premium pricing models, including foundational principles that guide insurance premium development. Chapter 4.5 introduces a conceptual framework that elucidates risk categorization and coverage management, while Chapter 4.6 delves into an informed insurance premium that takes into account temperature anomaly modeling that aligns with evolving climate scenarios. Lastly, Chapter 5 explores the historical evolution of temperature anomalies and their relationship with natural disasters and insurance premiums, showcasing the increasing risks insurers face and their implications for pricing and risk assessment in the context of Shared Socioeconomic Pathways (SSPs) forming premium projections for Europe and North America until 2030.

4 Climate risk transfer mechanism

In the context of an evolving economic landscape, insurance plays a crucial role in managing risk and protecting against potential losses. This chapter delves into the intricate mechanisms of insurance and reinsurance, highlighting how they pool risks and facilitate financial stability for businesses and individuals alike. As climate change intensifies, the insurance industry faces unprecedented challenges, particularly in relation to catastrophic events linked to rising global temperatures. By examining the relationship between risk assessment, premium structures, and the implications of climate science, this chapter aims to illuminate the critical intersection of insurance practices and environmental realities. Ultimately, understanding these dynamics is essential to develop effective strategies to mitigate the impacts of climate change on the insurance sector and society as a whole.

Insurance is a means through which risk and savings are grouped and transferred in the economic environment. Pooling the policyholders (sponsor's) risk, insurance and reinsurance companies (investors) improve the resilience of companies, households, investors, and financial institutions. In addition, insurance makes business development and commerce more feasible and prevents legal entities and physical persons from perils they are not capable of enduring. In order to bear the risk for the policyholder, the insurer requests a payment called premium. The policyholder enters into an agreement with the insurer, and the terms of the agreement are declared in the insurance contract. The terms of the contract announce the obligations of the insurer, meaning the cases which the insures has agreed to pay for and cover the damage if the adverse event happens, e.g. a factory catches fire. Part of the premium is the return on assets held to batch insurers' liabilities.

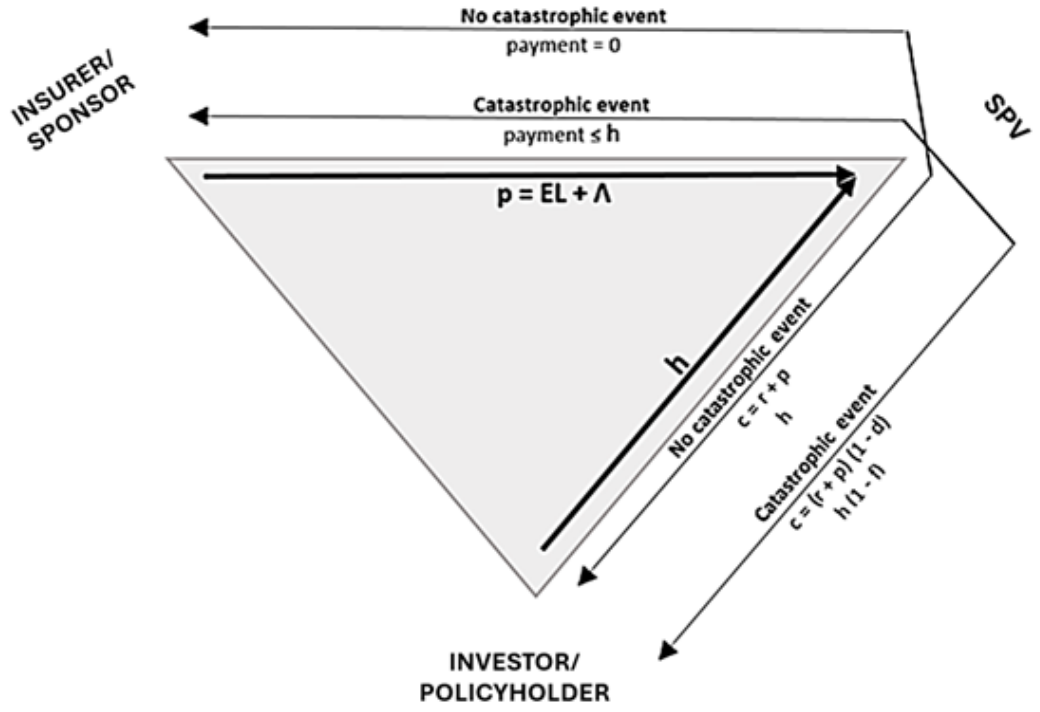


Figure 1: Catastrophic Risk Transfer Mechanism

Figure 1, illustrates the cash flow relationships in a catastrophic risk transfer mechanism. Initially, all the transaction parties in our system, e.g. insurance and reinsurance companies,

the government, and investors, recognize the risk of the occurrence of a catastrophic low-priority event, and infrastructure insurance is imposed by law galeotti2013accuracy. For this example, we consider the case of an infrastructure insurance contract between the insurer (sponsor) and a plant operator (policyholder). In the first stage, the plant operator enters the insurance contract together with the insurance company. As compensation, the plant operator pays a premium to the insurance company that carries a specific risk level under the contract. In the second stage, the insurance company creates a Special Purpose Vehicle (SPV) to isolate financial risk to underwrite a risky contract. In the context of insurance, an SPV is a legally distinct entity created to achieve specific objectives, such as isolating financial risk associated with catastrophic events. The SPV operates independently, with its own assets, liabilities, and legal status, ensuring that its financial obligations remain separate from those of the parent insurance company. This structure allows the SPV to continue operating even if the parent company faces financial difficulties or insolvency. The insurance company also pays the SPV premium in order to receive coverage up to the limit h declared in the contract. Setting the basic components that form the premium, we linearly express the relationship between the premium $p(X)$ and EL the expected losses related to the level of risk X. This relation is presented by the following equation.

Zooming in on the components of the premium, EL denotes the expected loss rate or the expected value of the loss, and Λ denotes the expected excess return (EER), or else the load factor which introduces the additional return the insurer charges the policyholder in order to cover for losses linked with high-risk events. Elaborate analysis on the elements of the premium function is presented in the Section 4.6.

$$premium(X) = EL + \Lambda$$

In the third stage, the SPV, to be able to provide insurance coverage to the insurer, issues catastrophe bonds (CAT bonds) to an investor who pays the par amount h on the issue date. Essentially, the parameter h represents the par amount of the CAT bond, which is the maximum coverage provided by the SPV to the insurer in the event of a catastrophic loss. CAT bonds refer to a high-yield debt instrument created to raise money for insurance companies in the occurrence of a catastrophic event. Throughout this paper, catastrophic events are liked to natural catastrophe events that cause economic losses of great magnitude to the policyholder and, by extension, to the insurer. If no catastrophic event has occurred, the investor receives the par amount h and a coupon $c = r_F + p(X)$ where r_F denotes the risk-free interest rate and p the premium presented above. More analytically, the parameter h is the full principal amount that the investor receives back at the end of the term of the bond. Since no catastrophic event has occurred, the SPV does not need to use the par amount to compensate the insurer (sponsor) for any losses. Instead, the SPV returns the entire par amount to the investor along with the coupon payment c as illustrated in Figure 1. However, if a catastrophic event occurs, the investor receives the par amount $h(1-f)$ and a coupon $c = (r_F + p(X)) \cdot (1-d)$. In this case, the par amount h is partially or fully used by the SPV to pay back the insurer for the losses incurred due to the catastrophic event. The parameter d where $0 \leq d \leq 1$, represents the proportion of the par amount h that the investor loses in the event of a catastrophic event. A higher d indicates a greater loss for the investor. In the same way, the parameter f where $0 \leq f \leq 1$ represents the fraction of the par amount h retained by the investor in the event of a catastrophic event. The two parameters are complements, as $f = 1 - d$. Moving backwards in Figure 1, in the occurrence of a catastrophic event, the insurer is covered by the SPV by a *payment* $\leq h$, meaning that is compensated by the SPV as specified in the contract up to a specified loss level h, while if there is no catastrophic event does not receive any payment. The aforementioned scheme represents an important characteristic that differentiates the insurance industry from

other industries. In this direction, a primary characteristic of the insurance industry is the inverted production cycle [Authority, 2015]. In that sense, the insurance premium is paid up-frond by the policyholder and any benefits become payable possible in a future instance provided the adverse event has happened. An other characteristic of the insurance industry following the banking sector is that insurers are obliged to maintain capital to provide a buffer against adverse experiences in their assets or liabilities such as financial returns.

But this is how the insurance industry has worked for decades. While the mechanisms of risk transfer, such as those involving SPVs and CAT bonds, have provided insurers with tools to manage financial exposure to catastrophic events, the increasing frequency and severity of such events pose unprecedented challenges. These challenges are largely driven by the growing impact of climate change, which reshapes the risk landscape for the insurance industry. As climate-related disasters become more frequent and intense, traditional models of risk assessment and transfer are being tested, necessitating a closer examination of how climate change affects the industry's operations and resilience. The historically high shifts in global temperature is advocated that trigger natural catastrophes and more severe and frequent extreme weather events, increasing the magnitude and frequency of insurance claims.

In particular, climate change scientists have set a 2°C global temperature threshold, and explain if the temperature on Earth rises more than this level, then the natural environment and human society and activity will face dangerous and possibly irreversible implications. Naturally, since temperature is spatially distributed, a global average temperature increase of 2°C implies a temperature of 3°C in some mid-continental regions and a temperature of 4°C to 5°C or more in the Arctic due to the polar amplification phenomenon[1]. Over the years, the reality of climate change has evolved from a controversial and speculative topic debated in conferences to an undeniable global challenge with far-reaching and tangible impacts. Studies highlight the increasing frequency and severity of high temperatures, extreme weather events, hurricanes, floods, and wildfires [Seneviratne et al., 2021], [Valavanidis, 2022]. Geography-specific surveys provide evidence of the adverse effects of the changing climate conditions. In China, estimates show that, wildfire exposure has increased by 54%, with heatwave-related deaths increasing by 342% and heat-related work loss by 24%. Over the past 20 years, human-caused climate change has contributed to 49.4% of heatwave-related deaths, 30.9% of heat-related labor productivity loss, and affected 98.8% of the population impacted by drought by 2020 [Zhang et al., 2024]. In the United States, the investigation of nine natural hazards (hurricanes, tropical storms, landslides, wildfires, earthquakes, drought, inland flooding, coastal flooding, and tornadoes) indicated a variant increase in frequency and intensity between 2000 and 2019 [Summers et al., 2022]. In the same direction, evidence from Europe link anthropogenic greenhouse emissions to increasing temperature anomalies in the continent and to the observed deterioration of underlying extreme weather conditions with highly nonlinear pattern [Chauvet et al., 2025].

Beyond academic research and scientific discourse, climate change now more that ever demands urgent action from various industries, particularly those directly exposed to its consequences, such as the insurance sector. These industries are compelled to adopt proactive measures, including revising risk models, enhancing disaster preparedness, and implementing sustainable practices, to mitigate the growing risks of excessive capital and financial losses. Insurers have raised concerns around the topic of climate change [Cochrane, 1975] since the 1970s when multinational reinsurance companies started investigating the potential increase

[1]According to NASA, since the mid-20th Century, average global temperatures have warmed about 0.6°C (1.1°F), but the warming has not occurred equally everywhere. Temperatures have increased about twice as fast in the Arctic as in the mid-latitudes, a phenomenon known as "Arctic or polar amplification. https://climate.nasa.gov/news/927/arctic-amplification/"

in catastrophic natural event occurrence leading to increased financial losses [Russell, 1970], [Mills, 2005], [Re, 2011].

As climate change intensifies, the insurance sector is essential in managing risk and protecting against losses. This chapter highlighted how mechanisms like Special Purpose Vehicles (SPVs) and catastrophe bonds enhance resilience. However, the increasing frequency of climate-related disasters challenges traditional risk models. Insurers must adopt proactive measures, including revised assessments and sustainable practices. By doing so, they can effectively address the impacts of climate change and foster greater resilience in society.

4.1 Evidence linking climate change and natural catastrophes

This chapter explores the compelling evidence linking natural catastrophes with climate change, highlighting the urgent need to understand their interrelationship. Recent extreme weather events have underscored the growing impact of climate change on the frequency and intensity of natural disasters. By examining various factors, including greenhouse gas emissions and natural climate cycles, this section aims to elucidate how human activities exacerbate these catastrophic occurrences. In addition, it discusses the methodologies used to assess the probabilities of extreme events and their implications for future climate scenarios.

Beyond doubt, extreme weather incidents announced the last years by various natural catastrophe observatories around the world, establish a relation regarding climate change, a relation that has become an urgent and political discussion. This subject is controversial because of its causes. For example, there is ongoing debate about the extent to which human activity or natural cycles contribute to the increase in natural disasters, which can be difficult for humans to observe due to our limited lifespan. Climate pattern differentiations in comparison to prior decades, are caused by two usually opposite but sometimes supplementary forces. On one hand, are the internal forces to the climate system regarding the natural climate cycles. On the other hand, are the external forces for example, changes in the sun's radiation due to the length of sun cycle, volcanic activity, but also anthropogenic forces resulting from excessive use of aerosol, emissions of greenhouse gases when burning fossil fuels, oil, land use etc.

Regarding greenhouse gases, the mechanism behind global warming is that gasses released by human activity in the atmosphere, trap the existing heat in the atmosphere that is responsible for preventing radiation from escaping into space. If the anthropogenic greenhouse gases didn't exist, it is considered that radiation would escape space, avoiding the earth's overheating and balance earths climate to a situation where fauna and flora have used to live and survive on this planet before human emitting societies. In addition, greenhouse gases display certain persistence, in the sense that it remains in the earth's atmosphere for multiple decades, denoting that climate change is bound to continue for the years to come even if we stopped emitting today. Shifts in temperature, promote a variety of secondary consequences on hydrological systems and terrestrial and marine ecosystems [Van Aalst, 2006]. Such influence involves global mean sea level rise, extensive retreat of glaciers, reduction of lands covered in snow, melting of permafrost areas, distortion of plant and animal ranges, early flower bloom, change in bird breeding seasons, excessive development of insect population, coral bleaching etc.

Nevertheless, apart from the frequently discussed adverse consequences of climate change there are also some positive outcomes. It is true that since climate change effects are highly correlated with spatial longitude and latitude, in some regions, increase in average temperature will improve and enhance agriculture on average as well as reducing the winter heating

energy needs. It worth mentioning the irony that regions which participated the minimum to greenhouse gases concentration, will experience the maximum environmental ramifications. [2].

On this framework, natural scientists state that external forces affecting the global average climate conditions, lead to changes in extremes [Seneviratne et al., 2012]. In this stage, is meaningful to define climate extremes. And this is crucial because "extreme" is a feature dependent on space and time, it is not an absolute property of an event. Accordingly, "climate extremes" are typically contingent on the probability of occurrence of a specific number of events or on the surpassing of a prior set threshold. Regarding the assumption of threshold, different thresholds are applied, however, conventionally probabilities of occurrence 10%, 5%, 1% or less across a specific time interval are used. In addition, absolute thresholds in comparison to the previous relative ones, are often used to describe the occurrence of an extreme incident, an extension example along the lines of this paper, could be to set an absolute temperature level above which health impacts are being observed [Seneviratne et al., 2012].

It is useful to group the extreme climate incidents in relation to natural disasters, into the following three categories. Firstly, we could observe extremes in climate variables such as temperature, precipitation and wind. Secondly, detect weather and climate events which impact on the occurrence of extremes in weather or climate variables such as monsoons, tropical cyclones e.t.c. Thirdly, monitor consequences on the natural environment among which droughts, floods, extreme sea level, waves, landslides sand storms, dust storms and so forth. Of course, a researcher may examine a specific natural catastrophic event aiming to understand its economics and social impacts, however nature has taught us that the only adjectives that we cannot assign to her is simple and linear. Having this in mind a very useful literature has been developed around the idea of compound events [Brink et al., 2005, Svensson and Jones, 2002]. In particular, the idea behind compound events is that several mild weather or natural events aggregated could cause or consist an extreme event.

An other meaningful remark around extreme natural incidents, is the distinction between extreme weather incidents and extreme climate incidents. The first concept is referred to fluctuating weather patterns, observed within small time frames e.g. lasting from some hours up to several weeks, in comparison to the second concept referring to longer time scales presenting more extreme natural events with higher persistence in time. Usually, in scientific literature, extreme indices regard "moderate extremes", in contrast exorbitant extremes are examined by employing the Extreme Value Theorem, a method aiming to derive the probability distribution of rare incidents based on the right and left tails of the general probability distribution, mainly below 1-5 % of the total sample [Coles et al., 2001].

In order to undercover the extremely significant link between unusual weather patterns and average condition trends, researchers utilize empirical analysis comparing present and historical data, theoretical analysis applying simulations in global and regional climate models (GCMs, RCMs), along with detecting patterns in insurance claims driven by catastrophes from extreme natural incidents [Pielke, 2005, Pielke Jr et al., 2005]. Specifically, middle and high northern latitudes (Tropic of Caner, Tropic of Capricorn and in the Arctic and Antarctic Circle) are anticipated to exhibit increased extreme precipitations and by extension shorter return period for intense rainfalls leading to increased floods and landslides. Middle latitude zones had typically four seasons (regarding the 19^{th}, 20^{th}, 21^{th}, centuries) but new data identifying the effects of climate change, show evidence of season deviation phenomena. Low latitude regions, close to the equator, are anticipated on the contrary to have long dry periods, which will give

[2]https://www.oecd.org/env/cc/2502872.pdf

rise to significant risk of extended droughts and wildfires, especially during the summer season.

An other determinant factor that could play an important role on climate change is the North Atlantic Oscillation. According to [Anderson and Bausch, 2006], when it is at it's negative phase may trigger dryer winter weather conditions resulting to less recharging of rivers, and by extension to more intense summer droughts. Analysis studying the Atlantic Oscillation decade per decade, since 1850, show that the increased frequency and intensity of Atlantic tropical cyclones over the past few years, might be a result of a combination of the natural cycle of Atlantic Oscillations and climate change. However from 1995 and the later years, it is indicated that higher impact on observed increased catastrophes, has climate change. In fact, climate models evidence that economic losses from winter storms, are anticipated to double until 2085 forcing some European regions to highly suffer from the impacts of climate change [Höppe and Grimm, 2008]. Within these lines, we can conclude that climate change shifts the existing hazard risks, but on the same time increases the uncertainty degree of intensity and frequency of catastrophic disasters and initiates new as well.

The evidence linking extreme weather events to climate change is undeniable and increasingly urgent. As this chapter illustrates, the interplay between natural cycles and human activities complicates our understanding of these phenomena. The distinction between extreme weather and long-term climate trends underscores the need for rigorous analysis and adaptive strategies. As we face an escalating frequency of catastrophic incidents, it is crucial to recognize that climate change not only shifts existing risks but also amplifies uncertainty regarding future events. Proactive measures and informed policies are essential to mitigate impacts and enhance resilience against an uncertain climate future.

4.2 Evidence linking global warming and natural catastrophes

The connection between global warming and natural catastrophes is becoming increasingly evident as climate change intensifies. Rising average temperatures are linked to a higher frequency of extreme weather events, including floods, droughts, and wildfires. This chapter examines the evidence supporting this relationship, highlighting how temperature anomalies can trigger catastrophic incidents and alter return periods for such events. By analyzing regional variations and the impact of human activities on climate patterns, we aim to shed light on the complex dynamics at play. Understanding these connections is crucial for developing effective strategies to mitigate the risks associated with climate change and protect vulnerable communities.

We already clarified that climate change, depending on the location, present different attributes. Among which, rising temperatures in some locations in contrast to decreasing temperatures in others. Now, focusing on the one of the heads of the multi headed hydra-climate change, temperature shifts will be on the center of our analysis. The average global temperature is on the top records when observing the data for almost two millennia [Jones and Mann, 2004]. Likewise, [Solomon, 2007] indicates that the mean global temperature has risen around $0.7°C$ and is expected to continue increasing within a range of $1.8°C$ to $5.8°C$. More precisely, the long-run trend from 1951-2006 shows that indeed climate-related catastrophic natural disasters correlate with increasing temperature. In contrast, short-run analysis indicated that no clear correlations were identified during the 11 year cycles. Observing the global picture, according to EEA[3] temperature presents a strong positive trend since the end of 19^{th} century. Especially

[3]https://www.eea.europa.eu/ims/global-and-european-temperatures.

evidence after 1970 indicates that every 10 years the temperature anomaly increases by $0.2°C$.

Zooming in spatially, evidence show that the geographical region of Europe presents a higher rate of temperature increase than the global average increase. Specifically, the year 2020 was the warmest year so far ranging between $2.53°C$ and $2.71°C$ across the different regions. The European regions that presented the highest temperature shifts were Eastern Iberian Peninsula, Scandinavia, and Eastern Europe. Additionally, according to [Hegerl et al., 2007], more than 0.5% of the rising in global average temperature, happened in consequence of human-induced greenhouse gas concentrations. In this context, it is claimed that temperature rising resulting from greenhouse gas concentrations, would be more intense if it weren't for opposite cooling forces such as aerosol, and other natural causes e.g. an increase in sun spots e.t.c. It is estimated that the probability of world warming linked to non external forces to the natural earth system is less than 5%, meaning that most of global warming today in comparison to the pre-industrial period is a result of human activity plus a small percentage impact from sun radiation fluctuations, whose exact number is yet under study.

Since space matters and every region is not affected the same way due to it's geographical longitude and latitude, it has been observed that high and low extreme temperatures are increasing globally, with probably less extremely cold temperatures [Anderson and Bausch, 2006]. Specifically in Europe, [Moberg and Jones, 2005] indicate that, summer temperatures present greater per day increase in comparison to winter's, an observation that is in accordance with [Wijngaard et al., 2003] who remark that warm extreme temperatures are increasing twice as fast relative to the way cold extremes are increasing. However, overall extreme temperature analysis for regional and global level, indicate that the lately observed shifts are consistent with the increasing planet temperature [Seneviratne et al., 2012]. In these lines, local historical restructure of empirical temperatures, enable comparing current temperature extremes to paleo-climatic data, so as to conduct a more accurate analysis of extremes fluctuations [Dobrovolnỳ et al., 2010].

A crucial topic, after having stated that temperature anomalies trigger indeed natural catastrophes, is that temperature as a distortion factor reduces the return periods for already existing catastrophic events. The term return period, is specified as an increase in frequency of a catastrophic incident, that once occurred every 10 years but now occurs every 7 without necessarily chance in it's catastrophic intensity. Reviews on this topic [Zwiers et al., 2011] point out that in a global scale, return periods in the 1960's were anticipated to arise in a 20 year basis, while in 2012 were re-estimated to exceed 30 years for the case of extreme annual minimum temperature and 35 years for the case of extreme annual minimum daily temperature. Nevertheless, models studying extreme high and low temperature changes, exaggerate changes in high extreme temperatures and underrate changes in extreme low temperatures in the course of 20th century [Christidis et al., 2005, Zwiers et al., 2011]. Existing studies [Seneviratne et al., 2012] present evidence of further increases in the length, frequency, or/and intensity of heat waves. A case study for Greece on maximum summer temperatures [Founda and Giannakopoulos, 2009], reveals that temperature distribution for 2007 is closer to the distribution of 2071-2100 compared to the distribution for the 2021-2050 period implying probably a larger temperature cycle .

Regarding intense precipitation events, rising temperature along with an increasing ambient water vapour point strengthens the probability of more intense rainfalls in the short-run, [Höppe and Grimm, 2008] accompanied with dryer periods in the long-run [Anderson and Bausch, 2006]. Empirical evidence, confirm this theoretical claim, revealing a higher intensity trend in European rainfalls since 1950 [Wijngaard et al., 2003]. Floods present a high proba-

bility of occurring over saturated soils meaning soil, moisture level and precipitation intensity present great importance on flood related catastrophes. Extensive snow melting and temperature distortions may affect the level of soil dampness, forming an endless relation of cause and effect. Further, droughts are the outcome of already existing dump soil and precipitation shortages. With respect to tropical storms, in the six ocean basins, [Höppe and Grimm, 2008] note that their increased intensity is a result of persistent rise in sea surface temperatures.

However, shifts in extremes, may be the result of shifts in the mean, the standard deviation but also the shape of extreme event probability distribution. On this framework, shifts in frequency of occurrence of days with high temperature, may be the result of shifts in the average temperature per day, in parallel with a shift in the variance or/and the shape of the daily maximum temperature's frequency distribution [Ballester et al., 2010, Brown et al., 2008, Orlowsky and Seneviratne, 2012]. In reality, for the most part of extremes of weather and climate conditions, the evolution mechanism of their distribution is partly known. The one fact that the majority of studies agree upon, is the direction of the extreme's trend, which seems to be growing.

Earlier investigations reveal that rising mean temperature have significant effects on hydrological process [Zhu and Fan, 2021]. These effects regard, deglaciation, melting of permafrost, long drought periods, increase in the frequency of rainfalls, floods, landslides, wind fires and earthquakes. Further, [Stott et al., 2004] show that half degree increase in average summer temperature doubles the risk of a strong heatwave with confidence interval more than 90%. The fact that extreme heatwaves are linked to subsequent floods, gives rise to question the scientific understanding of the mechanism that relates a natural variable such as temperature to correlated extreme catastrophes. Further, [Palmer and Räisänen, 2002] indicate, that the probability of intense rainfall during winter under the current climate is 2.5% (40 years return period) and is anticipated to rise by a factor of five, over the next 50-100 years (12.5% probability of occurrence, and 8-year return period).

In parallel with extreme events caused by human activity altering the climate, other elements of the global climate system are able to contribute significantly to extreme weather and climate incidents linked to global temperature. Such an element is the Thermohaline Circulation (THC), that according to [Stommel, 2020] and [Van Aalst, 2006] is a global system of water flows through the earth's oceans, which affect considerably the global temperature distribution. More precisely, sea water temperature and salt levels, impact on the global temperature. Glaciers melting in the poles, reduce the global water salinity since ice in the poles is "spring water" meaning non-salty water. Along with that, the polar amplification natural phenomenon indicates that temperature shift at high latitudes exceed the global average temperature shift [Brock and Xepapadeas, 2017]. This leads to higher sea surface temperatures in polar regions, increasing further glacier melting due to global warming. The combination of the two aforementioned phenomena, as reported by [Van Aalst, 2006], is expected to wear out the thermohaline circulation probably resulting to it's interruption, outcome which will most probably have irrevocable consequences to temperatures across Europe.

Beyond, a more quantitative relation of temperature and natural disasters is attempted by [Zhu and Fan, 2021], who focuses on the region of China. This analysis uses two important factors, the first is the elasticity coefficient describing an assessment for the number of catastrophes to come for a unit change in temperature, and the second is the length of temperature cycle period obtained by the Morlet wavelet analysis. Latest findings, detect a connection between temperature shifts and earthquake incidents. Specifically, the link is identified when increased mean temperatures lead to extended droughts and intensive precipitations [Zhu and

Fan, 2021, Masih, 2018]. This fact, by extension may result to mountain ranges gaining or loosing 10 millimeters of height which along with iceberg retreat, could prompt seismic activity as the crust isostatically rebounds [Che et al., 2014].

In this stage we should highlight that, climate change reflected through the increase of mean temperature causes the vast majority of catastrophes however it shouldn't be overlooked that temperature falls in certain regions, are observed to be lower than their typical volatility and as a result of climate change, would also be accountable for catastrophic natural disasters [Bergholt and Lujala, 2012], [Keim, 2011], [Semenza et al., 2011]. With respect to decreasing temperatures [Zhu and Fan, 2021] detect that natural catastrophes are more intense, in comparison to cases of rising temperatures, and highlight that more attention should be paid to this direction. These results, indicate that indeed temperature is a distortion parameter linked to natural catastrophes but probably would be biased if only increases in mean global temperature are blamed for catastrophes in earth's ecosystems and human economic activity. Specifically, [Knorr and Scholze, 2008], found that in middle latitudes, the risk of floods from intense precipitation, is a function of global average temperature, where there is a positive relationship between the two magnitudes, and the risk area affected by global warming presented a statistical explained variance of 0.35 for Europe.

Studies perceiving reality through a different prism, have proposed that oscillations in temperature data and by extension to catastrophic incidents are connected to the solar radiation cycles. More precisely, according to [Shaltout et al., 1999, Barliaeva et al., 2001], solar activity impacts on earth's climate conditions along with triggering earthquakes. In more detail, [Friis-Christensen and Lassen, 1991], observe a significant link between the length of the solar cycle (LSC) and the air temperatures in regions north of the equator. Short LSC indicate increase solar activity, on the contrary, extended LSC are linked to limited solar activity. The variant LSC trigger natural catastrophes for prolonged time periods. In general, high solar radiation and shorter LSC indicate increased temperature on earth. On this framework, since LSC controls to some extend global temperature, it is claimed that probably as a consequence, LSC controls also flood and drought incidents. It is understood that, earth's temperature is a natural variable affected by forces initiating from the planet, such as greenhouse gas concentrations along with forces outside of the planet, mostly from the suns activity. Even though we know for sure that the aforementioned forces impact on the earth's temperature, the exact percentage of impact of each force is unclear and the academic society seems to present slightly contradicting evidence. One part of the academic society supports that the observed increase on the average global temperature, is a result of human activity and consider the contribution of the sun irrelevant to climate change. In contrast, the other less popular side of the academic spectrum, advocates that solar activity impacts heavily on earth's climate. In practice, according to the second opinion, low solar radiation, means more sunspots, and in combination with an increase of cosmic rays penetrating the upper part of the earth's atmosphere, could increase cloud coverage and decrease global temperature. In the case of relevant solar activity to earth's climate, is noted that since greenhouse gases do increase global temperature, lower sun activity (the present 25 solar cycle) may balance to some point the global warming. However the exact magnitudes are not known and the individual statements are not widely accepted in the academic society. For [Friis-Christensen and Lassen, 1991] advocating this opinion, LSC is a good measure of long term shifts in solar activity which is linked to the global air temperature fluctuations, along with climate extremes.

Understanding the different implications coming along each climate change effects, it is rational to tackle man-made climate change impacts with adaptation and mitigation measures, e.g. shifting to a zero carbon energy model baring the transition risk as a society and in parallel

strengthen infrastructures against climate change. The consensus view seems to be that both external (the sun) and internal (man made and earth's natural cycle) forces influence earth's climate. In this framework, would be meaningful more studies to focus on this area, revealing useful approximations regarding the representative percentages of each climate change force.

The escalating link between global warming and natural catastrophes is increasingly evident as rising temperatures correlate with a higher frequency of extreme weather events, such as floods, droughts, and wildfires. This chapter highlights the complex dynamics of temperature shifts, emphasizing that although natural climate cycles play significant role, human-induced greenhouse gases is the main driver. As regional variations in climate impacts become clearer, it is crucial to develop effective adaptation and mitigation strategies to protect vulnerable communities. The consensus points to the interplay of external and internal forces driving climate change, underscoring the urgent need for further research to quantify these influences and guide our responses to this global challenge.

4.3 Climate change challenges the insurance industry

Climate change poses significant challenges to the insurance industry, fundamentally altering risk assessment and management practices. As the physical risks associated with extreme weather events increase, insurers must adapt to a landscape marked by the increased frequency and severity of natural disasters. This chapter examines how these evolving risks impact insurance portfolios and influence everything from premium structures to investment strategies. In addition, it explores the broader economic implications, including supply chain disruptions and increased liabilities related to climate events. By understanding these dynamics, the insurance sector can better navigate the complexities of a changing climate and enhance its resilience in the face of uncertainty.

There are various insurance risk types linked to climate change. To start with according to [Authority, 2015], physical risks are heavily coupled with potential increase in frequency and severity of catastrophic natural events. These events could be extended and repeated heat waves, drought increase in certain regions, coastal water rising, intensification of precipitation and disruption in the frequency of tropical cyclones. It is noted on [Haddad et al., 2015] that it is of certain chance weather related factors are changing and those changes are anticipated to be intensified in the future. Notably, compound events following climate and weather factors may increase the risk of portfolio managed by the insurer, resulting to a correlation different than zero. Besides, physical risks can directly affect the assets and liabilities of a company. Regarding property insurance, marine, aviation and transport companies, are heavily impacted by climate change. Thus, intensification of natural catastrophe events has already started reshaping real estate investments of insurance companies regarding mitigation and adaptation measures enhancing resilience in the industry. At the same time, climate change can have in parallel an indirect impact on companies and in the economy in general. That is, in terms of supply chain disruptions, resource scarcity, macroeconomic political or societal shocks or even increase in health deceases linked to life insurance liabilities.

As a result of the increasing physical risk, the insurance industry and related professional bodies conduct research and investigate advanced methods through which they can better understand the unsystematic part of extreme weather events causing financial losses. Further, it is important to note that the insurer's capability to adapt to the increase of natural catastrophe losses relies on multiple elements. Such elements could be operational factors concerning

differences in risk assessment methods varying between countries, perils and vendors, business model factors regarding the inverse production cycle of insurance premiums but also disruptions in portfolio diversification techniques due to increasing correlation of natural catastrophe events across different geographical regions. Additionally, structural factors involving the duration of insurance contracts and other stricter regulatory capital requirements affect heavily the sustainability of insuring/sponsor parties.

An other type of risk linked to climate change is the risk of transition to a lower carbon economy. The energy model of an economy has been significantly influenced by regulations set by policymakers. Over the past 20 years, these regulations have been pushing for a transition from the existing energy model to a new, low-carbon framework. More precisely, transition risk could be triggered by public policy when for example limiting the profitability of fossil fuel companies, promoting emerging technologies such as electric vehicles and home/industrial energy-storage devices that compete with older technologies. Changes in investor preferences translate the expectations concerning the climate risk. The new preferences, force climate science to redefine risk pricing methods. Finally, climate change triggers liability risks arising from parties that have suffered losses from physical or transitional risks associated with extreme weather events. Policyholders who experience losses due to physical or transitional risks often hold insurers accountable. When policyholders fail in their efforts to mitigate and adapt to these risks, and insurers do not adequately disclose relevant information, it increases the likelihood of financial losses for both insurance and reinsurance companies. Given this uncertain environment, and aiming to prevent major financial losses, insurance companies are establishing consulting relations with legal professionals assessing potential future litigation lawsuits and potential higher demand for insurance coverage.

The insurance industry's exposure to climate change manifests through various risk types, primarily physical, transition, and liability risks. Physical risks are directly tied to the increasing frequency and severity of catastrophic events, while transition risks arise from the shift toward a low-carbon economy driven by regulatory changes. Additionally, liability risks emerge as policyholders seek accountability for losses related to these changes. As the landscape of climate-related risks evolves, it is crucial for insurers to enhance their understanding and adaptability in risk management. Proactive strategies, including collaboration with legal experts and refined risk pricing, will be vital in mitigating potential financial losses and ensuring the industry's resilience in the face of ongoing climate challenges.

4.4 Survey of the field

In the realm of insurance premium calculation and risk management, the establishment of coherent risk measures is essential for ensuring rational decision-making and consistency within the industry. This chapter explores the four axioms of risk coherence—monotonicity, transition invariance, subadditivity, and positive homogeneity—which serve as foundational principles guiding the development of insurance premiums. These axioms dictate that insurance premiums must reflect the inherent risk levels associated with policies, thus maintaining fairness and predictability. Many models have been developed to determine the insurance premium, each aiming to incorporate these axioms while addressing the complexities of evolving risks, especially those posed by climate change.

In the framework of insurance premium and risk management, the four axioms of risk coherence are principles that ensure rationality and consistency when constructing risk measures.

First, the axiom of monotonicity imposes that if risk A is higher than a risk B, then the insurance premium charged to cover for A should be at least as high as that for B, implying that if a risk increases, the respective premium should not decrease. Second, the axiom of transition invariance imposes that if a certain amount of risk is removed from, e.g. a contract, the premium of that contract should decrease by the same amount. Third, the axiom of subadditivity, which imposes that the total risk of two combined portfolios should not exceed the sum of the risks of t individual portfolios. This axiom reflects the concept that diversification can reduce the overall risk for the insurer. Finally, the fourth axiom imposes positive homogeneity, meaning that if a risk is scaled up or down, the premium should change proportionally to that scale. For example, in the case of an insurance contract covering wildfire damages in a certain region, if climate change increases the wildfire risk of that region, then the insurer should also double the cost for covering the same type of loss in that region, the premium price.

Various calculation models have been developed to determine the insurance premium. In this section, the central premium models in the literature are presented as a basis for extending them to account for climate change in the form of temperature. Firstly, we consider the premium to be determined by the expected losses EL and a loading factor Λ [Galeotti et al., 2013]. The model is described by the following equation:

$$premium(X) = EL(X) + \Lambda(X) = PFL(X) \cdot CEL(X) + \Lambda(X)$$

and implies a linear relationship between the premium and expected losses. PFL stands for the probability of the first loss indicating the frequency of loss, e.g. if the annual probability of getting a loss is 1%, then the frequency of occurrence of the adverse event is once every 100 years, while CEL denotes the conditional expected loss related to the severity of the loss according to [Lane, 2000]. Regarding the loading factor Λ, it is crucial to include a risk load factor due to the nature of the insurance market, which accounts for excessive uncertain economic losses. In fact, market incompleteness makes risk-neutral valuation impossible.

Particularly, according to [Schlesinger and Doherty, 1985] markets are identified as complete in the case where an individual is able to eliminate any financial risk by buying insurance that provides a perfect hedge against all possible adverse scenarios; therefore, incomplete markets imply that a consumer behavior like the one described is not feasible. In these lines, the loading factor compensates the insurer for bearing the risk of the investment, e.g. to commit her risk capital. Financial markets refer to this portion as Expected Excess Return (EER), price of a security, or the net price. Elaborating, the market's nature calls for including this factor because in the case of a riskless or perfect market there is no need for such a compensation because the insurer is hedged from the beginning against all possible events. In contrast, the real market is not at all riskless. From the moment the risks are not totally hedgeable, EER or Λ constitutes the expected profit on the transaction over and above its financing return and expected losses.

In addition, [Berge, 2005] identifies the drivers that affect the premium, given that different risk factors in insurance are often interrelated.

$$premium(X) = \alpha + \beta \cdot EL(X) + \gamma_1 \cdot y_{peril} + \sum_{i=2}^{N} \gamma_i \cdot y_i$$

Here, the premium is affected by the expected losses meaning the anticipated cost of claims, with α the the intercept representing the baseline price of premium when all other factors are zero, β the sensitivity coefficient of premium to the expected loss, and γ the coefficient measuring the impact of a specific insured peril on the premium. y_{peril} is a variable that indicates a level

of peril, meaning a specific risk or cause of loss covered by an insurance contract as a loading factor. The sum accounts for other systematic or unsystematic risk factors that can influence the premium.

In these lines, [Dieckmann, 2010] explains that the trigger for indemnity that leads to moral hazard and illiquid market conditions affects the premium price. Indemnity or parametric insurance contract refers to a type of contract that covers the probability of a predetermined incident occurring instead of compensating the actual loss of that incident, offering an alternative method to traditional insurance. Events linked with parametric insurance are earthquakes, tropical cyclones, flood incidents, wildfires, etc. where insurers set as a parameter of the compensation the magnitude, wind speed, precipitation, or temperature level of the environment.

An other concept that should be introduced in this paper is the illiquidity of the insurance market. In an illiquid market, is complicated to sell and transfer insurance contracts, and risks because, the expense for risk transfer is high, there is absence of enough interested buyers, and in general there are obstacles limiting risk transfer among the interested parties. Dieckmann identifies that in comparison to pre-Katrina state, empirical data show catastrophe insurance premiums have increased and in an environment like this the diverse causes of uncertainty require different and specialized risk premium models. A similar expression for the premium is described by the form below where in this case the premium formula is a function of expected losses and a loading factor indicating that the risk load Λ is described by a Cobb Douglas or alternatively a "revealed risk preference" function following [Lane, 2000]. The loading consists of the probability of first loss times the conditional expected probability and is formed as follows:

$$premium(X) = EL(X) + \gamma \cdot PFL(X)^{\alpha} \cdot CEL(X)^{\beta}$$

with α, β, γ constants calibrated by the empirical data.

Testing different premium factors [Lane et al., 2007] suggest that it is interestingly explanatory for the premium to account for a cyclic index as a part of the risk load Λ. Further, [Lane and Mahul, 2008] examine how natural catastrophe reinsurers set the premium price they charge, or using the reinsurance jargon, the "spread over LIBOR". In more detail, reinsurers consider the price charged to be multiples of expected loss instead of fractions of expected loss as in traditional insurance. This occurs because the cost of reinsurance is inherently high due to the fact that it provides coverage for extreme, low-probability events. For that reason, they are obliged to maintain substantial amounts of capital "ready for use if needed", amounts that need to be charged somehow their clients, the insurance companies. This extra charge is observed in the high premiums for natural catastrophe coverage but it is not clear weather this high price level is justified. Lane and Mahul form the following linear model for single peril, where peril is considered a potential event or factor that can cause a loss,

$$premium(X) = \alpha + \beta \cdot (EL(X))$$

and they extend it to:

$$premium(X) = \alpha + \beta \cdot EL(X) + \gamma \cdot y_{Cycle_t}$$

giving the economic cycle factor explanatory power. For $\alpha = 0$, the cyclical factor could be explained as load factor independent of expected losses yet fluctuating over time. Alternatively the cyclical factor may be interpreted as a broad estimate of capital load dependent on the cycle. An other construction of the premium function taking into account the cyclical effect is the following:

$$premium(X) = Cycle_t \cdot [\alpha + \beta \cdot EL(X)]$$

where here for $\alpha = 0$, β may constitute the long term multiple and in extension the $Cycle_t \cdot \beta$ is the multiple of the expected loss anticipated to exist in different points in time. More generally, when multiple perils are taken into account the premium function ends up to be the following:

$$premium(X) = \alpha + \sum_p [\beta_p \cdot EL(X)_p]$$

where β_p is the sensitivity factor linked to peril p and $EL(X)_p$ is the expected loss linked to the same peril factor. In the same context, different risk measures can be applied such as the Tail Value at Risk ($TVaR$) which is commonly used in catastrophe risk management. This way, insurers gain more comprehensive understating of their anticipated risk, focusing in the concept of catastrophic tail events. The following model expresses the insurance premium as a function of the expected loss and the weighted $TVaR$:

$$premium(X) = EL(X) + \alpha \cdot TVaR(X).$$

With this formulation the linear relation of premium to the expected loss reflects the baseline risk the insures expect to pay out, while $TVaR$ quantifies the conditional expectation of how great financial losses could be, on average, given that a severity threshold has been exceeded, accounting for extreme economic losses. The weight α, scales the $TVaR$ component denoting the insurer's risk appetite for extreme losses. $\alpha TVaR$ could be perceived as the expected return on capital for a CAT bond linked to the quantity of $TVaR$. Formally:

$$TVaR(X) = E[X|X \geq q]$$

where q an extreme loss threshold in the tail of the distribution of X probability of occurrence. This risk measure satisfies the property of coherence, which implies that the model behaves consistently under various risk scenarios. Although, this model fails to abide with the subadditivity axiom, which imposes that the risk of a combined portfolio should not exceed the sum of individual risk. Along with that, $TVaR$ is sensitive to the model assumptions affecting the tail of the loss distribution. In practice, this means that if the model does not represent in a correct way the distribution tail behavior, it may lead to false estimates of risk and in extension false pricing the insurance premium. a different load factor, [Kreps, 2005] suggests the following premium model:

$$premium(X) = EL(X) + \alpha \cdot s$$

where the α factor represents the percentage of standard deviation s, added to the expected loss. Here, the standard deviation s measures the variability of the loss distribution. Thus, for a high s indicates greater uncertainty and risk associated with the potential economic losses for the insurer. Introducing s into the model, imposes the premium not only to account for the average expected loss but also the uncertainty around that average.

Deviating from the idea of a linear relationship between the insurance premium and its respective risk factors, [Major and Kreps, 2002] develop a loglinear relationship between the premium and the expected losses. This formulation, allows for more flexible modeling of relationships when dealing with multiplicative effects, and considers extra factors affecting the premium, such as the geographic location and the existence of a lead reinsurer in the market, depicted in the next equation:

$$\ln(premium(X)) = \alpha + \beta \cdot \ln(EL(X)) + \gamma_1 \cdot y_{geo} + \sum_{i=2}^{N} \gamma_i \cdot y_i.$$

Here, y_{geo} is a factor that takes into account the risk of a spatial dimension, and y_i other risk factors. Specifically, insurance premium price may vary based on the geographical location

and it's associated potential risk. Local climate and geomorphological characteristics along with climate change across various longitudes and latitudes impose different levels of risk to the insurer. However, based on the axioms of risk measure coherence, the aforementioned model does not satisfy the axiom of transition invariance. This means that adding risk-free capital to a portfolio does indeed increase the overall risk of the portfolio. On the one hand, the model allows for more tailored premium pricing strategies reflecting the unique profiles of different insured entities. However, omissions of other explanatory risk factors can lead to an inaccurate premium price, given that the use of logarithms imply multiplicative rather than additive relationships between the variables, thus omitted variables can amplify the model bias, leading to incorrect conclusions about the relationships between the included variables.

A different remedy for partial risk coherence is proposed by [Wang, 1996] and [Wang, 2000] who highlight that the four axioms for risk coherence can be met by transforming the initial relationship of premium and expected loss by inserting "filters" between them. The filtered relationship Wang proposes is the following:

$$premium(X) \cdot h = \int_a^{a+h} g(S_X(x))\, dx = EL(X)^+$$

where h is the last level of loss the specific insurance contract covers, a the attachment point, the threshold above which the insurance coverage begins, and $a+h$ the exhaustion point, which is the threshold that insurance coverage ends. EL^+ the modified expected losses that account for the transformed distribution of losses, while $S_X(x)$ accounts for the decumulative distribution function of the loss factor X and represents the probability of losses exceeding a certain threshold. The function $g : [0,1] \to [0,1]$ is the function that transforms the decumulative risk distribution. To ensure that the transformation maintains the characteristics of the original distribution, must hold the following properties:

1. $g'(u) \geq 0$, the transformation function is increasing and this way maintains the decumulative function properties
2. $g''(u) < 0$ to create a non-negative Λ that augments as a the attachment point increases
3. $g(0) = 0, g(1) = 1$, $0 < g(u) < 1 \ \forall \ 0 < u < 1$ ensure that the transformation map the probability interval correctly
4. $g'(u) \to +\infty$ as $u \to 0$, is needed for boundless relative loading at extremely high layers of covered risk. More analytically, in high layers of risk the insurer needs to account for extreme events that may have low probabilities, but if occur, will have catastrophic economic consequences for the insurer. The rapid increase in $g^{'}(u)$ as u approaches zero leads to higher risk loading, meaning that the insurer will charge more for coverage that includes the potential for extreme losses, reflecting the increased uncertainty and risk associated with these scenarios.

For $\Phi(x)$ the standard normal cumulative distribution function having a probability density function of the following form:

$$f(x) = \frac{d\Phi(x)}{dx} = \frac{1}{\sqrt{2\pi}} \cdot e^{x^{2/2}}, for -\infty < x < \infty.$$

$u = \Phi = S_X(x)$ and $x = \Phi^{-1}(x)$ to be its inverse function, Wang proposes $g_\lambda(\Phi(\Phi^{-1}(u) + \lambda)) = S_X^+(x)$ the distortion operator that modifies the determined probability of attaching the risk

layer to an empirical probability including a risk load. The factor $\lambda > 0$ is a parameter with real values. In the literature, this probability modification is known as the Wang 1 transformation. Although, as a result of parameter uncertainties Wang proposed a second modification changing its initial standard normal cumulative distribution to t-student Q leading again to a modified distortion operator $g_\lambda(Q_k(\Phi^{-1}(u) + \lambda)) = S_X^+(x)$ with k degrees of freedom, namely Wang 2 Transformation.

In conclusion, the understanding and application of the four axioms of risk coherence are vital for establishing fair and rational insurance premiums that effectively reflect underlying risks. As demonstrated throughout this chapter, various models have been crafted to derive premiums based on expected losses and loading factors, each with its strengths and limitations. The introduction of concepts such as Tail Value at Risk (TVaR) and Wang transformations further illustrates the adaptability required in premium calculations amidst the growing uncertainties of climate change. By embracing these coherent risk measures and continually refining premium models, the insurance industry can enhance its resilience and ensure that it adequately meets both current and future challenges.

4.5 Conceptual framework

Understanding the conceptual framework of risk in insurance is essential for navigating the complexities of coverage and loss assessment. This chapter introduces a model that categorizes risk as a non-negative random variable, highlighting the significance of different layers of insurance coverage. By defining key terms such as attachment point and exhaustion point, we clarify how insurers manage economic losses and determine their liability. The discussion extends to expected loss calculations for varying risk levels, emphasizing the implications of these calculations in the context of climate-related events. Ultimately, this framework serves as a foundation for analyzing how environmental factors influence insurance practices and risk management strategies.

We introduce X as the risk, expressed by a non-negative random loss variable $X \in [0, \infty)$. From the total range of X, the insurance coverage concerns only the $X \in (0, \overline{X}]$, with $\overline{X}$ the grater loss covered according to the contract. The range $X \in (0, \overline{X}]$ is characterized by the two *layers*, each layer refers to a different insurance product with $X \in (0, \overline{X}]$=$(\alpha_i, \alpha_i + h_i]$, and $i = 1, ..., n$ with each i representing one layer of insured risk. Catastrophe insurance applies to the last layer $(\alpha_n, \alpha_n + h_i]$ only, with α the attachment point and $\alpha + h$ the exhaustion point [Froot, 2001]. With the term attachment point, we define the level of economic loss at which the insurer first reacts to losses, while the exhaustion point is defined as the level of economic loss after which the insurer stops covering for any added loss. The insurer's range of coverage is the maximum dollar amount that the insurer has agreed to cover for and is computed by subtracting the attachment point from the exhaustion point. In case losses occur and are below the attachment point or greater than the exhaustion point, the insurance company is not involved in compensation, and therefore the losses are covered by the policyholder [Reguero et al., 2020]. In particular,

$$X(\alpha, \alpha + h] = \begin{cases} 0, X \leq \alpha \\ X - \alpha, \alpha < X \leq \alpha + h \\ h, X > \alpha + h \end{cases} \tag{1}$$

For $X \leq \alpha$ there is no loss in the layer $(\alpha, \alpha + h]$ for the insurer, any occurring loss is covered by the policyholder. For a loss $X - \alpha$, the loss is covered by the contract and for a loss $X = h$

the loss charged to the layer $(\alpha, \alpha + h]$ is the exhaustion point $-\alpha$, and thus $(\alpha + h) - \alpha = h$. After that point again the loss coverage is on the policyholder.

On this framework, for two different risk types, which could refer to two insurance contracts that cover different losses, the expected loss of the most risky contract is expected to be greater than the less risky contract. Specifically, let X be a random variable representing the risk level associated with economic loss. We define two risk levels $X1$ and $X2$ such as $X1 > X2$. The cumulative distribution function (CDF) is denoted with $F_X(x)$ and gives the probability $P(X \leq x)$. The expected loss (EL) corresponding to a risk level X can be expressed as follows:

$$EL(X) = E[x] = \int_0^\infty (1 - F_X(y))dy \tag{2}$$

where $1 - F_X(y) = P(X < y) = S_X(y)$, is the survival function of the probability function. Hence, for $X1 > X2$ the non-decreasing property of the CDF is satisfied, meaning $F_{X1}(x) < F_{X2}(x)$ for every x. This holds because if $X1$ represents a higher risk level than $X2$, it implies that as we look at a given threshold x, the probability of losses that exceed x for $X1$ is greater than for $x2$, $P(X1 \leq x) \leq P(X2 \leq x)$. The survival function $S_X(y) = P(X1 > y) = 1 - F_X(y)$ for $X1, X2$ is:

$$S_{X1}(y) = 1 - P(X1 \leq x) \tag{3}$$
$$S_{X2}(y) = 1 - P(X2 \leq x) \tag{4}$$

By (3) and (4), we get the following:

$$S_{X1}(y) \geq S_{X2}(y) \textit{ for every risk level } y. \tag{5}$$

This means that at very point y the probability of a loss exceeding y is higher for the risk level $X1$. Integrating the survival functions to derive the expected loss.

$$EL(X1) = \int_0^\infty S_{X1}(y)dy \tag{6}$$
$$EL(X2) = \int_0^\infty S_{X2}(y)dy \tag{7}$$

By (5),

$$\int_0^\infty S_{X1}(y)dy \geq \int_0^\infty S_{X2}(y)dy = EL(X1) \geq EL(X2). \tag{8}$$

For strict inequality, between the two expected losses we could claim that if $X1$ results in a higher risk of economic losses than $X2$ it implies there are scenarios or insurance claims that losses are much larger in magnitude or frequency for the higher risk compared to the lower risk level. Thus, there will be certain regions where (5) holds with strict equality when integrating for the whole range, and, by extension, (8) also holds with strict equality. In those certain regions, the specific risk ranges contribute more significantly to the overall area under the integral, the expected loss. The identification of these regions is crucial for insurance companies

when deciding to cover a loss level, leading them to prioritize management efforts and capital allocation.

We extend the analysis by investigating the expected economic loss while in a hotter world by defining EL of a risk level X (a specific insurance contract) as a function of temperature T as indicated in (9).

$$EL(X) = \int_0^\infty y \cdot S_X(y|T)dy \tag{9}$$

The conditional probability within the survival function represents the probability that economic losses exceed a certain threshold y under temperature T. Here, the integral accounts for all potential loss amounts y multiplied by the probability that the loss does not exceed each amount, summed over the range of possible losses. The term y has the role of a weight of the loss amount in each case. Following the empirical evidence in Chapter 3.2, the environmental temperature influences the catastrophic risk. As the temperature increases, there is greater volatility and severity in weather patterns. Increased probability of extreme events such as floods, storms, wildfires etc. affects the expected economic losses covered by the insurance product X. For two levels of temperature such as $T1 > T2$, the following expression holds:

$$S_X(y|T1) = P(X \leq y|T1) < P(X \leq y|T2) = S_X(y|T2) \tag{10}$$

The expression (10) indicates that for the higher temperature $T1$ scenario, there is a greater probability that losses will exceed the threshold y compared to the lower temperature scenario $T2$. Constructing the expected loss using the integral form, we have:

$$EL(X|T1) = \int_0^\infty y \cdot S_X(y|T1)dy > \int_0^\infty y \cdot S_X(y|T2)dy = EL(X|T2). \tag{11}$$

Expression (11) captures the evidence that as temperature rises, the integral associated with the expected loss at scenario $T1$ includes the higher probabilities of losses exceeding the threshold y, resulting in an overall higher expected economic loss, and by extension to:

$$EL(X|T1) > EL(X|T2). \tag{12}$$

The fact that $S_X(y|T)$ develops in the opposite direction of $EL(X|T)$ implies a monotonic relation between the two magnitudes. This key concept illustrates how the risk factors associated with environmental conditions such as increases in temperature leading to extreme weather and more frequent and more severe natural catastrophes, can directly influence economic damages for insurance companies by raising their expected losses. Insurers, based on this concept can better assess risk and set premiums that reflect the underlying estimated probability of claims associated with climate-related factors.

This chapter has established a comprehensive framework for understanding the relationship between risk, insurance premiums, and environmental factors, particularly in the context of climate change. By defining risk as a non-negative random variable and applying the four axioms of risk coherence, we clarified how insurers assess and manage economic losses. The exploration of expected losses associated with varying temperature scenarios highlights the urgent need for insurance models that adapt to the increasing severity and frequency of catastrophic events.

As climate change intensifies risks, it is critical for insurers to refine their risk management strategies to ensure that premiums accurately reflect these evolving threats.

Building on this foundation, the next chapter will focus on creating an informed premium model that is dependent on temperature anomalies, aimed at navigating the complexities of climate-related risks and fostering resilience within the insurance industry. Key components such as expected absolute loss (EAL), expected excess return (EER), and total expected layer loss (TEL) will be analyzed, providing essential insights for effective pricing methodologies.

4.6 Insurance premium modeling

In the face of increasing climate-related risks, effective insurance premium modeling has emerged as a cornerstone of the insurance industry. This chapter delves into the intricacies of developing a sophisticated pricing methodology that not only addresses economic losses, but also adapts to varying temperature scenarios. By rigorously establishing a framework that integrates expected loss functions risk layers, we illuminate the critical processes through which insurers evaluate and mitigate potential financial impacts. Key components such as expected absolute loss (EAL), expected excess return (EER), and total expected layer loss (TEL) will be thoroughly analyzed, revealing their interconnections and implications for risk management. This chapter is pivotal, as it not only presents essential mathematical proofs but also equips insurers with the analytical tools necessary to navigate the complexities of pricing in an increasingly volatile natural environment. The insights gained here are vital for fostering resilience and sustainability in the insurance sector, ensuring that it can effectively respond to the challenges posed by climate change.

In the preceding chapter, we established a conceptual framework that briefly summarizes the key elements forming the expected loss function of the insurer. Building upon this theoretical background, we now transition to the model which implements these elements into constructing a pricing methodology that covers for economic losses and accounts for different temperature scenarios. Firstly, following (1), (6) and (7) we specialize the risk range for $\alpha < X \leq \alpha + h$. This range is the range that the insurer has agreed to cover according to the contract. In this setting, we focus on the expected loss occurring within this interval, higher than the attachment point but less or equal to the exhaustion point. The survival function for this loss layer is formed as follows:

$$EL(X(a, a+h]) = \int_0^\infty S_{X_{(a,a+h]}}(y)dy \tag{13}$$

while changing the limits of the integral so as to set bounds of the economic loss withing the contract intervals, we end up with:

$$EL(X(a, a+h]) = \int_a^{a+h} S_X(x)dx \equiv EAL(X) \tag{14}$$

where $EAL(X)$ accounts for the expected absolute loss.
Now that we have quantified the financial impact of potential losses for the insurer, which is directly derived from the loss distribution, we built the expected excess return (EER) that integrates the quantified risk from EAL to account for potential excess returns for the insurer to accept this risk, that is, the load factor. Specifically, EAL provides the baseline for losses that may occur, while EER considers how these losses could translate into expected returns for the insurer based on the probability of occurring and the conditional loss metric. Essentially,

EER encapsulates what additional return the insurer could demand to take on losses associated with high-risk events highlighted by EAL. The EER is formulated as follows:

$$EER(X) = \gamma \cdot (PFL)^{a} \cdot (CEL)^{\beta}. \tag{15}$$

where γ, α and β are scaling parameters that adjust EER and represent the insurer's risk preferences or market characteristics. PFL is the probability of the first loss, which means the likelihood that a loss exceeds a certain threshold α, and is defined as follows:

$$PFL = S_X(a) = P(x > a). \tag{16}$$

As a probability $PFL \in (0, 1)$ and equals the survival function evaluated at a, indicating the probability that the losses will exceed the threshold α. In essence, expresses the chance of exceeding a particular loss, a crucial information for the insurer for setting aside capital and establish informative premiums. CEL is the Conditional Expected Loss and represents the expected loss given that a loss has occurred and is greater than α, indicating the monetary severity of the anticipated loss. CEL is defined as follows:

$$CEL = \frac{EL(X(a, a+h]|x > a)}{h}. \tag{17}$$

With respect to this formula, CEL is the average loss that is expected in a particular loss layer (from α to $\alpha + h$), given that a loss has already exceeded the loss level α. Dividing by h, the upper limit of the economic loss the insurer has agreed to cover normalizes the conditional expected layer loss across the interval, providing a per unit expected loss. Setting for simplicity γ, α and β equal to one, the expression for the Total Expected layer Loss (TEL) for the insurer is given by the following expression:

$$TEL(X) = AEL(X) + EER(X) = \int_{a}^{a+h} S_X(x)dx + P(x > a) \cdot \frac{EL(X(a, a+h]|x > a)}{h} \tag{18}$$

Expression (18), represents in general the average loss expected over a certain period or given certain conditions and it includes all potential losses along with those losses that may not be significant enough to warrant separate management techniques from the insurance company. Nonetheless, simplifying for the EER parameters is done so as to focus on the core relationship of PFL and CEL. In practice, γ, α and β can vary depending on the loss distribution and the thresholds analyzed. Defining a linear representation of a premium model charged by the insurer, we have the following formula:

$$premium(X) = \rho \cdot TEL(X) \tag{19}$$

where X represents the insurance contract declaring the loss layer the insurer agrees to cover, and ρ a factor that adjusts the premium reflecting the insurers mark up on the expected losses or a government upper limit to impose for a more accessible insurance price to the public.

Regarding the factor ρ, following the traditional insurance rule, is to set $\rho = 2$. This approach implies that the insurer will charge double the total expected loss, ensuring recovery of both expected and unforeseen losses. This way also targets the company's economic viability, accounting for additional viability and uncertainty inherent in loss predictions. However, in the field of natural catastrophic insurance, catastrophic adverse events present an up-warding trend in their expected frequency and severity, a factor that increases the public demand for insurance coverage. Maintaining a factor of $\rho = 2$ with an increasing demand for insurance contracts could decrease the available capital of the insurance company after a specific threshold, depending, of course, on the elasticity of demand for insurance. Specifically, the increasing

demand for natural catastrophic insurance contracts given they are relatively expensive could eventually lead to a decrease in the clientele of private insurance companies under the discussion that traditional premium pricing is not optimal and alternative approaches should be investigated by insurance companies for the hotter world scenario. In this framework, it is worth exploring a more competitive factor in market terms or a more optimal in pricing strategies terms premium factor ρ. This exploration could be the result of a more competitive market, where insurers can look to attract customers by offering premiums that are closer to the actual TEL adopting more efficient insurance pricing. However, a $\rho < 2$ could also be the result of improved risk modeling and data analysis (such as high-resolution satellite data) using which insurers can better understand the magnitudes and ranges of the climate risks they are exposed to. Adopting new physical risk methodologies could allow one to comfortably reduce the insurance mark up while not significantly compromising the maintenance of their economic profitability and sustainability. An additional reason for lowering the premium factor ρ could be the insurance company's strategy to increase customer satisfaction and retention.

Specializing the premium model to account for temperature, the general premium model will be a function of temperature as follows:

$$premium(X|T) = \rho \cdot TEL(X|T) \tag{20}$$

In this context, based on the empirical evidence we assume that as temperature increases it causes a positive shift in the frequency and severity of natural catastrophes. By (18), focusing on the EER component, statistical evidence from AR6[4] indicates that the increase in temperature linked to climate change has a positive relationship with the probability of the occurrence of catastrophic events. In mathematical terms, this translates into the following inequality:

$$PFL(X|T1) > PFL(X|T2),\ for\ T1 > T2 \tag{21}$$

Now regarding the severity of these catastrophic events, statistical evidence also show that economic losses are increased due to more severe weather events that by extension lead to a positive shift in the demand for insurance coverage. Mathematically, this is translated to:

$$CEL(X|T1) > CEL(X|T2),\ for\ T1 > T2 \tag{22}$$

Based on (15), for the parameters γ, α and β we could assume they are constants that does not change drastically over the studied temperature range, meaning they will not affect the inequality in terms of comparison. Combining $(12), (21)$ *and* (22), given that α and β are non-negative by the monotonic property, we have that $(PFL(X|T1))^a > PFL(X|T2)^a$ and $(CEL(X|T1))^\beta > (CEL(X|T2))^\beta$ for $T1 > T2$. Adding the parts, we have:

$$premium(X|T1) > premium(X|T2) \tag{23}$$

Yet, given that IPCC AR6 highlights the alarming anticipated climate risk for the next decades, insurance companies could alter their risk preferences shifting γ accounting for at least two different temperature scenarios. In that case, we assume that the factor γ, which reflects the insurer's risk appetite, also changes. Different γ's translate the anticipated higher climate risk following the IPCC temperature scenarios. In this way, insurers could elaborate on their risk tolerance scenarios by setting different γ's. Hence, for a temperature increase from $T2$ to $T1$ such that $T1 > T2$, the additional anticipated risks would lead the insurer to set $\frac{\gamma 1}{\gamma 2} > 1$. The

[4]https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/

last inequality captures that the insurer will require a higher risk premium to compensate for the additional uncertainty associated with the physical risks linked to a hotter world. Formally,

$$EER(X, T1, \gamma 1) > EER(X, T2, \gamma 2) \tag{24}$$

we get:

$$\gamma 1 \cdot (PFL(X|T1)^a \cdot (CEL(X|T1)^\beta > \gamma 2 \cdot (PFL(X|T2)^a \cdot (CEL(X|T2)^\beta \tag{25}$$

which by extension proves that:

$$premium(X|T1, \gamma 1) > premium(X|T2, \gamma 2). \tag{26}$$

At this point, it is meaningful to discuss the choice and deeper meaning of parameters γ, α and β in the insurance pricing context. More analytically, when pricing insurance products, those parameters are often assumed non-negative due to their role related to expected losses, pricing and risk aversion, scaling the frequency and severity of economic losses. Assuming negative parameters, this would imply an inverse relationship indicating for example that as frequency and severity of natural catastrophes increase, the expected economic losses would decrease, something that it is not conceptually rational neither is supported by the historical and empirical evidence. Further, in risk management and actuarial science, often monotonic relations are selected over non-monotonic ones in the lines that if the probability of loss for the insurer and the conditional expected loss (the severity of the expected loss) increase, insurers prefer the overall premium price to also increase, reflecting the higher risk. With that in mind, positive values of α and β may signify for α and $\beta < 1$ diminishing returns, for α and $\beta = 1$ linear increase of the returns, and α and $\beta > 1$ increasing returns for the insurer. Function (15) resamples the Cobb-Douglas production function, where in the case of a production function α and β represent elasticities or sensitivity measures that indicate how changes in the respective inputs affect the overall outcome, whereas in the expected excess returns function, they represent the relative importance - the contribution of PFL and CEL to the overall expected premium. The selection of γ, α and β at the end of the day reflect the risk appetite and the perception strategy of climate risk by the insurer, something that is decided in the board of directors of each company and then is set down to a mathematical formulation.

To effectively assess large natural catastrophic events, it is essential to define the distribution of these occurrences. According to [Xu, 2016], discrete natural catastrophe events are Poisson distributed. More precisely, in probability theory and statistics, the Poisson distribution describes well the volume of occurrences of natural catastrophes in a fixed time span. In the next paragraph, we describe briefly the foundational assumptions of the Poisson distribution in the context of natural disasters arriving. Firstly, we assume interdependence of events. This signifies that natural catastrophe events are assumed to occur independently, that is, the occurrence of one event does not influence the probability of an other event occurring, $P(A \cap B) = P(A) \cdot P(B)$, for any two events A, B when $P(A \cap B)$ represents the joint probability of both events occurring. Secondly, we assume for homogeneity, meaning that the characteristics of natural catastrophes (e.g. their intensity and loss magnitude along with their geographical distribution are assumed to be homogeneous. This assumption implies that over the specified time period and across different regions, the average rate of occurrence is constant. Mathematically, for λ the arrival factor (the expected rate of occurrence) for any two time intervals we have$E(N(t1)) = E(N(t2))$, where N refers to the number of natural catastrophe occurrences in two different points in time. Third, we accept that the time period in which we observe natural catastrophe events is fixed. The Poisson process operates over a

fixed time frame t, which means that there is a specific duration over which we observe the occurrence of events. In this paper, the fixed time interval refers to one year. In addition, the fixed time interval minimizes the impact of external time-related variability. For example, natural disasters may have seasonal patterns (e.g. floods in the winter, wildfires in the summer), but by selecting a fixed time interval (e.g. a full year) we can capture all occurrences within that period without having to adjust for seasonal variations. Given these assumptions, the expected number of natural catastrophic events within the fixed time interval is denoted by the parameter $\lambda > 0$ representing the average rate of occurrence of these events. For smaller λ, the density function falls closer to zero on the x-axis, denoting that there is a higher probability that the catastrophic even does not occur. In contrast, as λ becomes larger, the mean value of the curve increases, denoting that the probability of a catastrophic event increases. The probability mass function (PMF) of a Poisson random variable N, for the number of occurrences in the specific time interval is given by:

$$P(N = n) = \frac{((\lambda)^n \cdot \ e^{-\lambda})}{n!}$$

where n the actual number of natural catastrophe events that occur and e the base of the natural algorithm. Expanding our analysis to address the implications of climate change on natural catastrophe occurrences, we introduce a relationship between the frequency of such events and temperature. Following [Xu, 2016], we model the arrival rate λ as a function of temperature (T).

$$\lambda = \delta \cdot T \tag{27}$$

where δ is a scaling parameter reflecting the sensitivity of natural catastrophe occurrences to temperature shifts. This assumption could also imply that the premium variation is dependent on the temperature anomaly when the premium covers for climate change related catastrophic events. The revised PMF function reflecting this temperature-dependent occurrence volume by (27) becomes:

$$P(N = n) = \frac{((\delta \cdot T)^n \cdot \ e^{-\delta \cdot T})}{n!} \tag{28}$$

Formulation (28) accounts for the implications of temperature shifts on the occurrence of catastrophic events, illustrating how environmental factors can influence the underlying risk exposure insurers must evaluate.

Following the theoretical framework set in this chapter, Figure 2 depicts the ratio of insured damage compared to the simulated insurance premium. The analysis is based on real temperature data for Europe and North America from the World Bank Climate Change Knowledge Portal[5]. The dashed red line at 0.5 represents the traditional theoretical benchmark in the industry, where premiums are expected to be about twice the insured damages. Both regions show significant fluctuations in their damage-to-premium ratios, particularly in earlier years, with both North America and Europe highly overpricing their expected losses by more than twice before 1993. After 2002, data again revealed a more restricted and steady overpricing in comparison to previous years [Hunter, 2008]. As natural disasters have become more frequent and unpredictable since 2000, insurers face significant challenges in their financial sustainability [Born and Viscusi, 2006]. Existing premium models often underestimating the true scale of potential claims that it itself is uncertain are a well-known reality in the insurance industry and are the driving factor of the expansion of this research field [Kalfin et al., 2022]. Furthermore, voices calling on the industry to set premiums lower than the traditional rule are increasing

[5]https://climateknowledgeportal.worldbank.org

[Charpentier et al., 2022] in the light of the inevitable increase in the demand for coverage due to the systematization of extreme natural disasters registered worldwide.

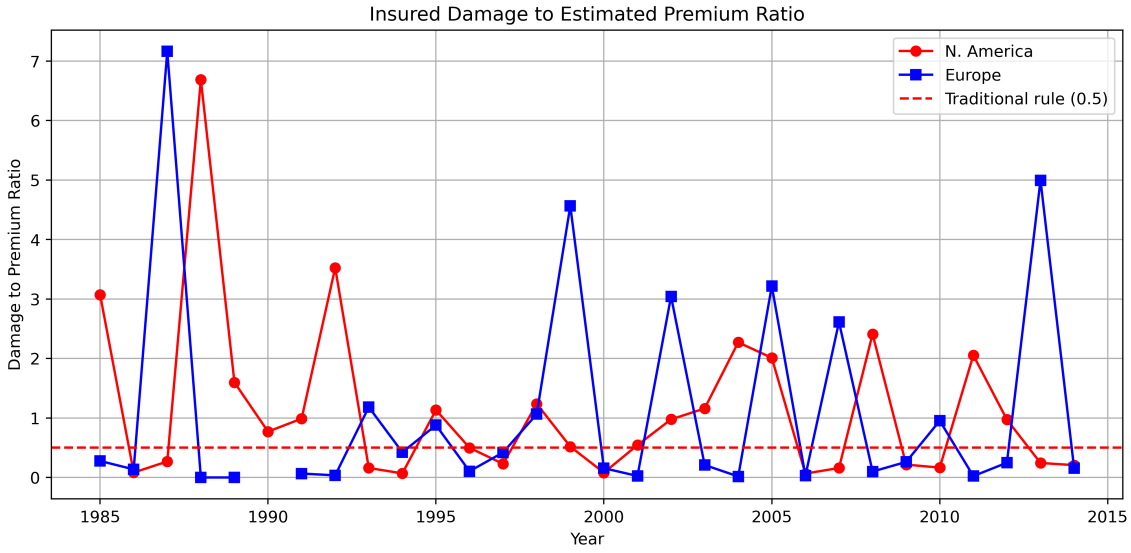


Figure 2: Insured Damage to Estimated Premium Ratio

To illustrate the historical evolution of insured and total damages from climate-related natural disasters compared to simulated historical premiums, the following graphs represent data for insured damage, total damage, and estimated premiums in Europe and North America.

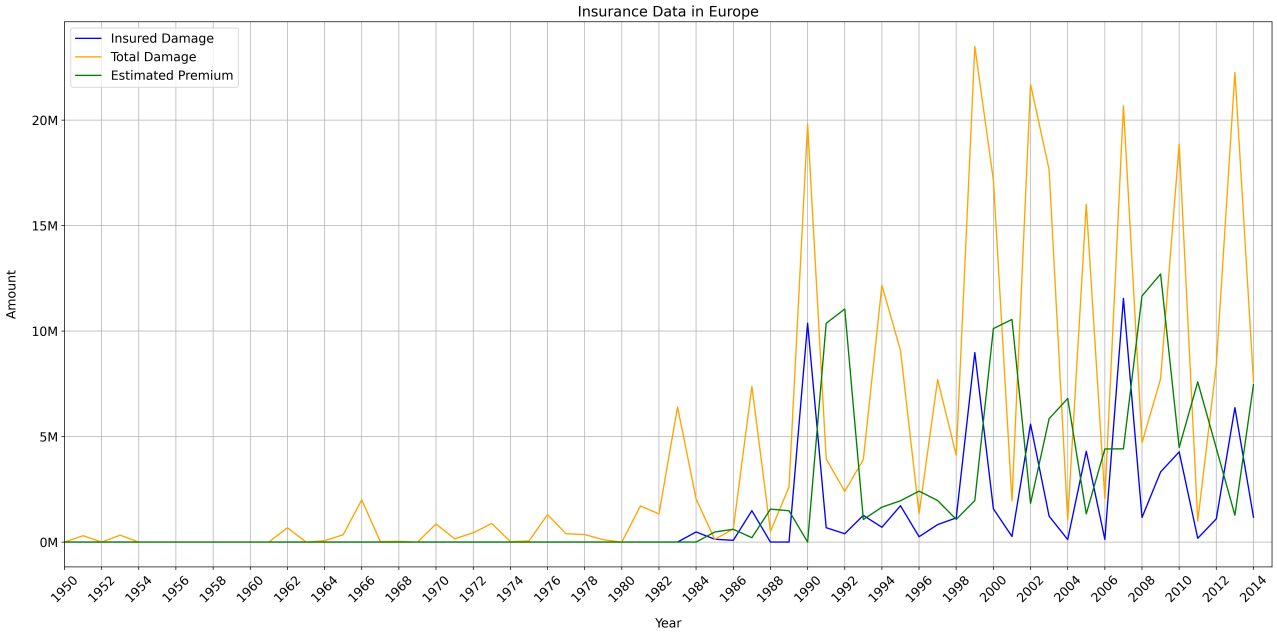


Figure 3: Historical insurance premium simulation for Europe

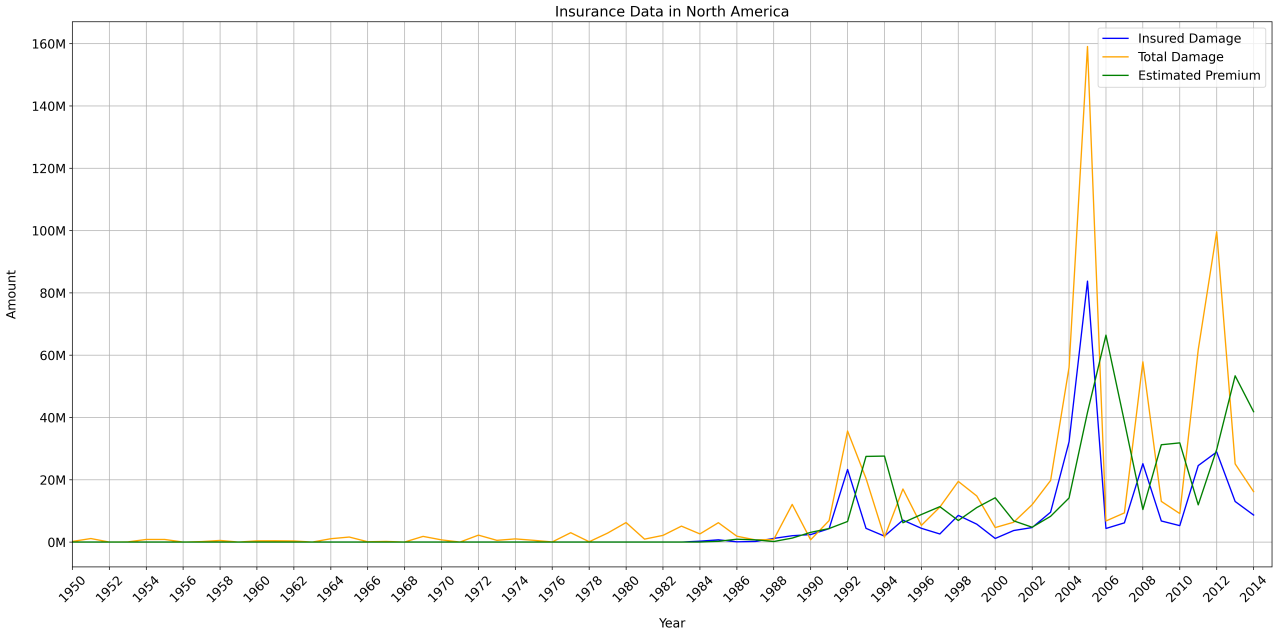


Figure 4: Historical insurance premium simulation for North America

Historical data in Europe Figure 3, indicate that after years with increased insured damages, the insurance industry typically responds by increasing premium prices, a lagged co-evolution evident until 2000, indicating the incorporation of new risk information. However, post-2000, the analysis reveals a contrasting trend: premium peaks coincide with significantly low insured damages, reflecting a reduction in coverage amid persistently high total registered damages. On the other side of the Atlantic, historical data for North America Figure 4. Presenting similarities with the Europe trends, the North American graph illustrates that following

years of heightened insured damages, premiums also tend to peak. Further, we note a more informed pricing scheme in North America, where total damages have been recognized more gradually compared to Europe, which experienced extreme total damages earlier. Notably, since 2004, North America has also seen a decrease in the coverage offered, yet the insurance market continues to adhere more closely to traditional premium pricing principles[6].

This chapter has established a comprehensive framework for effective insurance premium modeling amid climate-related risks, emphasizing the significance of integrating expected loss functions and temperature anomalies. Transitioning to the next chapter, we will conduct a detailed examination of the historical evolution of insurance data, highlighting descriptive statistics and premium estimations aligned with Shared Socioeconomic Pathways (SSPs). This analysis will further elucidate the relationship between historical data trends and future pricing models in the context of climate impacts.

[6]Data from 2025 onward, along with projections until 2030, will be presented in the next chapter. This aligns with the World Bank database methodology, which classifies the years 1950-2014 as historical values, with subsequent years split into projected SSP scenarios for consistency.

5 Descriptive Statistics and Forecasts

This chapter aims to explore the evolution of temperature anomalies and their consequential relationship with natural catastrophes and insurance premiums. Although various factors contribute to climate change, temperature anomalies play a crucial role in the triggering of natural disasters, which in turn result in significant economic damages. Understanding these dynamics is essential for the evolving landscape of the insurance industry, as these anomalies reveal the increasing risks faced by insurers and have important implications for premium pricing and risk assessment. In addition, this analysis encompasses Shared Socioeconomic Pathways (SSPs), which provide structured narratives for plausible future climate scenarios. These narratives underscore the critical role of insurers in both adapting to and mitigating the financial challenges presented by climate-related risks.

For the scope of this paper we will first study the evolution of the temperature factor and then investigate its relation to natural catastrophes and by extension to insurance premiums. Indeed climate change is expressed through various factors, however the factor of temperature is considered one of the most informative factors. More analytically zooming in the notion of temperature, is advocated that temperature anomalies are more essential in climate change research than absolute temperatures. The anomaly is defined as the distance from the average or baseline temperature. Temperature anomalies greater than zero indicate that the observed absolute temperature is higher than the baseline absolute temperature, whereas temperature anomalies less than zero signify that the measured absolute temperature is lower than the fixed baseline. According to the National Centers for Environmental Information, in the process of measuring the absolute temperature, technical factors, such as the location of the station or the elevation of the measurement thermometer mechanism, have an important effect on the data. For example, higher elevations are cooler than lower elevations, while metropolitan regions are warmer than rural ones. In contrast, when the anomaly of absolute temperature is observed instead, the measurement factors are less critical[7]. For example, calculating the temperature anomaly in a summer month on a mountain top and in a valley could exhibit the same temperature anomaly, but in absolute terms, those two regions could present significantly different values.

While focusing on temperature anomalies, it is meaningful to refer to Shared Socioeconomic Pathways (SSPs). The five SSP pathways can be characterized by the socioeconomic challenges they present to mitigate and adapt to climate change. SSP1 (Sustainability) faces few challenges, focusing on clean energy and environmental preservation, while SSP3 (Regional Rivalry) encounters many due to its reliance on fossil fuels. SSP4 (Inequality) shares an energy outlook with SSP1 but faces significant adaptation challenges, whereas SSP5 (Fossil-fueled Development) has many mitigation challenges. Finally, SSP2 (Middle of the Road) represents moderate challenges for both mitigation and adaptation with a balanced energy development path. Understanding climate change as primarily anthropogenic, SSPs provide narratives that describe possible future development pathways for human society, particularly with respect to fossil fuel use and the social and economic factors that drive it. Five SSP scenarios that span a range of plausible climate futures were prioritized for use in CMIP6 climate model experiments: SSP1-1.9 (closest to the Paris Agreement target of 1.5°C), SSP1-2.6 (approximately equal to RCP2.6), SSP2-4.5 (approximately equal to RCP4.5), SSP3-7.0 (a medium-high scenario) and SSP5-8.5 (a high scenario similar to RCP8.5). These pathways explore various technological, socioeconomic and policy futures, as well as challenges to mitigation and adaptation.

[7] https://www.ncei.noaa.gov/access/monitoring/dyk/anomalies-vs-temperature

The analysis was based on temperature data from the World Bank public data[8]. Along these lines, as was mentioned in Chapter 4.2 there is a rapidly glowing literature advocating that there is strong evidence that temperature anomalies trigger natural disasters in a more systematic way. Thus, on this framework, this paper studies the link between these two variables in the two regions. Initially, it is meaningful to clarify the distinction between the types of natural catastrophes. Natural perils for the insurance industry are classified into two categories. In the first case, are the primary perils which refer to large-scale natural catastrophes, such as tropical cyclones, earthquakes and European winter storms. Alternatively, to primary perils are the secondary perils which typically generate economic losses of low to medium magnitude, but with high frequency. These include "independent secondary perils" such as thunderstorms, hail and tornadoes, droughts, wildfires, snow, flash floods and landslides.

The natural disaster data was based on the public EM-DAT database[9]. Specifically, temperature anomalies were constructed from the absolute temperature as deviations from the 1950-1980 average for Europe and North America and refer to air-surface temperature. For alignment with the World Bank database, the analysis in this paper considers as historical values the temperature values of the period 1950-2014. The temperature values for the period 2015-2024 are used for model validation, and the temperature values from 2025-2030 are projections under the SSP scenarios, used for economic damage and premium estimations. The disaster data analysis for Europe and North America is based on information on the number of natural disasters per year along with their respective economic damages (total and insured) that are the result of droughts, wildfires, floods, extreme temperatures and storms, incidents that are strongly related to climate change patterns. The following graphs illustrate the co-evolution of climate-related natural disasters and temperature anomalies in Europe and North America. Historical data from Europe Figure 5 from 1950 to 2024 illustrate a notable upward trend in both variables. Although the number of natural disasters exhibits some fluctuations, it generally increases in tandem with rising temperatures. The temperature anomaly shows a consistent increase, reaching over 1.7°C, indicating a significant warming trend. The spikes in natural disasters around the late 1980s and more recently align with periods of pronounced temperature anomalies, suggesting a potential correlation between increasing temperatures and the frequency or severity of climate-related disasters in the region.

Historical data from North America Figure 6 display a similar upward trend in temperature anomalies. However, the number of climate-related natural disasters tends to be lower than in Europe, with less pronounced fluctuations. The temperature anomaly closely follows the trend seen in Europe, peaking around the mid-2020s at approximately 1.7°C. However, Europe experiences a higher frequency of natural disasters, suggesting that the impacts of climate change may manifest more acutely there than in North America. This difference in disaster frequency could indicate regional variations in climate resilience and vulnerability.

Regression analysis of climate-related disasters in Europe and North America reveals a pressing connection between rising temperature anomalies and increased frequency of disasters. In Europe, historical data analysis indicates a striking sensitivity to temperature changes: for each one-degree Celsius increase in temperature, a remarkable 415.50% increase in the number of climate-related disasters is estimated. This highlights an alarming trend where even slight temperature changes can significantly escalate the frequency of extreme weather events in the European geographical region, underscoring the vital need for immediate and effective adaptation strategies.

[8]https://climateknowledgeportal.worldbank.org/download-data
[9]http://public.emdat.be/data

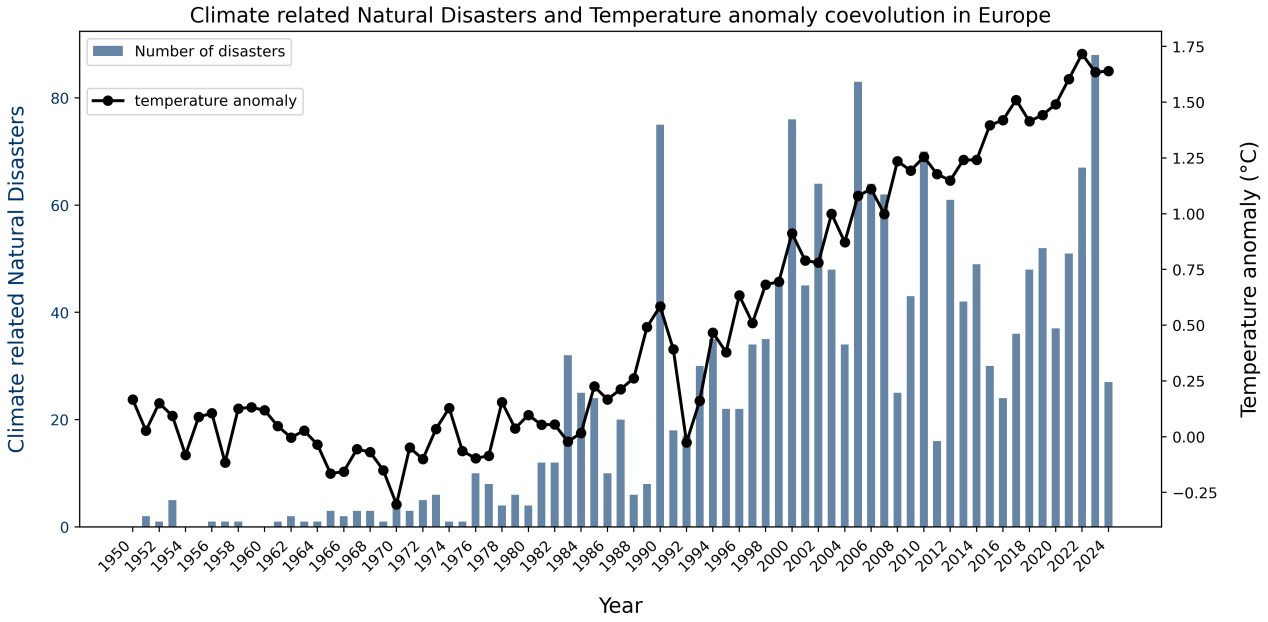


Figure 5: Coevolution of climate-related natural disasters and air surface temperature anomaly in Europe. Data source:Temperature data from World Bank and Natural Disasters from from EM-DAT.

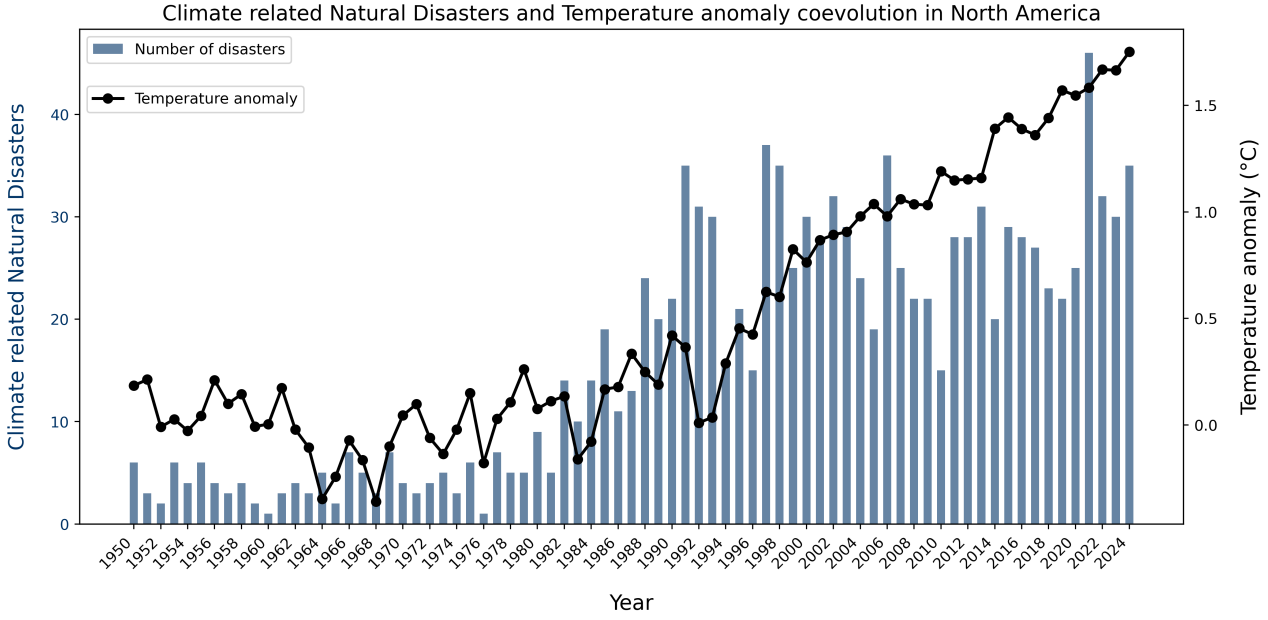


Figure 6: Coevolution of climate-related natural disasters and air surface temperature anomaly in North America. Data source:Temperature data from World Bank and Natural Disasters from from EM-DAT.

In contrast, in North America the effect of one-degree Celsius rise in temperature anomaly is expected to trigger a positive increase of 15.32 disasters[10]. Although both regions are expected to face significant increases in climate-related disasters, the impact of rising temperature anomalies is clearly greater in Europe than in North America. This disparity highlights the unique vulnerabilities of each region, the urgent need for targeted adaptation and preparedness measures, and the potential benefits of sharing best practices to enhance resilience to climate-related disaster challenges.

Extending the impacts of temperature anomalies and the increase in climate-related natural disasters is crucial to understanding their implications for the insurance industry. Observing the last four decades of disaster incidents Figure 7, we observe that in terms of total economic damage, North America exhibits a more pronounced upward trend, particularly evident in the peaks around 2005 with 159 million dollars of total economic damage (year of Hurricane Katrina)[11]. It is worth mentioning that this was the first year that the temperature anomaly overpassed the +1 degree Celsius of the 1950-1980 average. 2011 was a record-breaking year for climate extremes such as the Extreme Southern Drought, Historic Flooding on the Ohio and Mississippi Rivers, Record Summer Heat, Hurricane Irene, Northern Plains and Missouri River Floods, South and Southwest Wildfire Season, Southern Tornado Outbreak, Tropical Storm Lee[12] with total economic damages almost 62 million dollars. Finally, 2017 was a noteworthy year for the catastrophic tornadoes and flooding such as the EF-4 tornado in Missouri, the historic flooding in southeast Missouri where Current River rose 8 feet above the previous record and remnants of four tropical systems that brought heavy rain in summer and early fall)[13] with 190 million dollars of total economic damages. The data indicates a significant exponential increase in the total economic damages from climate-related disasters over the decades. The average total damages rose from 0.37 million in the 1950s to 0.60 millions in the 1960s, 1.11 millions in the 1970s, and 3.88 millions in the 1980s. This trend accelerated in the 1990s, with damages reaching 13.31 million, followed by 34.49 million in the 2000s and 56.65 millions in the 2010s. In particular, in the early 2020s, total damages have already surpassed 119.57 million, underscoring an alarming increase in the frequency and intensity of climate-related disasters in North America. Europe, while displaying fluctuations and a less pronounced increasing trend, showcases comparatively lower total damage amounts over the same period. Notably, the damage remains relatively stable with occasional spikes, particularly the notable recent peak in 2021 with total economic damage of more than 51 million dollars (year of record-breaking precipitation and flooding across Belgium, Germany and surrounding countries)[14]. Europe, demonstrates a volatile trajectory over the decades in comparison to North America. Average damages increased from 0.06 million in the 1950s to 3.01 millions in the 1960s, followed by fluctuations in the 1970s and 1980s, with damages of 0.46 million and 2.27 million, respectively. The 1990s saw a significant rise to 8.80 million, but this was followed by a decrease to 11.07 million in the 2000s and a drop to 8.07 millions in the 2010s. In particular, total damages in the early 2020s have already surpassed 17.99 millions, a magnitude that shows a slightly increasing trend but significantly less than the average damages in North America.

The divergence in total damage between the two regions emphasizes North America's

[10] Application of Negative Binomial regression in Europe over 75 observations, with R^2=51% and OLS regression in North America oven 75 observations, with R^2=58%. Both estimated coefficients are statistically significant

[11] https://www.weather.gov/media/hazstat/sum05.pdf

[12] https://www.weather.gov/media/hazstat/sum11.pdf

[13] https://www.weather.gov/pah/top10of2017

[14] https://climate.copernicus.eu/esotc/2021/flooding-july

increased vulnerability to climatic events according to Munich RE[15], a situation that can be attributed to various factors, including differences in infrastructure and development. North America's infrastructure seem to be more exposed to extreme weather because of its geography and urban planning, leading to greater economic losses when climate-related disasters occur. In addition, rapid urbanization and population density in certain areas can exacerbate the impacts of natural disasters, overwhelming emergency response systems.

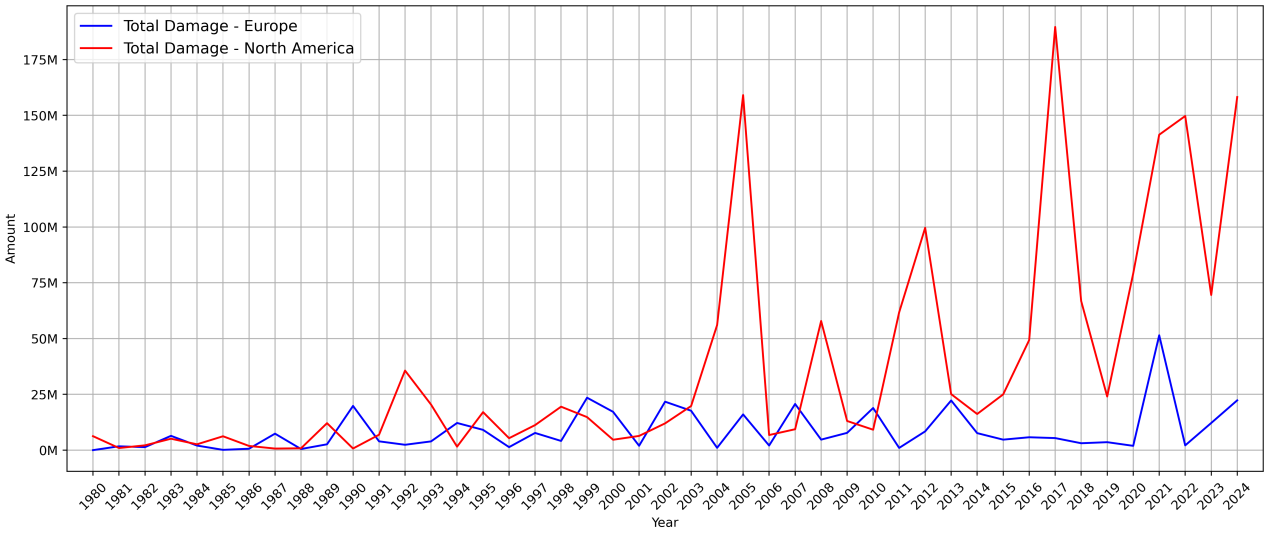


Figure 7: Historical total damages from climate-related natural disasters. Data source: EM-DAT.

Zooming in on the analysis of insured damages out of total damages resulting from climate-related disasters offers an important lens through which to evaluate the efficacy of risk mitigation strategies in both regions. These data elucidate the extent of protection provided by insurance frameworks and reveal emerging trends in coverage that indicate evolving perceptions of risk attributable to climate change. Specifically, observing the last four decades of insured damage incidents Figure 8 North America exhibits a significantly more pronounced upward trend compared to Europe. In addition, the peaks coincide with the disastrous weather events described above. Insured damages covering for the climate-related losses cost 84 million in 2005, 29 millions in 2012, 86 millions in 2017 and 65 and 51 million dollars, respectively, for 2022 and 2024 in North America. In the same period in Europe, insurance industry losses are comparatively very restricted, with 2021 claims reaching 10 millions and 2024 claims reaching 8 millions. Observing the evolution of insured damages, it is evident that North America exhibits a decreasing arrival factor for extreme insurance claims related to climate-related disasters. This trend suggests that, while catastrophic events continue to occur, the frequency and volume of claims tend to increase compared to previous peaks. In contrast, in Europe, the arrival factor remains comparatively less pronounced, indicating that the impact of such disasters on insurance claims is less consistent. This divergence reflects various underlying factors, including differences in exposure to extreme weather events due to geography, regional preparedness measures, response strategies, and the varying levels of insurance penetration in the two regions.

Examining the insurance gap Figure 9, which further emphasizes the differences in coverage

[15]https://www.munichre.com/content/dam/munichre/mrwebsitespressreleases/MunichRe-Mediarelease2025-NatCat2024.pdf/$_jcr_content/renditions/original./MunichRe - Mediarelease2025 - NatCat2024.pdf$

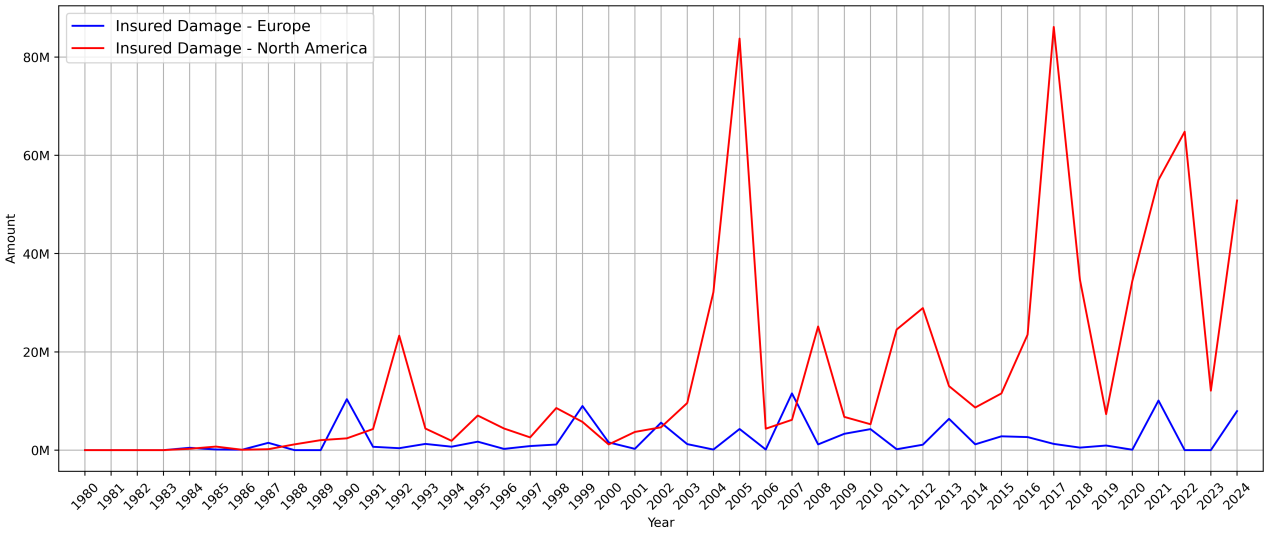


Figure 8: Historical insured damages from climate-related natural disasters. Data source: EM-DAT.

and risk mitigation between the two regions, we identify that North America shows higher volatility, especially notable peaks and lows, particularly in the late 1980s, indicating a period of severe claims and adjustments in the insurance market given the significant increase in climate-related disasters, as shown at Figure 6. According to Munich RE[16] the increasing trend of insured losses (e.g. claims) is driven by supposedly smaller natural catastrophes such as severe thunderstorms, hail, flooding or wildfires that are known as "non-peak perils" or "secondary perils", evidence that supports our defined 'climate-related' disasters as adequate sources of investigation of disaster insurance evolution. Munich Re also highlights that since the 80s only around a third of climate-related damages were insured, a situation that led many of the people and companies affected then to had to bear the brunt of the total economic damage themselves. In contrast, Europe indicates a more stable trend with less dramatic fluctuations, reflecting a generally stable insurance environment over the decades, yet presenting a pattern of higher climate-related insurance gap over the years than North America.

In terms of volatility, North America's insurance gap is characterized by notable volatility due to several interrelated factors, including the cyclical nature of extreme weather events, economic fluctuations, and varying insurance policies. This volatility suggests a greater susceptibility to external shocks, as evidenced by significant spikes in uninsured damages from disasters such as wildfires and floods. In terms of magnitude, Europe presents a generally larger insurance gap. Differences in regulatory environments, varying levels of public welfare support, and cultural attitudes toward risk[17]. In North America, the regulatory framework varies significantly by state, creating a fragmented market where coverage options can be inconsistent. This contrasts with Europe, where standardized regulations, often influenced by the European Union, promote a more unified insurance market. Furthermore, North Americans typically experience less public welfare support, compelling individuals to rely more on private insurance. In Europe, comprehensive welfare systems reduce this pressure, leading to a lower uptake of insurance products in certain segments of the population. Cultural attitudes also play a crucial role; in North America, there is a strong emphasis on personal responsibility, which can drive higher insurance participation. In contrast, European cultures often prioritize communal support, leading to a greater reliance on government safety nets rather than pri-

[16]https://www.munichre.com/en/risks/natural-disasters.html
[17]https://www.ecb.europa.eu/pub/pdf/other/ecb.policyoptions$_E IOPA$ *c0adae58b7.en.pdf*

vate insurance solutions. Thus, while North America demonstrates a more volatile insurance landscape, Europe's insurance gap reflects deeper systemic and cultural differences.

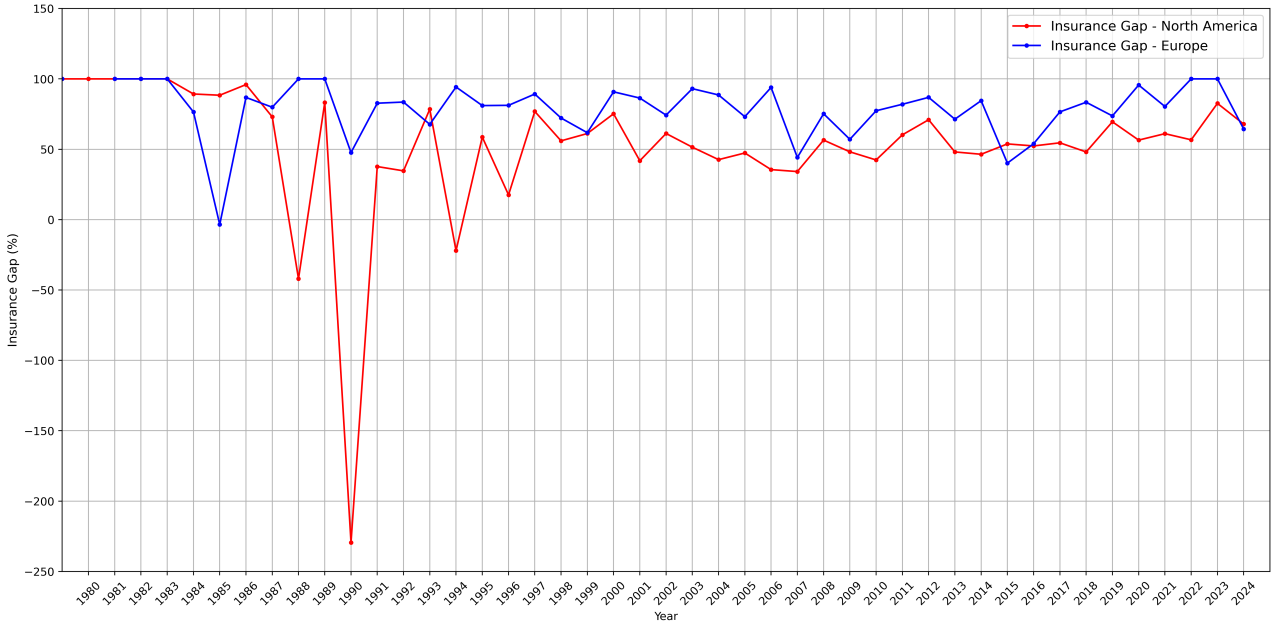


Figure 9: Historical insurance gap. Climate-related insurance cap is calculated as 100 minus the percentage covered and it represents the proportion of total damages that remains uninsured. The percentage covered is the insured damage divided by total damage, multiplied by 100, and indicates the proportion of damages that is covered by insurance. Data source: EM-DAT.

The insurance industry in Europe began to address comparatively higher claims a decade earlier than in North America Figure 10. Insured damages in both areas tend to exceed the average of the decade every two to three decades[18]. This phenomenon led the insurance industry to rethink coverage limits in both Europe and North America with the aim of economic sustainability, evidence that is consistent with Figure 9.

Having established the historical data that track the trajectory of temperature anomalies through 2024, we now focus on the outcomes of our modeling and forecasting analysis. Figure 11 illustrates the evolution and projections of temperature anomalies for North America and Europe through different Shared Socioeconomic Pathways (SSPs). Notably, SSP 1-1.9 is regarded as the "as is" scenario, assuming that the production model and legislative framework will remain unchanged through 2030. Under this scenario and SSP 5-8.4, both regions exhibit significant increases in temperature anomalies, indicating the potential for substantial climatic shifts that could exacerbate weather-related challenges. Additionally, SSP 2-4.5 is considered the most probable scenario for temperature anomalies, characterized by the highest variability across the variables examined in this paper, underscoring the complexity of future climatic projections. A key observation from the data is the higher baseline temperature anomalies in North America compared to Europe, particularly evident in historical trends. However, Europe is expected to experience rapid increases in temperature anomalies under all SSP scenarios, indicative of potentially greater regional sensitivity to climate-related events, specifically floods, wildfires, extreme temperatures, and other related factors, with the analysis excluding tornadoes. This heightened sensitivity is likely to exert significant implications for adaptive management strategies, thereby necessitating the development of targeted interventions to effectively

[18]The arrival factor is calculated per decade by calculating how many registered insurance damages are greater than the average insured damages for each decade, and then divide the count of above-average instances by 10.

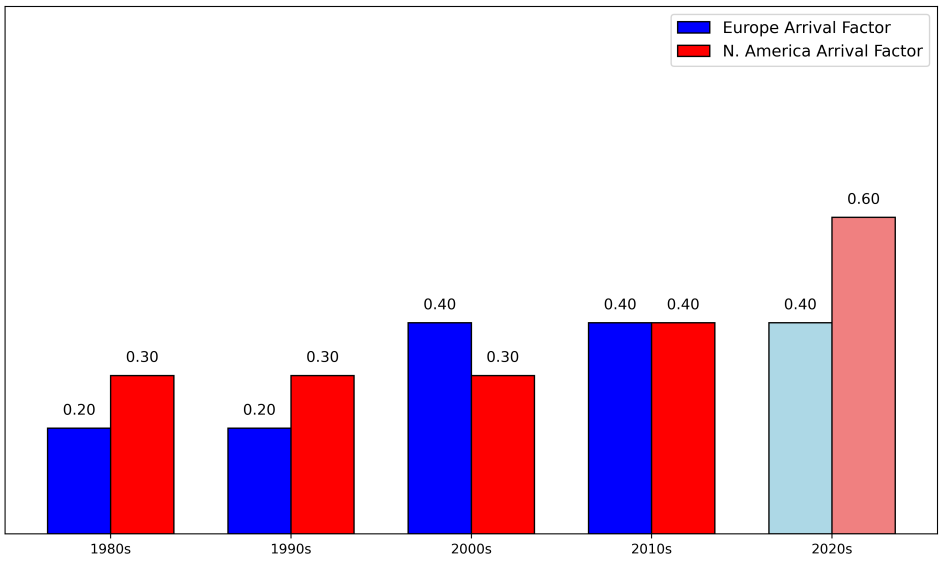


Figure 10: Historical arrival factor of extreme insured damages. Note: the arrival factors for the 2020s refers to the years 2020-2024. The arrival factor is calculated per decade by calculating how many registered insurance damages are greater than the average insured damages for each decade, and then divide the count of above-average instances by 10. Data source: Historical insured damages from EM-DAT.

address the projected climate impacts. A profound impact of the sensitivity implication is visualized in Figure 12. Temperature anomalies produce distinct implications and challenges for the societies in both North America and Europe, leading to an increase in the intensity and frequency of climate-related natural disasters, which result in significant losses in human life and substantial economic damages. Specifically, data reveal a stark contrast between North America and Europe in terms of total economic damages, with North America projected to experience damages that are orders of magnitude greater than those in Europe, even under the most optimistic SSPs. Notably, SSP 5-8.4 demonstrates a steep increase in economic damage projections for North America, indicating that higher greenhouse gas emissions correlate with increasingly severe economic consequences. While Europe exhibits lower baseline economic damages, the SSP 2-4.5 scenario illustrates notable variability, suggesting that even moderate emissions pathways may lead to unexpected economic repercussions by the end of 2025. This finding underscores the importance of robust adaptive strategies to address potential financial risks associated with climate impacts, particularly as they relate to insurance industry losses, which are likely to escalate in tandem with rising economic damages as illustrated in Figure 13. The variations in insured damages reflect the regional differences in coverage and existing exposure along with the anticipated climate-related risks under the SSP pathways. Specifically, North America demonstrates significantly higher historic insured damages compared to Europe and this trend is estimated to continue across all SSP scenarios until 2030, indicating not only a greater economic exposure but also a more developed insurance market capable of addressing larger claims. The systematic relatively low insured damages in Europe also across the projected scenarios point out a lack of adequate coverage, which could pose risks to economic stability in the face of the expected increase of climate-related disasters. According to Munich Re[19] for 2024 Europe presented US$108 billion on insured damages with an insurance gap of 45% while North America presented almost double losses with smaller insurance gap covering

[19]https://www.munichre.com/content/dam/munichre/mrwebsitespressreleases/MunichRe-Mediarelease2025-NatCat2024.pdf/$_jcr_content/renditions/original./MunichRe - Mediarelease2025 - NatCat2024.pdf$

more than 57% of the total damages caused by climate-related natural disasters. We should also note that, the divergence between the projections on the insured damages under SSP 1-1.9 and SSP 2-4.5 illustrates the potential benefits of effective climate mitigation strategies in a government level and in the insurance sector level, emphasizing the importance of adapting insurance models prioritizing risk reduction and ensuring adequate but also economically viable coverage against emerging climate-related threats.

Insurers fundamentally base their premium charges on the anticipated losses they expect to incur when underwriting contracts. Traditionally, the practice has been to charge at least twice the expected losses if an adverse event occurs. However, this tactic has come under scrutiny in recent years, with calls for more socially and economically optimal insurance pricing. As climate-related natural disasters become more frequent and severe, the interplay between projected economic and insured damages directly influences the pricing strategies adopted by the insurance industry. By analyzing historical data and modeling future scenarios Figure 14, it becomes evident that fluctuations in expected losses, driven by climate projections under various Shared Socioeconomic Pathways (SSPs), will require adjustments in premium structures to better align with current realities and community needs. In detail, the analysis reveals a significant disparity in estimated premiums between North America and Europe in all projected scenarios. North America exhibits as anticipated significantly higher premiums, which reflects a stronger correlation between the region's exposure to climate risks and the financial requirements of insurers following the results of total and insured losses presented previously in Figure 12,Figure 13). This disparity highlights the varying risk landscapes and economic vulnerabilities in both regions, urging insurers to adopt differentiated pricing strategies that adequately account for the unique threats posed by climate change. Under the SSP 5-8.4 scenario, the model predicts a dramatic escalation in estimated premiums for North America, which underscores the urgent need for the insurance industry to reevaluate its pricing strategies. As climate-related risks intensify due to higher greenhouse gas emissions, especially in the worse case of SSP 5-8.4, the resulting increase in expected losses makes it imperative for insurers to reflect these risks in their premium structures. This is further highlighted by our modeling assumptions since the premium model was based on the traditional risk pricing tactic charging twice the expected insured loss. The model forecasts a substantial escalation in estimated premiums for Europe around the years 2026-2027 under both middle and worst-case scenarios, projecting an increase that is nearly four times the premiums of 2024.

Such significant price hikes pose considerable financial challenges for individuals seeking insurance for their infrastructures, while also threatening the economic viability of the European insurance sector. Moreover, the cultures of intervention prevalent among European social planners can compel governments to allocate substantial portions of their budgets as a form of last resort coverage. This reliance on public resources could disrupt the balance of payments, indicating that this is not merely a private sector concern, but a wider socioeconomic challenge [Wang, 2025]. Such dynamics suggest that urgent action is needed to recalibrate pricing strategies in response to the increasing climate risks associated with higher greenhouse gas emissions.

In the occurrence of adverse events, such high prices would greatly cause significant financial challenges for people wanting to buy insurance for their infrastructure, to the economic viability of the European insurance industry [Moore, 2025], but also to the social planner agents who based on the intervention culture of Europe would direct large amounts of their government budgets as a coverage of last resort, disturbing their balance of payments. [Afonso et al., 2024] notes that although fiscal decentralization in terms of redistributing financial responsibilities and decision-making powers from central to local authorities and let alone the privet

sector typically improves public sector efficiency, its benefits diminish during severe natural disasters, leading to increased inefficiencies. This underscores that climate risk management is not only a private sector issue; rather, it represents a broader socio-economic challenge that requires collaborative efforts between the insurance industry and public policymakers to ensure sustainable solutions and economic stability for affected communities.

In summary, this chapter underscores the significance of temperature anomalies in understanding the risks posed by climate change, particularly regarding their potential to trigger natural disasters that directly impact the insurance industry. The analysis reveals a clear correlation between rising temperatures and the increased frequency of climate-related disasters in both Europe and North America. Moreover, these findings illustrate the pressing need for adaptive management strategies within the insurance sector to address the expected increase in financial liabilities. The complexities surrounding fiscal decentralization further complicate the issue, emphasizing that climate risk management is not solely a private sector concern but a broader socio-economic challenge. This necessitates collaborative efforts between insurers and policymakers to ensure sustainable solutions and economic stability for affected communities.

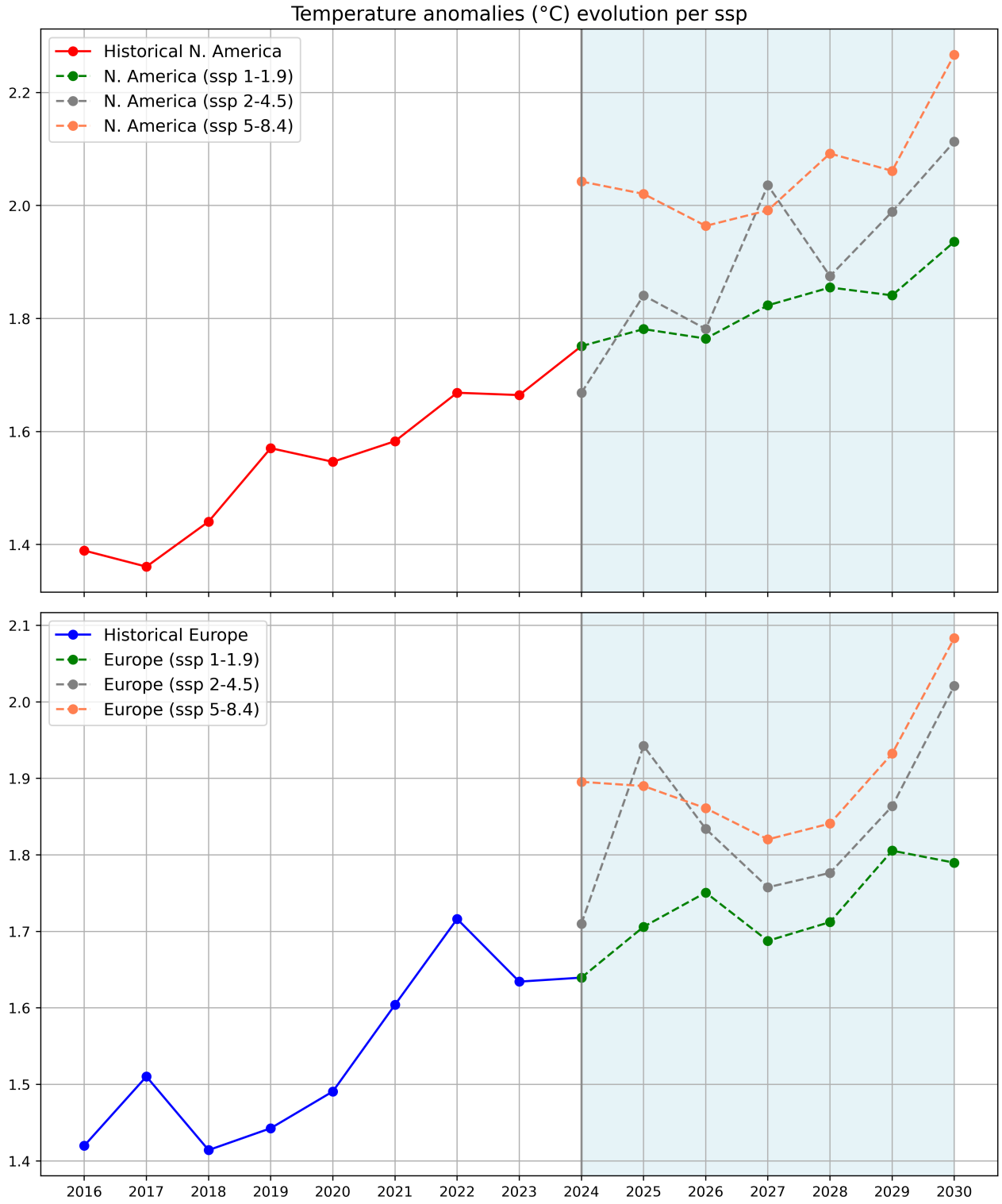


Figure 11: Temperature anomalies evolution and projections per ssp. Data source:Temperature historical and projection data from World Bank.

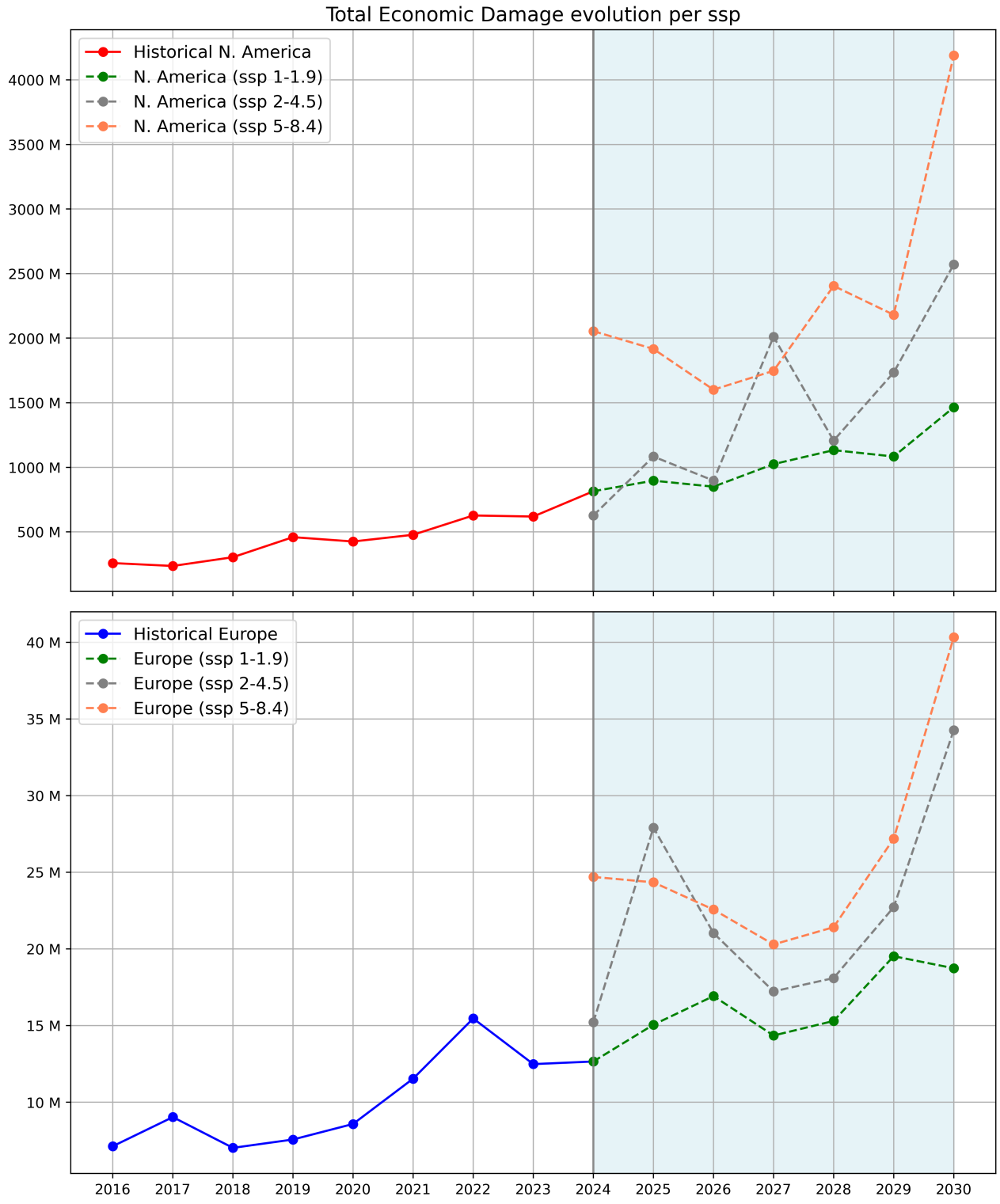


Figure 12: Total economic damage ($) evolution per ssp caused by climate-related incidents. Data source: Historical total economic damage data from EM-DAT. The projections after 2024 are derived from developed log-linear regression model.

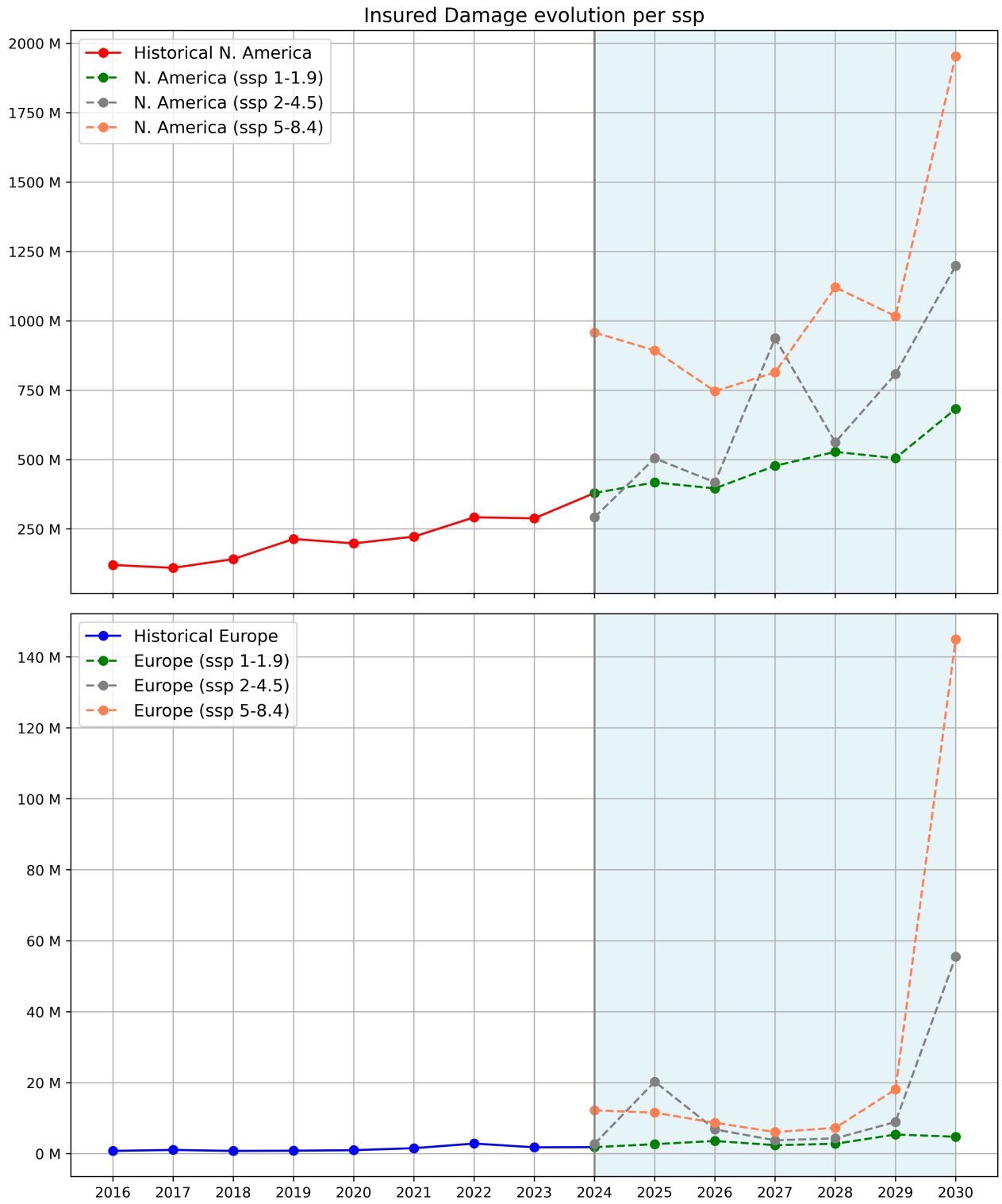


Figure 13: Insured damage ($) out of the total economic damage caused by climate-related incidents per SSP. Data source: Historical insured economic damage data from EM-DAT. The projections after 2024 are derived from developed log-linear regression model for Europe and developed linear model for North America.

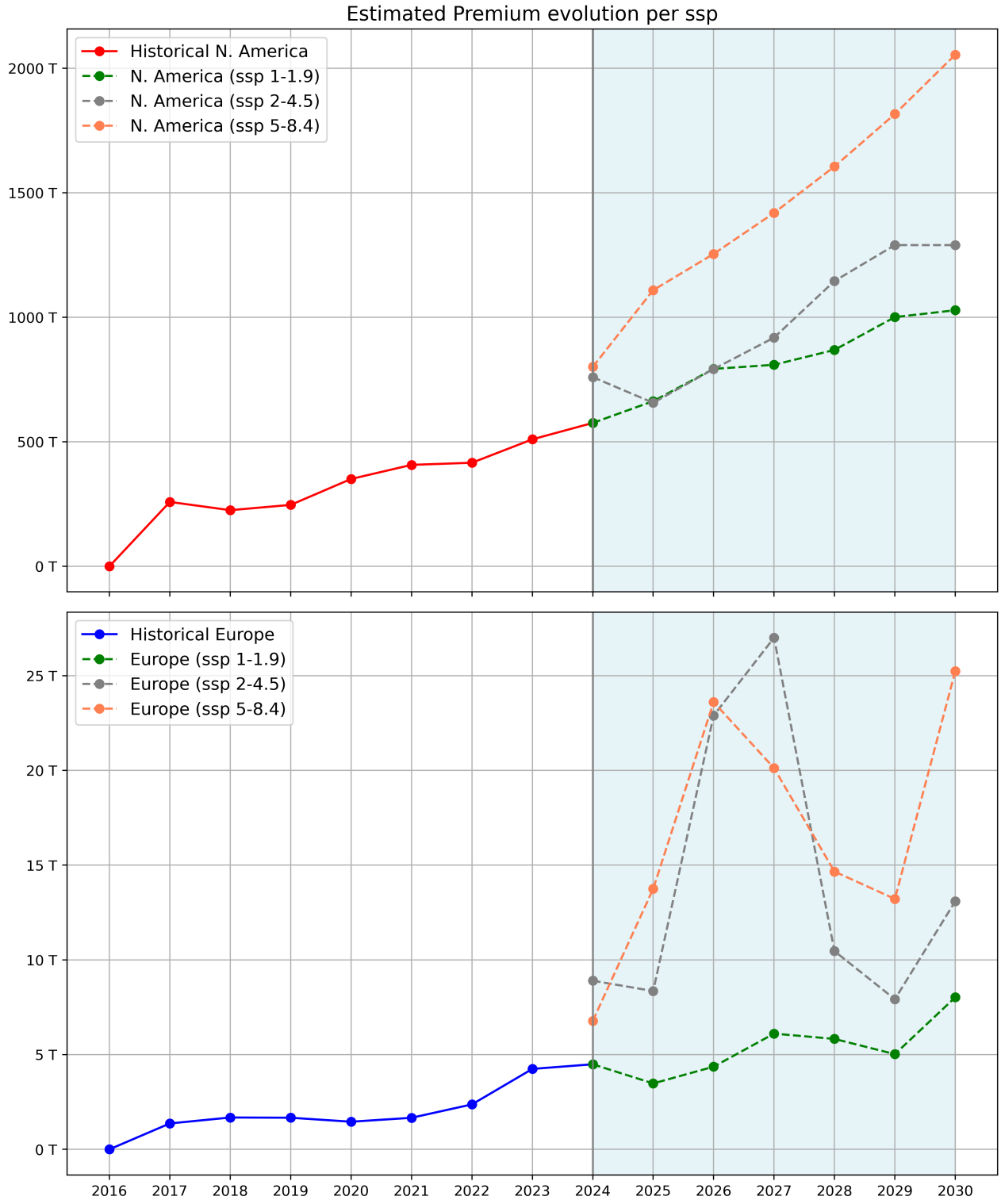


Figure 14: Estimated Premium ($) evolution per ssp adequate to cover the anticipated risk of future climate-related incidents. Data source: Results of model estimation.

6 Conclusion

Insurance plays a crucial role in managing risk and protecting against potential losses related to climate change. By pooling the risks of policyholders, insurance enhances the resilience of businesses, households, and financial institutions against unforeseen events. To further stabilize the industry, mechanisms such as Special Purpose Vehicles (SPVs) are employed to isolate risks, while Catastrophe bonds (CAT bonds) are utilized to mitigate financial exposure to catastrophic events. Central to this process are the concepts of expected loss rate (EL) and expected excess return (EER), which serve as key components in determining the appropriate insurance premiums. However, the landscape is shifting as climate change intensifies the frequency and severity of catastrophic events, creating unprecedented economic challenges for insurers. In response to this evolving risk environment, insurers are required to revise their risk models and adopt proactive measures to manage the financial impacts of climate change effectively. Historical data indicate a troubling trend: climate-related disasters are becoming more severe, which necessitates significant changes in traditional risk assessment and pricing practices. This increasing likelihood of disastrous events underscores the urgent need for innovative insurance models that can adapt to the complexities of evolving climate risks. There is a compelling relationship between natural catastrophes and climate change that necessitates urgent understanding. Recent extreme weather events have raised awareness on the impact of climate change on the frequency and intensity of natural disasters. Both greenhouse gas emissions and natural climate cycles significantly exacerbate such catastrophes. While climate change can lead to adverse outcomes, it can also produce positive effects, such as improved agricultural yields in certain regions. To navigate this complex landscape, extreme weather events can be categorized according to temperature, precipitation, and their economic impacts. Distinguishing between short-term extreme weather incidents and longer-term climate impacts is crucial for accurate risk assessment. This interplay between natural cycles and climate change emphasizes the necessity for adaptive strategies to manage the growing uncertainty surrounding future climate impacts.

The link between global warming and natural catastrophes is becoming increasingly evident as temperatures continue to rise. Higher average temperatures are associated with an elevated frequency of extreme weather events, such as floods, droughts, and wildfires. Regional variations in temperature shifts reveal significant disparities that affect the likelihood of natural disasters. Over the past two millennia, the average global temperature has increased by approximately 0.7°C, with Europe experiencing a more rapid rate of temperature increase compared to the global average. Such changes influence the frequency and intensity of extreme precipitation events or droughts, thereby affecting flood and fire risks and other climate-related natural disasters. Human activities, particularly greenhouse gas emissions, are identified as the primary drivers of climate change, while natural climate cycles, although influential, play a comparatively lesser role in driving temperature changes. As climate change continues to unfold, it significantly alters risk assessment and management practices within the insurance industry. Physical risks associated with climate change include the increased severity and frequency of natural disasters. Therefore, insurers must adapt to evolving risks that directly impact their insurance portfolios and premium structures. Increasing liability risks also emerge as policyholders hold insurers accountable for climate-related losses. To meet these challenges, the insurance sector is actively conducting research to enhance understanding of extreme weather events and the associated economic losses that may arise. Regulatory pressures further compel insurers to redefine their risk pricing methods and adapt their strategies to effectively account for climate impacts.

Establishing coherent risk measures is essential for rational decision-making in insurance premium calculations. The four axioms of risk coherence, transition invariance, subadditivity, and positive homogeneity serve as guiding principles in the development of insurance premiums. These principles ensure that premiums reflect inherent risk levels with fairness and predictability. Various models have been developed to determine insurance premiums, incorporating the complexities associated with evolving risks. Here, estimation of factors such as the expected loss (EL) and other loading factors are critical in formulating premium calculation models. Furthermore, when climate-related events are interconnected, they create compound events that are often difficult to estimate in terms of their occurrence and the resulting economic damage. To support our analysis, we introduce a conceptual framework that defines risk as a non-negative random variable, which is crucial for understanding insurance coverage and expected losses. Insurance coverage is defined across two layers: the attachment point and the exhaustion point, which outline the insurer's coverage limits. Catastrophe insurance applies only when losses exceed the attachment point, while losses below this threshold are covered by the policyholder. The expected loss is calculated based on the probability of financial loss, thereby highlighting the relationship between risk levels and their impact. Additionally, the survival function indicates the probability that losses will exceed a certain threshold, emphasizing the importance of accurate risk assessment. Our analysis reveals that higher risks lead to higher expected losses. In this context, we calculate an expected loss that incorporates various temperature scenarios, influencing how risks are evaluated concerning climate change. This supports the argument that environmental factors, such as rising temperatures, correlate with the likelihood of significant economic losses. Notably, as temperatures rise, expected economic losses are also projected to increase, underscoring the critical connection between climate change and insurance risk.

Furthermore, we establish a comprehensive framework for effective insurance premium modeling in response to climate-related risks, focusing on the variability of economic losses under different temperature scenarios in Europe and North America. The rationale for comparing North America and Europe lies in their distinct climatic challenges and varied insurance market structures. Each region's regulatory framework significantly influences how climate risks are managed and how economic vulnerabilities related to natural disasters are addressed. Moreover, the availability of extensive historical data facilitates a robust analysis of the evolution of insurance premiums in response to temperature anomalies and disaster frequency. Through this comparative study, we gain valuable insights into effective adaptation strategies and best practices for the global insurance industry. Our model integrates key components such as expected absolute loss (EAL), expected excess return (EER), and total expected layer loss (TEL) to efficiently manage and predict financial impacts. In our framework, the expected loss for specific layers of risk is formulated based on the survival function, which captures the likelihood of claims within defined limits. The relationship between EAL and EER is particularly crucial; EAL serves as a baseline for potential losses, whereas EER adjusts the insurer's expected returns based on the associated risks. Conditional expectations are calculated to ascertain potential economic losses when a particular risk threshold has been exceeded. The total expected loss (TEL) merges EAL and EER, thus provides a holistic view of the insurer's risk exposure over a specified period. Furthermore, the insurance premium pricing model is informed by TEL, reflecting not only expected losses but also necessary adjustments for fluctuating market conditions.

Finally, through an examination of historical data, we discern the evolution of temperature anomalies and their interplay with natural catastrophes and insurance premiums, underscoring their significance in climate change models. Temperature anomalies, defined as deviations from baseline temperatures, significantly influence the frequency and severity of natural disasters.

Historical data reveals that air-surface temperature anomalies in Europe have consistently increased, reaching approximately 1.7°C by 2024, signaling a notable rise in climate-related events. In contrast, North America has experienced a similar upward temperature trend, though with less pronounced fluctuations compared to Europe. Specifically, regression analysis indicates that in Europe, a one-degree Celsius increase is correlated with an estimated four-fold increase in the number of climate-related disasters, while the same temperature increase in North America is expected to trigger nearly 50% of the registered climate-related disasters. Interestingly, this pattern reverses when evaluating economic damages. Comparative figures demonstrate that while Europe experiences a higher frequency of disasters, it incurs comparatively lower total damages given it's physical exposure, reflecting different vulnerabilities and socio-economic responses in the two regions under study. In our examination of the insurance market structure, we observe that the insurance gap between North America and Europe has fluctuated over the years, with Europe consistently presenting a smaller insurance gap than North America. Regarding extreme insured damages, the analysis indicates that during the decade from 2020 to 2030, Europe has a 40% probability of experiencing insured damages (claims) that exceed the decade's average, maintaining the same risk level as seen in the previous two decades. In contrast, North America presented a 30% probability of extreme insured damages in the 2000s, increasing to a 40% probability in the 2010s, and an estimated as high as 60% probability for the period from 2020 to 2030, necessitating an urgent re-evaluation of traditional climate risk models. Simulations of the future evolution of insurance premiums under various socioeconomic pathways reveal an increasing trend in both regions, with Europe exhibiting considerable volatility, particularly in the mid-term period from 2026 to 2028. Additionally, SSP 2-4.5, regarded as the most probable scenario for temperature anomalies, is characterized by the highest variability across all examined variables (air temperature anomalies, total economic damages, insured damages, and estimated insurance premiums). This underscores the complexity and the urgent need for informed climate risk models to be applied within the insurance industry. As anticipated, insurance premiums that incorporate climate factors in Europe are projected to experience a steeper increase compared to North America, resulting from a number of factors. These include a comparatively less expanded insurance scheme, which reduces competition and increases dependency on private insurers. Stricter regulatory environments necessitate higher reserves, influencing premium costs. Additionally, Europe's heightened vulnerability to severe climate events and rising reinsurance costs further contribute to the upward pressure on premiums. This observation underscores that climate risk management is not solely a private sector issue; rather, it represents a broader socio-economic challenge requiring collaborative efforts between the insurance industry and public policymakers to ensure sustainable solutions and economic stability for affected communities. The regional differences in risk perception and policy responses indicate that insurers and policymakers must work together to enhance resilience against climate impacts. Ultimately, this research highlights the critical differences in insurance premiums between North America and Europe, addressing the paper's primary objective of analyzing the underlying factors influencing these disparities. Geographically, while North America presents higher potential losses this doesn't mean that Europe faces lower climate-related risks, rather Europe seems more unprepared for the unanticipated high risks that are estimated to arise earlier than North America. The findings reveal that while both regions grapple with rising climate risks, their distinct approaches to risk assessment and premium pricing significantly shape their insurance landscapes. Furthermore, this comparative analysis contributes to the body of knowledge by shedding light on how regional nuances affect insurance market dynamics, ultimately offering valuable insights for insurers and policymakers. By focusing on these regional differences, we underscore the necessity for collaborative efforts in extending the existing insurance premium methodology into an adaptive and sustainable insurance modeling orientation capable of effectively addressing the compounded risks posed by

climate change.

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