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Unraveling the Enigma of Black Swan Events: A Multidisciplinary Examination of Financial and Climatic Extremes

The factors contributing to Black Swan Events and their varying effects

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Preface

This thesis, comprising 30 ECTS, has been a delightful and educational experience for us. It has allowed us to delve into a new and relevant topic, providing us with insights and knowledge that we are confident benefit both practitioners and academics in the field.

We would like to express our heartfelt gratitude to Associate Professor Håkon Otneim for his invaluable guidance and unwavering support throughout the development of our Master of Science in Economics and Business Administration thesis at the Norwegian School of Economics, majoring in Business Analytics.

His excellent mentorship and expertise have been instrumental in shaping the quality of our thesis. When faced with challenging topics and obstacles, he consistently provided encouragement and direction, enabling us to forge ahead with confidence. His valuable feedback has been crucial in refining the content and structure of our paper, elevating its overall quality.

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Abstract

Black Swan events (BSE) are events that are highly improbable, unforeseen, and, many times, completely unpredictable and unknowable. The term itself was popularized by Nassim Taleb in his book, *The Black Swan: The Impact of the Highly Improbable* (2010). The study of extreme events is something that has gained popularity recently, and we aim to add to the growing literature by examining cases of extreme financial events and extreme weather events. We use a Monte Carlo simulation to look at potential extreme weather events in Sindh, Pakistan, to see if there are any changes in the frequency and severity of certain variables given small changes in variable means. With a qualitative and quantitative look at Black Swan events, we find there are some similarities between different systems that can be helpful for preparation and future study of extreme events.

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1. Introduction

1.1 Background

Black Swan events (BSE) are events that are highly improbable, unforeseen, and, many times, completely unpredictable and unknowable. The term itself was popularized by Nassim Taleb in his book, *The Black Swan: The Impact of the Highly Improbable* (2010). These events are the outliers, the tip of the tails within a distribution, and the extreme values. Examples are the invention of the computer, the laser, terrorist attacks, extreme weather events, and even the existence of humans. One example Taleb (2010) uses to explain BSE: imagine a chicken's point of view who is raised by a farmer. After being sheltered and fed for its entire life, a chicken would have no reason to believe that the farmer would have any harmful intent towards the chicken. The previous data on the intent of the farmer is refuted the day the farmer wants to cook a chicken dish. One of the most critical components of BSE is that while these events are exceedingly rare, their impact on society can be monumental. Another part of what categorizes BSE is the hindsight that the event was more predictable than previously thought. There are many different types of BSE, but what we focus on are knowable but highly improbable events. The weather and financial systems are extraordinarily complex, and humans trying to predict events within these systems accurately is still quite a challenge. Many experts in their field, especially in finance, make long-term forecasts that are reliably incorrect (Tetlock, 2009; Zhang et al., 2019). Weather forecast accuracy varies, as we see in our discussion later. We focus on past BSE that have taken place in finance and weather to draw any similarities and/or connections between the two systems.

Many models that experts build to predict financial, or weather (and many other complicated systems) forecasts rely on past data. With a constantly changing environment, past data limits the accuracy of predictions, and when these BSE occur, it is outside the confidence of these predictions. Many of the experts use classical statistics in their forecasts, and the assumptions within these models may be incorrect. For example, the broadly popular Gini Index, a measure of statistical dispersion intended to represent income inequality or wealth distribution, is usually calculated under the assumption that the input variables are normally distributed. Nevertheless, the normality is broken under infinite variance data (Fontanari, Taleb, Cirillo, 2017). This means the incorrect assumptions of the measure lead to inaccurate conclusions.

What we believe to be a frequent mistake in forecasting models is the assumption of Gaussian distribution(s) within the data.

Another potential failure is measurement errors in extreme values. Suppose we have a dataset of historical temperatures in a particular region, and we are interested in estimating the probability of an extremely hot day (e.g., a temperature exceeding a certain threshold, such as 40 degrees Celsius). In this example, we will assume that the temperature follows a Gaussian distribution. Now, let's say there is a small measurement error in the recorded temperatures. Due to this error, some of the measured temperatures might be slightly higher or lower than the valid values. This error can introduce noise into the dataset, affecting the estimation of the underlying distribution. As a result, the mean and standard deviation of the Gaussian distribution used to model the temperatures might be slightly biased. This slight bias can have a significant impact on the tail probabilities. For example, if the mean is overestimated and the standard deviation is underestimated, it would shift the entire distribution towards higher temperatures. Consequently, the estimated probability of exceeding the threshold for an extremely hot day would increase. Thus, even a small measurement error can have a substantial effect on the odds associated with extreme events in the tail of a Gaussian distribution, highlighting the sensitivity of such estimates to data quality and measurement precision.

Distributions have an instrumental role in statistical inference. For example, if you randomly select two people in a population where the mean height is 4 feet tall, and the combined height of the two selected people is 8 feet, it is likely that the two people are both 4 feet tall. In contrast, if you randomly select two people from the same population where the mean net worth is $70,000, and the combined net worth of the two people is $20,000,000, would you expect the net worth of each person to be $10,000,000? It is more likely that one person has $19,940,000 and the other has $60,000 (Taleb, 2010). Wealth follows the power law distribution, also known as the Pareto distribution, and height follows a Gaussian distribution. To outline the vast changes in probability within the Gaussian distribution, the probability of exceeding three standard deviations is 0.00135, and the probability of exceeding six standard deviations, twice as much, is 9.86×10^{-10}. The probability of two 3-standard deviation events occurring is 1.8×10^{-6}. Therefore, the probability of two 3-standard deviation events occurring is considerably higher than the probability of one single 6-standard deviation event. If someone says an event is a 10-standard deviation event, it is more likely that the distribution of the data is not Gaussian (Taleb, 2020). Because the convergence of the mean in a data set is often not enough to hold the law of large numbers, the distribution properties cannot be assumed (which is often the case) (Taleb, 2020). Many of the distributions should have been what are called "fat-tails". These fat-tails look like a flatter version of the Gaussian. These fatter tails do not mean that the black swans are more likely to occur, but the consequences of the improbable events change the properties of the distribution. To further describe what fat-tails are, fat-tails do not mean that there is a higher chance of a higher/lower observation, but it means that the very few large or low observations change the properties of the distribution (Taleb, 2010). The consequences of the very large or very low observations impact the distribution and statistical properties of the data set.

Another body of related research, which BSE may have stemmed from, is extreme value theory (EVT). This area has become a relevant branch of probability theory and is a tool for considering probabilities associated with extreme and rare events. The application of the theory is appropriate to many areas, especially the ones studied in this paper. EVT invariably deals with random variables and their extremes within a series, and this theory has been applied in fields such as insurance (Bensalah, 2020) and weather (Reis, 2022). Within finance, in contrast to value-at-risk approaches, EVT is used to model the behavior of maxima or minima in a series and to model the tail of the distribution (Bensalah, 2020). The implementation of this theory can be challenging given issues such as the scarcity of extreme data, determining whether the series is "fat-tailed", choosing the threshold of the tail (where the extreme value distribution is used), and choosing the methods of estimating the parameters (Bensalah, 2020). We address these issues with parameters set by published papers and international organizations.

1.2 Purpose

Taleb (2010) discusses in his book about, what he calls, “mediocristan” and “extremistan” mathematical views on the world. The first view, “mediocristan”, is where Gaussian statistics are almost perfect, and the average will describe the world around us without much surprise. But “extremistan” is, Taleb claims, where the world really exists. This view is where extreme events shape our world. The most significant events in our world are BSE and are often unforeseen events. The good and the bad, the inventions, discoveries, ideas, plagues, wars, and market crashes that shape our lives. Since these events are rare and their consequences are enormous, we will attempt to have a better understanding of the anatomy of these events. The causes and effects of these events may help us better mitigate the negative consequences in the future and potentially maximize the benefits of the positive. If we can influence the frequency and severity of these events, then we could create a more stable future.

Research questions:

What factors contribute to the severe consequences of BSE on society? How do variations in probability distributions affect the occurrence and severity of extreme events?

1.3 Motivation

We will utilize hindsight bias to uncover any similarities among these events, even when taking part in different systems. Our goal is not to precisely predict events but to gain practical insights from prior extreme events to explore what factors lead to such an impact and better understand their occurrence.

In this paper we explain specific black swan events and what factors go into making them so severe. The case studies would aim to identify similarities across events in diverse systems as well as factors that made impacts especially severe. In addition, we use a Monte Carlo simulation of a weather system to see the change in potential extreme events from a change in location of standard variables' probability distributions. Through case studies and simulation, we could highlight important factors that current statistics cannot capture. The findings could then highlight ways to better analyze complex systems and prepare for potential black swans in the future.

1.4 Structure

The thesis consists of several chapters, all of which contribute to the paper's overarching goal. The first chapter presents the concept of Black Swan events, discusses their significance, introduces the research question, outlines goals, and provides a brief overview of the rest of the thesis. Chapter two details the methodology for gathering data, selecting cases, and conducting analyses. Chapters three and four analyze BSE and CWE, their causes and consequences. Chapter five presents a simulated weather scenario in Pakistan, investigating potential changes in extreme event occurrence in the future, given a small change in probability distribution. Chapter six discusses case study findings and integrates insights with existing theories to understand complex systems under extreme conditions. The study's limitations are discussed, and suggestions for future research are provided in the final chapter, which also provides a summary of the study's findings.

2. Methodology

The thesis methodology is divided into Thesis Philosophy, Approach, Choices, Data Collection Techniques, Strategy for Research, Time Horizon, and Methodologies and Procedures for Research. The limitations and conclusions are further discussed in the following chapters.

2.1 Thesis Philosophy

To answer the research questions and provide future-relevant insights, qualitative and quantitative methods are employed in this thesis, utilizing a pragmatic approach applicable to research problems, as Saunders et al. (2016) suggested.

2.2 Thesis Approach

Compound weather events (CWE) are characterized by the interconnected occurrences of multiple meteorological factors and/or hazards, resulting in elevated risks for human societies and ecosystems (Bevacqua et al., 2021), which are usually Black Swan Events themselves. We deduced the following hypotheses:

There are two or more factors that contribute to the occurrence of a BSE; and due to a combination of climatic, environmental, and human factors, the frequency and severity of extreme weather events in Sindh, Pakistan, are changing over time.

2.3 Thesis Method

Qualitative case studies and quantitative simulation are utilized to achieve the research objective of this paper, indicating an exploratory and explanatory approach. The case studies generate insights, while the simulation explains changes in probability distributions.

2.4 Data Collection Techniques

Secondary data is used for the case studies. NASA meteorological data and CEMS LENS projections data are used for the simulations.

2.5 Thesis Strategy

A selection criterion is defined for the case studies, and six instances of black swan events are chosen to achieve data saturation. Published research, government reports, media sources, and other secondary sources of information are utilized. For the simulation, probability distributions are estimated using NASA's historical weather information, and thresholds for extreme events are defined using quantiles of historical data and general definitions of negative weather events.

2.6 Thesis Time Horizon

We adopt a cross-sectional approach in our case study research that analyzes the cases at a specific time. The simulation employs longitudinal data, collecting simulated data over a period.

2.7 Thesis Procedures

For both case studies and data simulation, the thesis follows the steps to analyze data and conduct the conclusion. The case studies thematically analyze data to identify common factors, while the simulation estimates probability distributions, modifies distributions using projected future means, generates random numbers based on specified criteria, and measures the frequency and severity of extremes.

2.8 Thesis Findings, Discussions and Limitations

The results of the case studies and simulations are compared to reach broader conclusions. In addition, data, bias, and generalizability limitations are discussed to provide a comprehensive understanding of the research.

3. Black Swan Case Studies

3.1 Background

There is evidence in the literature that the main cause of financial crises is excessive credit growth and a subsequent downfall from defaults (Engle, Ruan, 2019). We present some of the past BSE in the financial markets, described as an unforeseen recession or financial collapse. Excessive credit growth may be a large player, but we explore what other factors may have played a role in the severity of loss during these events.

Many large financial institutions rely on large quantitative modeling to set policies and investment strategies (Murphy, 2008). These models rely on statistics that are subject to relationships between variables, increasing modeling error, and heavy assumptions. (Murphy, 2008). Many of the measures still used in financial institutions are criticized by the literature and are shown to be less accurate than other measures (Kourouma, Dupré, Sanfilippo, Taramasco, 2010). Not only are the predictions less accurate than expected, but the timing of their predictions is not strong either, as there is no strong evidence of market return timing or volatility timing of fund managers (Alam & Ansari, 2020).

A large portion of financial theory, including portfolio theory, assumes that multivariate probability distribution of asset returns is, explicitly or implicitly, normal (Adcock at el., 2015; Kourouma, Dupré, Sanfilippo, Taramasco, 2010). The Value at Risk (VaR) approach has become the gold standard for determining market risk for many financial institutions and the issue with this is, typically, the assumption of normally distributed variables (Bensalah, 2020). Although, VaR is empirically justified while the market is under normal conditions (Danielsson, Jorgensen, Samorodnitsky, Sarma, 2013), the VaR measure significantly underestimates losses in non-normal conditions when normality is assumed on underlying variables, such as the 2008 financial crisis (Hendricks, 1996). Additionally, empirical evidence suggests that macroeconomic variables are seldom normally distributed (Ascari, Fagiolo, & Roventini, 2015). Taleb (2020) states that practically every single economic variable and financial security is thick tailed. While some of the finance and scholar community understand that financial securities are fat-tailed (Haas & Pigorsch, 2010), Taleb's main point is that understanding past risk is no guarantee of future risk assessments.

The “experts” in finance still have trouble predicting what will happen in the financial future (Heilemann & Stekler, 2003). As far as predicting and forecasting financial markets, the research shows that the experts are not the best at forecasting accurately, especially extreme events (Heilemann & Stekler, 2003). Financial experts have trouble predicting the future course of the market itself and fund managers have a hard time persistently attaining returns that outperform the appropriate benchmarks (Andersson, 2004).

Financial BSEs have not only a huge impact on the wealth of humans, but also have a relationship with the health of humans. A study by Doer and Hoffman (2020) showed that there is a proportional decrease in mortality compared to the severity of a recession. This study showed an effect that recessions lead to a significantly higher death rate, up to 10 years, and a higher child mortality rate for up to 12 years. Unfortunately, times of growth do not lead to a decline in mortality rates. This study highlights the importance of studying extreme events in finance.

A common problem seen in economics and financial forecasting is the lack of variables that are not quantitative. One study showed that the predictive models used by regulators forecasting default rates on loans fail to account for a change in the relationship between observable characteristics of a good and its long-term quality that is caused by a fundamental change in the behavior of economic agents that produce the good (Rajan, Seru, Vig, 2010). The same predictive models suffer from simplification and fail to consider inter-related systemic risks (Murphy, 2008). Historically, the use of qualitative variables in finance is seen as unreliable and subjective, but nevertheless, they are important for measuring certain risks within business and economics as we will see in financial case studies. These additional variables are part of the issue in underestimating the joint probabilities of negative effects within finance. What we expect to explore in these case studies, and what Taleb discusses, is that the severity of BSE is influenced by the many joint events that exacerbate the negative effects of the main event.

Although the three cases chosen have been focused on the USA stock market and economy, these cases were chosen because they are well documented and studied within the literature. Also, with the globalization of the world's financial markets and the current macroeconomic influence of the American economy, it is important to every other financial system to study American economic BSE (Engle, Ruan, 2019).

3.2 2008 Financial Collapse

The 2008 financial collapse has been the largest US market downturn of the 21st century so far. The crash caused the bank, Lehman Brothers to file for bankruptcy, which was the largest in US history. Investment bank, Bear Stearns and insurance company, AIG, had to be given funds from the government to avoid bankruptcy, as the failure of these organizations "would worsen the crisis" (Bordo, 2008). At the lowest point, $10 trillion was wiped out of global equity markets (Murphy, 2008). Because the financial system is so complex, we assume this BSE had many factors, as many BSE do.

As the US economy had been shaken by the dot-com bubble, September 11th terrorist attacks, and corporate scandals, the US Federal Reserve dropped interest rates from 6.5% in May 2000 to 1% in June 2003 (Bernanke, 2007). The result was a huge increase in borrowing for home-buying, including sub-prime mortgage loans (Federal Reserve Bank of St. Louis, 2010). With so many new mortgages, the banks created new mortgage-backed securities called Collateralized Debt Obligation (CDO) and Credit Default Swaps (CDS). The sale of these investment vehicles created a large market for sub-prime mortgage loans (Baily, Litan, Johnson, 2010). The housing market peaked in 2004 when ownership saturated and interest rates began to rise again (Federal Reserve Bank of St. Louis, 2010). As home prices began to fall, many American families suffered because their homes were worth less than what they paid for them. Many adjustable-rate mortgages began to increase the interest rates on the mortgage loans thus, increasing the cost of the homes while the market decreased the value (*US Housing Market Condition,* 2007). This decline in the housing market was occurring while the banks continued to create and sell CDOs and CDSs.

With relaxed monetary policy and poor regulatory oversight financial institutions had overleveraged themselves by borrowing to purchase these mortgage-backed securities (Baily, Litan, Johnson, 2010). Many wanted these securities so much that they created off-balance sheet affiliated entities to purchase more mortgage-backed securities that were not subject to regulation (Baily, Litan, Johnson, 2010). When these masses of subprime loans began to default, the CDOs and CDSs also began to default. Starting in 2007 many of the sub-prime loan lenders began to file for bankruptcy after making loans to people who couldn't afford the mortgage payments in the first place (SEC report, 2008). To outline how aggressive this market swing was, the sub-prime mortgage company, New Century Financial, made $60 billion in loans in 2006, and filed for bankruptcy in 2007 (Stempel, 2007). During February and March 2007, more than 25 sub-prime lenders went bankrupt (SEC report, 2008). This was becoming a problem internationally as the interbank market froze due to collapse fears. The Swiss bank, UBS, posted a $3.4 billion loss in October 2007 due to the sub-prime loan market (Singh, 2023). While these events were occurring, the stock market started to decline towards the end of 2007. The following year would be a severe BSE.

The economic outlook in the months before the crash was promising according to the models used. Published April 11th, 2007, the International Monetary Fund predicted 2008 global markets outlook saying global growth is projected at a solid 4.75 percent, supported by generally sound fundamentals and strong momentum in emerging market economies. They hinted at potential risks in inflation, oil, and foreign exchange inflows while urging policymakers to push the market to more normal conditions (*World Economic Outlook*, 2007). Even though this analysis was in a global context, their models predicted growth throughout 2008. From the peak in October 2008 to the trough in March 2009 stock prices fell roughly 50% in the NYSE and the 2008 return was –22.6% for the S&P 500 (Federal Reserve Bank of Atlanta, 2010). As mentioned before, because many investors and financial institutions use the Gaussian distribution to make predictions, the frequency of returns on the markets on the Gaussian distribution that year means that the –22.6% return would not happen for several billion lifetimes (Taleb, 2020). There were several factors that went into the financial crisis, and the ones described in this paper were shown to contribute to this Black Swan event. While it is not possible to describe a –22.6% using joint Gaussian variables, the idea that this decline would not happen for several billion lifetimes and the many non-Gaussian factors, may suggest that joint probabilities are more appropriate for security returns.

Now that we have described the crisis, we will explore the causes. Again, the main culprit for causing the crisis is pointed to Credit Default Swaps (CDS) and CDOs (Murphy, 2008). The securitization of loans was a key innovation that allowed so much risk to enter the market without people raising alarms (Baily, Litan, Johnson 2010). The two main government sponsored organizations, Fannie Mae and Freddie Mac, devoted to mortgage lending developed the securitized loans in the 1970s but these were only for "prime" loans and included dollar thresholds (Baily, Litan, Johnson 2010). It wasn't until the early 2000s that "sub-prime" loans made their way into securitization and were adopted by the industry. Ironically, on September 6th, 2008, Fannie Mae and Freddie Mac were placed into conservatorship by their Board of Directors because their financial condition had become so poor (Federal Housing Finance Agency, 2022). Credit Default Swaps had principal amounts around $55 trillion and were unregulated and contracted over the phone without documentation (Simon, 2008). The banks used these instruments to shift their default risk away from themselves and onto the consumer (Bordo, 2008). Because of the housing market's historical stability, many overlooked the risks involved. The rating agencies gave these securities high ratings, despite there being so many sub-prime loans backing them (Bordo, 2008). The idea was that with enough sub-prime loans bundled into a security, the risk was now considered diversified. In addition, if the banks didn’t get the ratings they wanted, they were able to go to another rating agency for a better rating (Rajan, Seru, Vig, 2010). While the investors had the characteristics of the loan's observable, as the quality of the loan pools worsened, the rational investors could anticipate the effects of the drop in quality (Rajan, Seru, Vig, 2010). Statistical models estimated on past data ignore the change in mapping between observable characteristics and likelihood of default (Rajan, Seru, Vig, 2010). A key dynamic of the crisis is information asymmetry, which shows the spread between risky and safe securities (Bernanke, Mishkin, 1997). The institutions monitoring securities like CDS have made the mistake of equating free markets and unregulated markets, which can lead to bigger issues for the end consumer when being acted for by the institutions (Spence, Leipziger, 2010).

The severity of the crisis shows how much our financial system is connected. While people were not paying their mortgages, the banks continued to issue sub-prime mortgages and use them in these CDS (Bordo, 2008). This spread to investment banks and commercial banks because many banks were using these CDS as investment vehicles and borrowing from each other to invest (Bordo, 2008). By increasing the distance between a homeowner and the ultimate investor, securitization changes the incentives of lenders. The contract between investors of securitized loans is based on only a set of observable characteristics of the loans. Some information that is verifiable is excluded from the contract and is not reported to the investors (Bordo, 2008). This creates a moral hazard as the lender originates loans that rate high based on the characteristics that affect its compensation, if the reported information implies a lower quality (Bordo, 2008). Because these CDS were rated high by the rating agencies, this led to a higher price. The institutions providing CDSs were using theoretical modeling based on unrealistic assumptions (Murphy, 2008). Given the eventual addition of sub-prime loans into securities and the unregulated nature of this market, the unquestioned stability of these securities was a time-bomb for the market that blew up in 2008 leaving many with a large portion of their wealth gone. The lack of predictability involved with this event, the severity of the consequences involved, and the clear hindsight bias that comes with the study of this event make the 2008 recession relevant in the Black Swan theory.

3.3 Financial Crisis of 1987

In October 1987, the market had its largest single day fall in US history. On October 19th, known as “Black Monday”, the S&P 500 saw a 20.47% drop (McKeon, Netter, 2009). To make things worse, the market dropped 10.12% in the three days prior, which was the largest in more than 40 years (McKeon, Netter, 2009). The crash of the markets in 1987 is not are not just a significant event because of the swiftness and severity of the market decline, but it highlights the potential weakness of the trading system and the strain caused in extreme conditions. The reasons for the severity of the decline are many different influences. A one-day drop of 20.47% on the Gaussian distribution is another event that should not have happened for billions of lifetimes.

There are several factors that contributed to the severity of the market drop but the largest factors that are often pointed out are illiquidity and market news. Program trading, a form of high-volume trading done by computers when certain conditions are met, played a large role in the illiquidity within the market. Some argue that the declining prices led these computer systems to make large sales of stocks thus feeding the fire that was the price decline (Carlson 2007). As for the market news, there was news of a change in regulation by the US government, discussed below. In addition, the reporting of the crash itself is said to have prolonged the situation (Amihud, Mendelson, Wood 1990).

In the years before the crash, markets posted strong gains and some thought the market had become overvalued (Anders, Garcia, 1987). In the months before the crash, the macroeconomic outlook was becoming bleak as interest rates were rising globally, the growing US trade deficit, and decline in the value of the dollar were leading to concerns about inflation (Winkler, Herman 1987). While market sentiment was negative, no investor expected the unprecedented drop in market value.

On Wednesday, October 14, 1987, news agencies reported that the Ways and Means committee of the US House of Representatives had filed legislation that included the elimination of tax benefits associated with financing mergers (SEC Report 1988). This was not good news for the value of some stocks with the potential to become mergers. There is evidence that this news was the initial trigger for market decline and the eventual crash on the 19th (Mitchell, Netter 1989). Second, the Commerce Department publicized the trade deficit for August, being higher than expected (Wall Street Journal, 1987a). This led to interest rate increases and was more bad news for stock prices (Carlson, 2007). Thursday, the 15th, the market continued to decline. Investors began to move into less risky investments, such as bonds and heavy selling by portfolio investors increased anxiety among investors (Wall Street Journal, 1987b). As the market's decline continued into Friday the 16th, anxieties continued to increase. Because several kinds of stock index options expired on Friday, the large price changes eliminated at-the-money contracts for investors to use to hedge against dropping stock prices (Carlsen, 2007). Because of the increased selling of futures contracts, this created a price discrepancy between the futures contracts and the value of the stocks on the NYSE. To capitalize on this discrepancy, many index investors bought the futures and sold stocks, further exacerbating the downward pressure of the stock prices (Brady Report 1988, Study III).

By Monday, October 19th, the number of sell orders was so vast compared to the buy orders that it overloaded the system. To some extent the problem was technological because normally, when there are overwhelming sell orders in place, rational investors would buy some of them based on value (Amihud, Mendelson, Wood, 1990), but the technology of the market operation made that impossible (Amihud, Mendelson, Wood, 1990). In this situation many specialists didn’t open stocks for trading right away (NYSE allows the specialists to delay opening of the trading of stocks when there was an order imbalance priority above an orderly market) (Brady Report 1988, Study III). This delay confused investors and they didn’t know whether limit orders had been executed or new orders had to be set (Brady Report 1988, Study III). While this delay continued for stocks, and the prices for non-trading stocks stalled at their closing price from Friday, futures continued trading. Again, with futures still trading this was what created a discrepancy between the stock's values and futures values (Miller, Hawke, Malkiel, Scholes, 1987). After the delay, and stocks opening considerably lower than closing the Friday prior, the program trading continued to sell stocks (Carlson 2007). Around 1:00pm on the 19th, there were rumors of a complete halt of trading after the SEC chairman made a comment after a speech where he reportedly said “...there is some point, and I don’t know what that point is, that I would be interested in talking to the NYSE about a temporary, very temporary, halt in trading” (Carlson 2007). This further pushed prices down as there was even more incentive to sell, given that there was a potential halt in trading and locking in investors' positions (Carlson 2007).

Margin calls, program trading, and news are the main culprits that contributed to the severity of the crash (Carlson 2007). As Amihud, Mendelson and Wood (1990) argue that a main cause of the crash was a lack of liquidity, Carlson (2007) supports that margin calls were a factor in illiquidity. Only after receiving all margin calls in the day could clear houses credit the futures contracts margins, that went up in value during the day. Because of the sharp movements in price, the payments were about 10 times the normal amount (Carlson 2007). This limited the number of new positions an investor and/or institution could buy into because the cash on hand went towards the margin calls (Carlson 2007).

Program trading is another debated factor in the severity of the crash (Dolan, 2022; Carlson, 2007). By the 19th, the exchanges halted the use of program trading temporarily. The idea was still new to Wall Street, and it had never been tested before (Dolan, 2022). The large sales volumes produced by this algorithmic trading created a negative feedback loop that prompted more and more trading (Carlson, 2007). As most of these trading strategies are played in the futures market, this may have been the reason for the discount in the futures market relative to the cash market. The SEC itself reported on the negative ways the program trading could be disastrous for the market (SEC, 1988). It is debated that while program trading may have played a role in the crash, it is mentioned in the literature that it was more of the trade system mechanism that couldn't handle the trades rather than the program trading itself that was the issue (Miller, Hawke, Malkiel, Scholes, 1987; Amihud, Mendelson and Wood, 1990).

Fear, panic, and difficulty finding information all played a large role in the crash itself. Many knew of program trading and the continued selling drove many investors to sell as well (Miller, Hawke, Malkiel, Scholes, 1987). Price quotes for stocks and stock indexes weren't that reliable given that some of the stocks were temporarily stopped from trading (SEC, 1988). Rumors of the market closing also added to the confusion (Siconolfi, Kilman, 1987). A market survey done shortly after the crash showed that many investors were reacting to the market based on the price changes rather than any kind of news information, indicating herd behavior given the lack of information (Shiller 1989). While there are several factors that led to the crash, it is important to note the importance of the news in relation to market behavior, the technology that is new to a system and is untested, and the use of credit in finance/business, which lowers liquidity. The new technology involved, and the unprecedented loss highlights why this BSE is important to study.

3.4 The Great Depression

Beginning in September 1929 and continuing to July 1932, the stock market lost about 85% of its value and some 7,000 banks failed (Wheelock, 2013). This period is still the longest and most severe economic downturn in USA's modern history, marked by a nearly 50% drop in industrial production, a drop in aggregate consumer prices by approximately one-third, banking panics, and an increase in poverty (Cecchetti, 1992). For comparison, the 2008 crisis saw a decline in GDP of 4.3% and unemployment reached almost 10%, while the Great Depression saw a decline in GDP of 30% and unemployment reached a peak of 25% in 1933 (Duignan). The Great Depression also lasted substantially longer. Some note the end of the great depression in 1932 while the Dow Jones Industrial Average didn't reach the nominal levels of September 1929 until the mid-1950s (Cecchetti, 1992). The Great Depression was not just a stock market crash, but several events happened to further the severity and duration of the economic recession (Wheelock, 2013). This BSE was a devastating hit to the world economy and examining the factors at play is important to BSE study.

In the years before the crash, the economy had seen very healthy growth. The "roaring 20s" was a prosperous economic period where the stock market saw a boom, production was steadily increasing, and many investors from the middle-class were starting to invest using credit when investing was mostly an upper-class activity before (Cecchetti, 1992). Shown in Dominguez, K. M., Fair, R. C. and Shapiro, M. D., (1988), Harvard and Yale, the dominant forecasting services available to the public during the 1920s, both had economic forecasts that didn't predict the downturn and had optimistic messages shortly after the stock market crash. Also shown in the paper, the stock market crash itself was not likely forecastable using measures common in economic theory, even when forecasting the measurements used in different theories on what was the main cause of the crash (Dominguez, Fair, Shapiro, 1988). They go on to conclude that, "The leading explanations of the Depression are thus based on unforecastable policy and economic disturbances" (Dominguez, Fair, Shapiro, 1988). In early 1929, the announcements from these forecasting services suggested there was a soon a potential "recession from the current level of business" based on high interest rates, weak commodity prices, and money tension but, their overall tone was optimistic given that speculation and general business activity was increasing (Harvard Economic Service, 1929). The week prior to Black Friday, the assessment was that "If the recession should threaten serious consequences for business (as in not indicated at present) there is little doubt that the reserve system will take steps to ease the money market and so check the movement." (Harvard Economic Service, 1929). Ironic, as the U.S. Federal Reserve failed to provide the banking system with needed reserves and emergency liquidity, contributing to the banking panics (Friedman and Schwartz, 1963).

It is debated on what exactly caused the stock market crash. It is agreed that the economy began to decline in 1929, but the reasons the crash happened have several perspectives. Some say the prices were overvalued (Marks, 2021). But standard measurements of stock value, like price-dividend ratios and price-earnings, were shown that stock prices were not too high (Bierman, 1991). Economic fundamentals were also sound as mentioned in the previous paragraph, there were no obvious trends that indicated a drastic downturn (Dominguez, Fair, Shapiro, 1988). Supporting evidence shows that the Federal Reserve behavior, along with statements by government officials were a large contributor to the stock market crash (Hamilton, 1987; Friedman & Schwartz 1963). The Fed made an announcement on February 2, 1929, stating that it wanted banks to lower the amount of loans intended for stock investments as the Fed's president, Adolph Miller, and president, Herbert Hoover thought that stock prices were overvalued (Cecchetti, 1992). Shortly after the announcement interest rates on broker loans rose dramatically, almost producing a stock market crash on March 26th when call money rates opened at 12% and went up to 20% by noon (Cecchetti, 1992). Stock prices fell nearly 10% that day but recovered when the Fed provided liquidity in the form of broker loans. In addition, during August 1929, the Fed increased the interest rate from 5 to 6% (Duignan). According to his *Memoirs* book, President Hoover wrote that he asked many major newspapers and magazines to warn the public of speculation and the overvalued stock prices (Hoover, 1952). He also asked the Secretary of Treasury to make repeated statements supporting the public to convert their stocks into bonds (Hoover, 1952). But the stock market crash perhaps was not the main cause of Depression, but the contractionary monetary policy set (Hamilton 1992; Cecchetti 1992).

With the stock market losing its value in 1929, many people sold off their stocks and moved their cash into banks (Wheelock 2013). At the same time, because of the bank's loans to margin contracts, those loans defaulted, and many banks failed (Wheelock 2013). Now that banks were failing, in 1930, there was a banking panic where people were withdrawing all their money from the banks, dubbed the "Banking Panic of 1930" (Wheelock 2013). A combination of defaults and banking runs contributed to bank failures and without FDIC (insurance on deposited money at banks that was initiated after the depression), everyone with an account at those banks lost the entirety of their savings. There is debate that the banking panic of 1930 was a factor that led to the severity of the depression. Friedman and Schwartz (1963) provided evidence that the banking panic was a major deflationary shock to the economy while Temin (1976) contests the view. In the second and third years of the depression, drops in consumer prices were about twice as expected, discouraging new borrowing and investing, likely increasing the severity of the depression (Hamilton, 1992). In 1930, the Smoot-Hawley act was signed, enacting a tariff on imports. This led to a cascade of retaliatory tariffs by other countries, and thus decreasing globalization. World trade, valued at $3 billion in 1929, fell to less than $1 billion in 1933 (Wheelock, 2013). This was not good news for global financial markets and economic health. By 1932, 30 million people were unemployed globally. In 1931, German industrial production decreased more than 40 percent; 29 percent in France; and 14 percent in Britain from 1929 levels (Rothermund, 2002). Temin (1976) argues that the spread of the Depression to other countries is because of the structural flaws of the gold standard, as well as policy responses dictated by the gold standard's standard rules of operation, led to an inevitable international monetary contraction and deflation.

The reasons for the Great Depression severity are controversial. Cecchetti (1992) argues that the leading reason is debt-deflation hypothesis presented by Fisher in 1933 and supported by Bernanke and Gertler (1990). The hypothesis states that the approximately 30% deflation from 1930 to 1932 was the primary reason for the severity of the Great Depression. Because of the unanticipated deflation, it made it more likely that debtor's default on loans and led to bank failures. There is evidence that the deflation was more anticipated than what was argued in the previous papers (Hamilton 1992), meaning that theories that rely on high real interest rates and the resulting collapse of consumption and investment, are more appropriate (Cecchetti, 1992; Wheelock, 2013).

The theory on the length of the depression is less debated. Bernanke (1983) provided evidence that the collapse of financial intermediation was the main culprit contributing to the length of the depression. Wheelock (2013) also supports this theory, explaining that the debtors who were creditworthy at one bank, and the bank fails, the debtor cannot acquire the same amount of loans from a new bank with the severed relationship with the old bank, and loss of credibility. The banks that survived the banking panics were now risk averse and charged a premium on the additional risk to new debtors. The reasons for the financial collapse are not always clear but, the evidence shows that the monetary policies that led to deflation was the spark of Great Depression while many other contributing factors exacerbated the severity of the economic depression. This Black Swan event had a lasting effect on the world economy and the factors that went into causing this event are important to note and watch for in the future.

4. Compound Weather Event Case Studies

4.1 Background

Whilst the discussed financial events are fundamental examples of Black Swan Events, it is believed that there are similarities among all BSE across different fields, in this section, severe weather disasters are study focus. Goetzmann et al., (2013) suggested that a connection might exist between weather and finance major events. Hirshleifer and Shumway (2001) published a study showing a relationship between sunshine and stock prices. Extreme weather conditions in the location of essential supply chain locations for businesses can disrupt markets. Extreme weather conditions could result in loss of wealth, life, and impact the economy at both micro and potentially macro levels (Tasri et al., 2022). Due to the consequences of the events, scientists place a greater emphasis on identifying Compound Weather Events (CWE), determining their contributions, and attempting to predict them. This report examines CWEs, their characteristics, and their repercussions.

Natural disasters, hazards, and catastrophes comprise CWEs. As BSEs are CWE are natural disasters that are infrequent, unpredictable, and uncontrollable on regional and global occurrences. They may or may not pose a threat to humans and are incredibly harmful to the environment. Dangerous natural disasters are referred to as hazards. Catastrophes are catastrophic events with extreme and far-reaching effects on society and the environment. It is necessary to determine their time and place of occurrence and the society's and events' characteristics. (Leroy et al., 2010).

Extreme values of compound events can constitute BSEs in the context of weather and climate. Compound weather events are characterized by the interconnected occurrences of multiple meteorological factors and/or hazards, or a "domino effect" of events that results in negative consequences, elevated risks for human societies and ecosystems. These complex occurrences necessitate an interdisciplinary, comprehensive research, risk management, and adaptation planning strategy. These compounding occurrences can be classified as preconditioned, multivariate, temporally compounding, or spatially compounding. Each type requires a unique set of analytic techniques to reveal its specific physical implications. Preconditioned events occur when one event facilitates the occurrence of another, such as a prolonged drought facilitating the occurrence of a wildfire. Multiple factors converge to produce multivariate events, such as a hurricane accompanied by high tides and heavy precipitation. Similar to successive heatwaves, temporal compound events occur when one event intensifies the repercussions of another that has occurred within a window. Multiple events occurring simultaneously in the same geographical area, such as simultaneous flooding incidents, constitute spatial compounding events (Bevacqua et al., 2021). These events may involve the simultaneous occurrences of multiple hazards. Combinations of precipitation, temperature, and atmospheric pressure can cause flooding, for example. Either a single variable or all variables are extreme (Leonard et al., 2014). In the summer of 2003, high temperatures were recorded in southern Europe, which was an example of a weather BSE. This heatwave was estimated to have caused the deaths of approximately 30,000 people (Smith, 2009).

In some cases, the variables of weather events lack extreme values, but their combination results in a catastrophe. Some extreme events are not qualified as statistically extreme; however, their effects on human lives, the environment, and the economy are significant. Depending on the nature of the extreme event, when, where, and how it takes place, the consequences may be severe or mild (Leonard et al., 2014; Seneviratne et al., 2012). However, the frequency and intensity of extreme events are anticipated to increase. According to Seneviratne et al. (2012), the phenomenon results from human actions and natural climate variability.

Analysis of extreme values in climatological time series is a highly active area of research (Trenberth et al., 2015; Easterling et al., 2016). Extreme weather and climate events and temperature or precipitation series are examples of this type of data (Mueller & Seneviratne, 2012; Alexander, 2016). High temperatures are one of the most frequently researched extreme events (heat waves, thermal stress, atmospheric, hydrological, soil, and agricultural drought), which influence human society, agriculture, water resources, energy demand, and human mortality (Allen et al., 2010; Christidis et al., 2011). This phenomenon also affects the environment, as some animal species lose their natural habitats and ecosystem diversity decreases, particularly in tropical biomes (Bailey & Van de Pol, 2016).

Besides natural hazards that create CWEs, human activities also contribute. Greenhouse gases, especially carbon dioxide and methane from the human footprint, trap heat in the atmosphere. Consequently, the Earth's surface temperature has increased by at least 1.1 degrees Celsius from preindustrial times. While this increase may seem trivial, the consequences can be critical. Global warming can lead to several results, such as shifting weather patterns and setting the past extreme events as the usual events now (Gramling, 2022). This shift in extreme frequency is explored further in the simulation section.

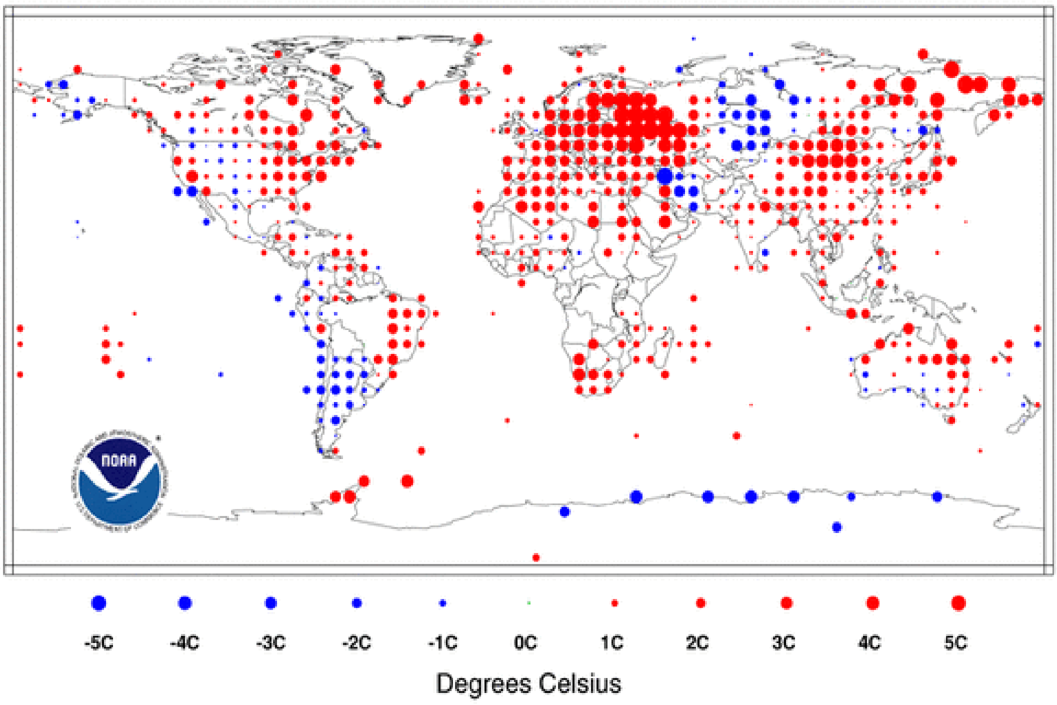
Another concern that is related to global temperature increase extreme events is climate tipping points, which are defined as abrupt and/or irreversible changes in the Earth's climate system that occur beyond critical thresholds. In other words, they occur when a small amount of climate variables, which may be associated with global warming, affect the climate system. If they are exceeded, the effects may cause climate change from one state to another abruptly and/or irreversibly, as well as damage to ecosystems, economies, and societies. Initially, scientists believed that an increase in global temperature of 5 degrees Celsius above the preindustrial level could trigger tipping points. Recently, the threshold has significantly varied from 5 degrees Celsius to between 1 and 2 degrees Celsius, and tipping points are now possible. The melting of Antarctic ice sheets and Greenland ice sheets is evidence that the climate tipping points have already been reached (Lenton et al., 2019; Leahy, 2019; Lenton, 2021; Lee et al., 2021).

Since there are many factors that contribute to CWE and their impacts vary, we analyze three CWE cases to better illustrate their causes and consequences.

4.2 Russia Heatwave 2010

The summer of 2010 was one of the most abnormal that modern society has experienced. The temperature from the sea surface began to decrease due to the La Niña. La Nina is a climate pattern in the Pacific Ocean that influences the trade winds, bringing cold water to the ocean's surface and pushing warm water toward Asia. Wintertime temperatures are consequently higher in the South and lower than average in the North (NOAA, 2023). The situation was expected to be more extreme and expand to the end of 2010 (NOAA National Centers for Environmental Information, 2010). Consequently, continents saw the warmest July, and the global temperature was anomalies between -5°C to 5°C (Figure 1)

Figure 1: Global Temperature Anomalies in July 2010. (NOAA National Centers for Environmental Information, 2010.)



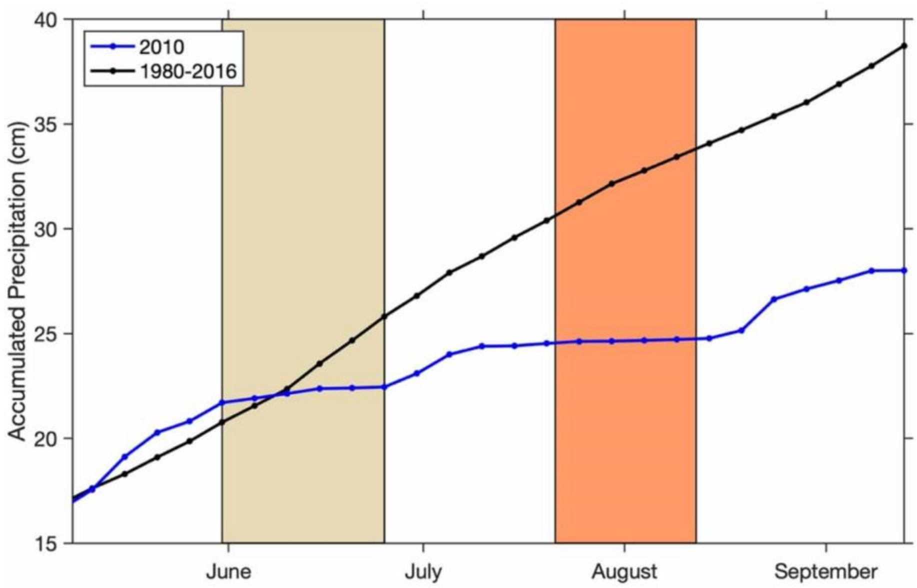
The blue spots indicate that the temperature saw colder anomalies in some areas of Alaska, South America, Kazakhstan, and the eastern part of Russia. Nevertheless, the rest of the world dealt with the warmer conditions. Globally, there was 1.03°C (1.85°F) higher than the average in the 20th century, which caused July 2010 to be the warmest month on land and the fifth warmest month on the oceans' surface temperature. Europe, especially Russia, and Asia, had the most significant impact from the temperature anomalies regarding the increased temperature. Both in western Russia and Joensuu, Finland, there were new records for the warmest July, 39°C (102°F) and 37.2°C (99.0°F), respectively. Also, the number of hot days (above 25°C) is 27 days (about four weeks), which is another new record (NOAA National Centers for Environmental Information, 2010).

In Russia, the situation got worse. Since it was the warmest July in recorded Russian history, the heatwave occurred in the western region of Russia, Moscow specifically (NOAA National Centers for Environmental Information, 2010). The heatwave contributed to the consequent wildfires and furthered the catastrophe. Human lives, the economy, and the environment faced terrible risks from the heatwave.

Heatwaves are seen as high temperatures for an extended period, putting human lives and the natural ecosystem in danger (Raei, 2018). For some regions worldwide, heatwaves not only cause the most cases of deaths related to natural hazards, but also prevent other industries from operating normally (Steffen et el., 2014).

The heat from the summer of 2010 was especially unusual in western Russia. It is the warmest July since 1880 and caused thousands of illnesses and deaths (Dole et al., 2011). On July 30, it was 39°C in Moscow, creating a new record for the warmest summer in Russia. For July and August, the temperatures were higher than the previous year's temperatures (Grumm, 2011). Besides the heat, the dry condition and little rain fueled wildfires (NOAA National Centers for Environmental Information, 2010). The amount of accumulated precipitation in August 2010 is just above half the amount between 1980 and 2016 (Figure 2) (Christian et el., 2020)

Figure 2: The Russian Precipitation in June, July, August, and September in 1980-2016 vs. 2010. The black line shows the average amount of rain between 1980 and 2016, and the tan column shows when there was a drought. The blue presents the precipitation in 2010, and the orange column indicates when the heatwave happened. (Christian et el., 2020)



Some research attempted to explain the causes of the Russian heat waves in 2010. The atmospheric blocking pattern that appeared at the Euro-Russia was shown to have caused it. Atmospheric blocking is the large-scale circulation pattern consisting of a persistent high-pressure anomaly that displaces the midlatitude jet northward, preventing it from impacting a particular region. It occurs typically over the northeastern Atlantic Ocean, Europe, and the northern Pacific Ocean (Xoplaki et al., 2012). Dole et al. (2011) claimed that the blocking phenomenon typically happens in the area, indicating that natural causes were a factor in the 2010 heatwave. Secondly, La Niña increased the temperature, both on the land and sea surfaces globally. The land surface temperature in July 2010 beat the warmest July record in 1998, above the average of 1.03°C (NOAA National Centers for Environmental Information). Under the combination of high temperatures and little precipitation, a flash drought is created in June (Grumm., 2011). Also, under the effect of the block, there was little rainfall, which boosted the evaporative demand. Consequently, the demand for evaporation rockets the stress of moisture worse and makes the heat waves more extreme (Christian et el., 2020).

Besides the natural reasons presented by Dole et al. (2011), human activities also played a role in the 2010 heatwaves event. Using statistical models and Monte Carlo Simulation, Rahmstorf and Coumou (2011) showed that climate warming caused global temperature increases. Their research showed only a 20% chance that the 2010 Russian heatwaves would happen without climate change.

The heatwaves in Russia in 2010 seriously affected Russian mortalities, the environment, society, economy. The abnormal, extreme heat, directly and indirectly, connects with the risk of death (Joacim, Kristie, Bertil. 2011). There were approximately 55,000 death reports, including 1600 people by drowning and 40 people by wildfires (Hoag, 2014; NOAA National Centers for Environmental Information, 2010; Gutterman, 2010).

There were 18 provinces that experienced natural fires, which totaled 948 forest fires. The fires put a risk to human lives and the air pollution from the fire's smoke. In the Moscow area, air pollution was eight times higher than the average index, caused mainly by smog from forest fires (NOAA National Centers for Environmental Information, 2010).

In the agricultural sector, around 20% of the cultivated area was destroyed, which is nine million hectares (NOAA National Centers for Environmental Information, 2010). It was estimated to cause a 0.18% of GDP loss in the Russian economy (US$ 1.7 billion) and led to an increase in grain prices (Niggli, 2022). This compound event was unprecedented in the area and shows that BSE in the climate context directly and indirectly impacts human mortality and the economy. The weather cases show a relationship between weather and its economic influences. There is also an argument to be made that the economy influences the weather as humans, directly and indirectly, increase greenhouse gases and pollute the environment.

4.3 The 2010 Pakistan Floods

Pakistan locates between 25° 35' north and 37° 05' north and between 61° and 78° east longitude, with a total area of 796,095 km^2. Its climate is typically dry and cold, with the north experiencing mild winters and dry summers and the west and south having arid regions (Annual National Report of Environment of Pakistan, 2016).

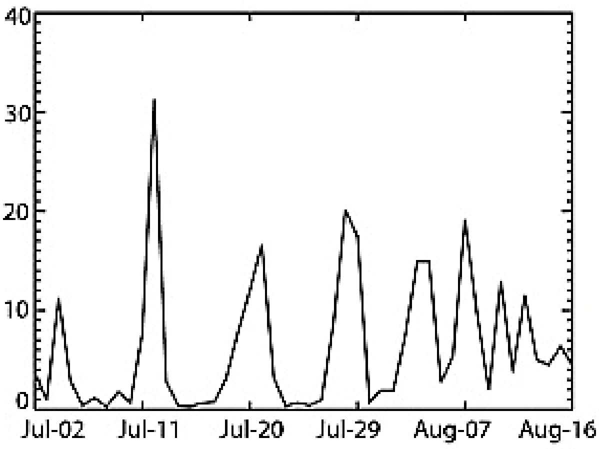
Understanding the geographical location of the water sources is essential to identifying flood risk. The Indus River is an important water source that provides water to the countries it flows through. Its upper reaches are in China, flowing through India and Afghanistan before entering Pakistan and emptying into the Arabian Sea. The system of the Indus River has numerous tributaries. The Chenab, Ravi, Sutlej, Jhelum, Beas, and Indus are the major tributaries that enter India before Pakistan. The other defining river from Afghanistan that flows into Pakistan is the Kabul River (Michel, 2013). The Basin River's various water sources vary depending on their locations. At the upper elevations, the glacier is the primary water source. Typically, snow falls during winter and spring.

In contrast, the climates of the lowlands south of the Indus River range from subtropical and semi-arid to temperate and subhumid. This region receives precipitation during the monsoon season, from June to September. While Pakistan's climate is arid and cold, the average precipitation in the Lower Indus region is low, ranging from 100 to 500 millimeters (about 1.64 ft) to 2,000 millimeters (about 6.56 ft) or more in the Himalayan Mountain region (Michel, 2013; Annual National Report on the Environment of Pakistan 2016).

Figure 3: Indus Basin River and its tributaries (Michel, 2013)

During the last week of July and August 2010, an abnormal quantity of monsoon rain caused a flood in Pakistan that broke all previous records. Typically, storm-generated precipitation occurs in the Bengal region, which is distant from Pakistan and uncommon here (Houze et al., 2011). During the monsoon season, the Bay of Bengal receives approximately 16mm/day of precipitation, followed by Northern India with 8 to 10 mm/day and Northern Pakistan with only 6 to 8 mm/day (Webster et al., 2011). Starting in July 2010, the amount of rain was several times higher than the usual level in previous years. In certain regions, the amount of water from rainfall exceeded 300 millimeters in four days. The rain level in the northern Swat Valley was nearly 300 percent greater than the average precipitation for the same ten days, approximately 500 millimeters. Consequently, the runoff Indus Basin River and its tributaries overflowed, causing the worst flood in Pakistan's history (Webster et al., 2011; Lau & Kim).

Figure 4: Northern Pakistan's daily Precipitation from July to Mid-August 2010 (mm/day) (Webster et al., 2011)



The Pacific Ocean initiated the La Nina phenomenon in the summer, which intensified the monsoon in the northern region of Pakistan and was deemed a factor in the disaster (Webster et al., 2011). In addition, Lau and Kim (2012) demonstrated the link between the two extraordinary events: heatwaves in Russia and floods in Pakistan. They believed that the atmospheric blocking event that caused the Heatwave in Russia in 2010 also triggered heavy rainfall from the southeast of the Himalayan foothills and abundant precipitation from the Bay of Bengal, which boosted monsoon activities.

Safdar et al. (2012), who concurred that abnormal precipitation was the primary cause of the 2010 floods in Pakistan, also cited poor human management as a contributing factor to the severity of the BSE that caused thousands of fatalities.

Table 1: Floods and their consequences in Pakistan from 1950 to 2014 (Yaqub & Doğan, 2015)

Year	US $ million	Lives Lost	Affected villages	Area (km2)
1950	488	2190	10000	17920
1955	378	679	6945	20480
1956	318	160	11609	74406
1957	301	83	4498	16003
1959	234	88	3902	10424
1973	5134	474	9719	41472
1975	684	126	8628	34931
1976	3485	425	18390	81920
1977	338	848	2185	4657
1978	2227	393	9199	30597
1981	299	82	2071	4191
1983	135	39	643	1882
1984	75	42	251	1093
1988	858	508	100	6144
1992	3010	1008	13208	38758
1994	843	431	1622	5568
1995	376	591	6852	16686
2010	10000	1985	17553	160000
2011	3730	516	38700	27581
2012	2640	571	14159	7145
2013	1500	287	8297	4080
2014	2000	367	2235	4046
Total	37554	11893	190766	609984

The General Secretary of the United Nations, Ban Ki-Moon, stated that the Pakistan floods in 2010 were one of the most catastrophic events he could recall. The number of affected people from it was more than all the victims from the Indian Ocean tsunami, the Kashmir earthquake, Cyclone Nargis, and the earthquake in Haiti combined (Houze et al., 2011; UN News, 2010).

Table 1 indicates that the 2010 floods accounted for approximately a quarter of the total losses and area affected by all floods in Pakistan between 1950 and 2014, which was $10 billion US dollars and 160,000 km2. In addition to its effects on humanity, the 2010 Pakistan disaster triggered landslides and flash floods. Infrastructure was destroyed in flooded areas where 17,553 villages were submerged under floodwater. The erosion caused by the sudden flood devastated soil quality (World Bank and Asian Development Bank, 2010; Yaqub & Doğan, 2015).

In the agricultural sector, the 2010 floods affected approximately 16% of Pakistan's agricultural territory or 17 million acres (about twice the area of Belgium) of the country's most productive farmland. In addition to crops and vegetation, 274,334 farm animals perished, while others suffered from malnutrition and disease. The agricultural loss amounted to roughly 429 billion rupees (~$1.5 billion) (Bukhari & Rizvi, 2017). The direct and indirect costs of Pakistan's recovery from the 2010 floods were estimated by the World Bank and the Asian Development Bank (2010) to be USD $10.85 billion. This BSE had such an impact that the consequences are still seen today.

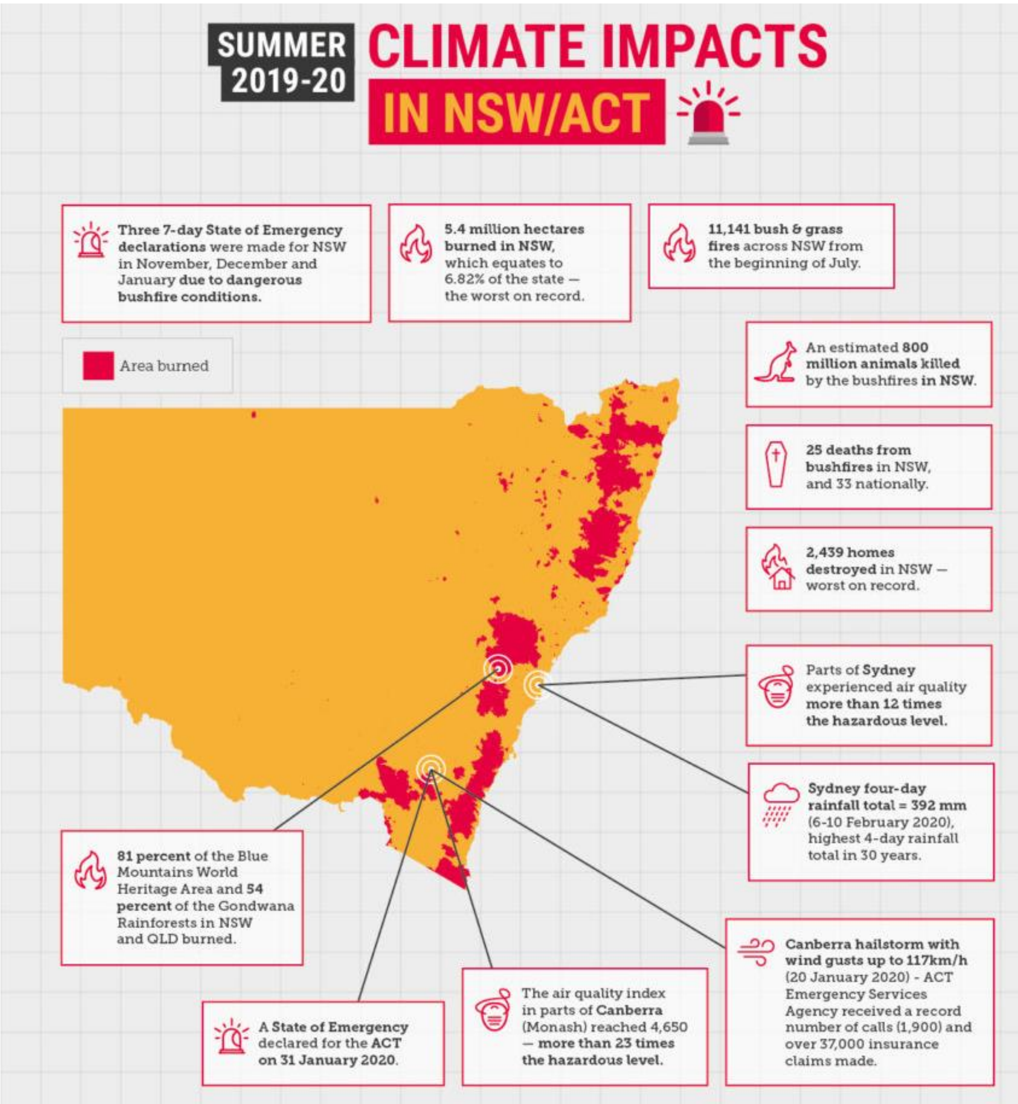
4.4 Australia’s Wildfire 2019-2020

The 2019-2020 Australian wildfires, also known as the Black Summer bushfires, were an enormous catastrophe, as they caused unprecedented damage to the environment, economy, and public health and had long-term effects on the ozone layer and temperature (Humphries, 2022).

A combination of weather-compounding elements caused the Australian Black Summer bushfires. The second half of 2019 saw minimal precipitation in eastern Australia and established a new record for the driest period in Australian history (van Oldenborgh et al., 2021). According to King et al. (2020) and Van Oldenborgh et al. (2021), El Niño aggravated the severity of the drought. The Manning River catchment experienced a drought, receiving only about 40% of its annual average rainfall of 1040 mm (about 3.41 ft). There were also temperatures that set records. The lack of precipitation and high average temperatures contributed to the drought, which was a significant factor in causing Australia's Black Summer (Kemter et al., 2019).

The wildfires of 2019-2020 have had a significant impact on the economy and environment of Australia because of a significant number of land areas in Australia being consumed by fires; an area is nearly equivalent to that of the United Kingdom, the Black Summer cost insurance companies approximately AUD 2.328 billion in damage claims. Over a third of the claim values were for commercial losses, while the rest was for domestic losses (Ayres, 2020). It was nearly double the number of insurance claims for Australia's Black Saturday in 2009 (Victorian Bushfires Royal Commission, 2010). The situation in New South Wales was graver than others. Hughes et al. (2020) report that 3,100 residences and 24 million hectares of land were destroyed by fire, which set a record.

Figure 5: The Black Summer 2019-20 impacts (Hughes et al., 2020)



Furthermore, several recent studies suggested that the aftereffects of the event would cause long-term negative impacts on the Australian climate (Bowman et al., 2020; Deb et al., 2020; van Oldenborgh et al., 2021). According to Davey and Sarre (2020) and Hughes et al. (2020), major cities' land incineration and air pollution levels have reached a new high. The Black Summer may undermine our efforts to restore the ozone layer by enlarging the breach (Humphries, 2022). The event raised the temperature in Australia by three degrees Celsius and by 0.7 degrees Celsius in the stratosphere. Ash from the fires could join the river runoff when raining heavily. It may cause damage to the infrastructure and water quality (Alexandra& Finlayson 2020), and the minerals from the fires' ash could infiltrate the ocean and destroy marine life by causing algal blooms (Humphries, 2022).

Table 2: The land burnt in Australia 2019-20, until March 2020 by location (adopted from Davey & Sarre, 2020)

State	Deaths	Homes lost	Total native forest area burnt (000 ha)	Total commercial population area burnt (000 ha)	Total other forest	Total forest area burnt (000 ha)	Total area burnt (000 ha)	Proportion of burnt area that was native forest (%)	Proportion of burnt area that was forest (%)
Australian Capital Territory	0	0	83	0	0	83	90	93	93
New South Wales	25	2448	5014	92	16	5122	5681	88	90
Queensland	0	49	367	3	0	370	419	88	88
South Australia	3	188	118	17	2	137	313	38	44
Tasmania	0	2	27	3	0	29	42	64	70
Victoria	5	405	1444	10	3	1457	1583	91	92
Western Australia	0	8	1138	4	0	1143	2044	56	56
Total	33	3100	8191	129	21	8341	10172	81	82

The fires have had detrimental effects on humans both directly and indirectly. The bushfires destroyed 22 million hectares of land and killed 33 people directly (Humphries, 2022; Kemter et al., 2019). More smoking-related deaths were documented, with over 600 cases reported in Queensland, New South Wales, the Australian Capital Territory, and Victoria (Borchers Arriagada et al., 2020). In New South Wales, more than 1,500 people had heart and lung issues due to inhaling smoke-laden air (Kemter et al., 2019).

Case studies of CWEs illustrate the diversity of causes and effects of extreme phenomena within the Earth's complex climate system. Now we will examine a Monte Carlo simulation of future weather in Pakistan to determine how small changes in variables’ probability distribution can affect the frequency and severity of extremes over time.

5. Pakistan Weather Simulation

5.1 Background

Using 35 simulations from the Community Earth System Model Large Ensemble (CESM LENS), we investigate the long-term extreme values of precipitation, daily maximum temperature, and relative humidity in Sindh, Pakistan under the high-emissions Representative Concentration Pathway (RCP) 8.5. This pathway is the "worst case" future scenario based on the continued increasing emissions. To estimate monthly probability distributions, historic daily data was used from NASA's Prediction of Worldwide Energy Resource (POWER) Project. An important distinction between the data, and potential drawback of this simulation is the future means data is based on the entire region of Sindh, while the historic data is collected from a weather station in Hyderabad, a city located in central Sindh. While the city is located in central Sindh, this could cause small discrepancies in the analysis.

The simulation and analysis were conducted with RStudio (seen in the appendix folder). The R packages used in the data analysis were extRemes, fitdistrplus, and fitur. These packages have built-in functions to estimate Generalized Extreme Value distribution parameters and provide goodness-of-fit measurements to assess distribution fits. They also include random number simulation methods using estimated distribution parameters that were used.

Within Extreme Value Theory the general extreme value distribution consists of three distribution families, Gumbel, Frechet, and Weibull. In literature, the Frechet is found to fit precipitation and the Weibull is found to fit temperature (Rieder, 2014). This was consistent with our analysis when assessing distribution fits on the historic data. Relative humidity, being a percentage and not continuous variable, is not typically modelled under extreme value distributions. Instead, we found the probability distribution of relative humidity for each month using goodness-of-fit measurements (KS-statistic, AD-statistic, and AIC) using probability distributions, Normal, Logistic, Gamma, and Weibull. We found that there was no consistent probability distribution for relative humidity on a monthly basis using the historic data.

Once probability distributions were estimated, we simulated random numbers based on the estimated distribution parameters. The simulations were in 20-year intervals up to the year

2100 and starting in 2020. The location of the probability distributions could be shifted using the estimated future means for each variable.

To identify the frequency and severity of extreme values and weather events, we defined "extreme" as values below 1% and above 99% quantiles based on the historic data. The frequency of extreme values was then the total number of outliers for each simulated 20-year period. The severity of the extreme values was measured as the average (both mean and median) outlier value, as well as the maximum value.

Extreme weather could also mean harm done to humans beyond a certain threshold. We examined the potential for heatwaves, floods, and daily heat index exposure. To set the thresholds for the conditions in which one of the specified events would occur we used the National Weather Service's Heat Index, The World Meteorological Organization's definition of a heatwave, and flooding thresholds used in a published paper analyzing floods in the area. (Papagiannaki et al., 2022). The World Meteorological Organizations definition of a heatwave is 5 or more consecutive days where the daily maximum temperature exceeds the average maximum temperature by 5 degrees Celsius. The flooding threshold set in the paper was where the last 30 or less days sum to 150 or more millimeters of precipitation or 40 or more millimeters in 1 day. To assess the change in extreme events, we will compare the results of historic extreme values with simulated future extreme values.

5.2 Results

Table 3: Extreme Temperatures

Extreme Temperatures

TimeFrame	Total Outliers	Delta	Mean Outlier	Mean Delta	Median Outlier	Median Delta	Max
2000-2019	130		30.94		21.41		48.47
2020-2039	110	-15%	28.07	-9%	21.34	0%	48.37
2040-2059	123	12%	39.89	42%	46.49	118%	49.87
2060-2079	198	61%	46.70	17%	46.94	1%	49.95
2080-2100	491	148%	47.36	1%	47.28	1%	52.32

Note. Extreme defined as lower than 1% and higher than 99% quantiles of 1991-2021 data

Extreme temperatures were shown to decrease in the 2020-2039 period in comparison to historical figures and increased greatly by the 2080-2100 period in all measures of extremity.

Table 4: Extreme Precipitation

Extreme Precipitation

TimeFrame	Total Outliers	Delta	Mean Outlier	Mean Delta	Median Outlier	Median Delta	Max
2000-2019	78		25.43		18.89		104.40
2020-2039	99	27%	7.50	-70%	0.01	-100%	218.72
2040-2059	142	43%	3.17	-58%	0.01	-19%	52.30
2060-2079	84	-41%	6.49	104%	0.01	-1%	106.66
2080-2100	48	-43%	15.18	134%	0.01	40%	175.36

Note. Extreme defined as lower than 1% and higher than 99% quantiles of 1991-2021 data

Extreme precipitation increased in total outliers in the first two periods and then decreased in the last two. The mean and median measures were all significantly less than the historical data.

Because total outliers were generally higher and the average measure of extreme values was much lower in the simulation, this could imply an underestimation of severe extreme precipitation in comparison to historical figures.

Table 5: Extreme Humidity

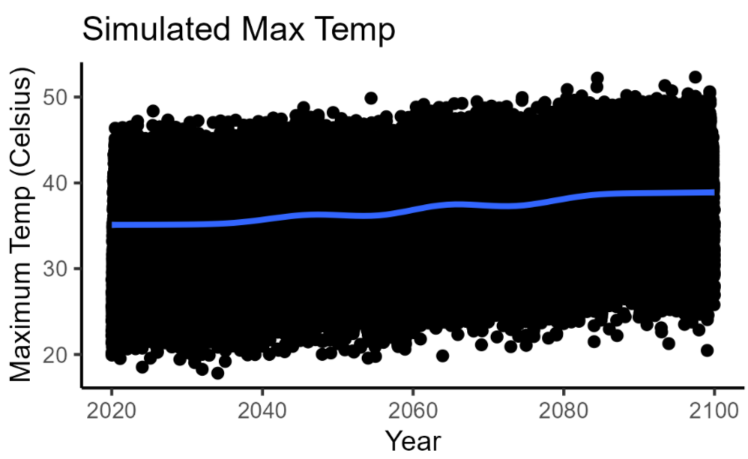
Extreme Humidity

TimeFrame	Total Outliers	Delta	Mean Outlier	Mean Delta	Median Outlier	Median Delta	Max
2000-2019	149		49.43		77.25		88.88
2020-2039	332	1.23	81.56	0.65	80.85	0.05	100.00
2040-2059	300	-0.10	81.00	-0.01	81.70	0.01	100.00
2060-2079	369	0.23	81.53	0.01	81.37	-0.00	100.00
2080-2100	566	0.53	81.96	0.01	81.00	-0.00	100.00

Note. Extreme defined as lower than 1% and higher than 99% quantiles of 1991-2021 data

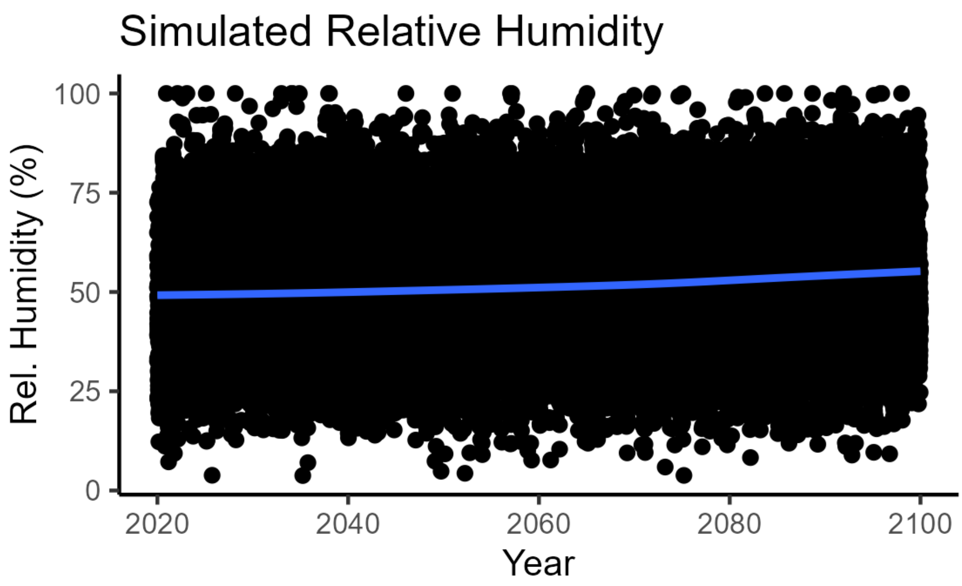
While relative humidity had not reached 100% in the historical data, we see it reaches 100% in all simulated time periods. We see a 123% increase in total outliers in the 2020-2039 period and the following periods continue to stay much higher than the historic frequency of outliers. We also see a 65% increase in mean outlier while the median does not change much, showing the effect of a small number of extreme values.

Figure 6: Simulated Max Temperature



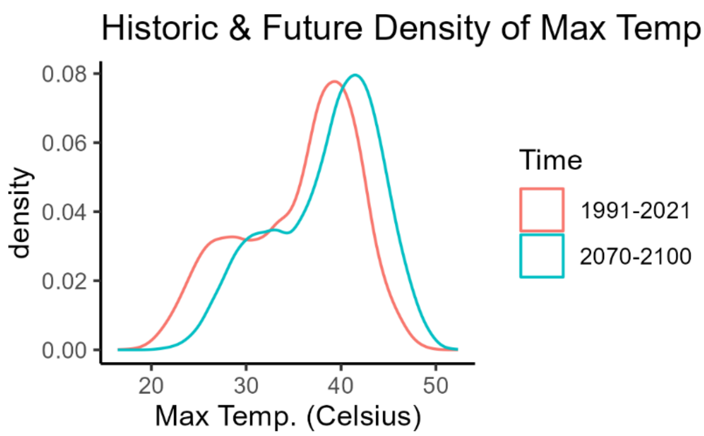
The *Simulated Max Temp* plot shows the steady increase of temperature in a time-series. This increase is in line with CEMS projections of increased temperature.

Figure 7: Simulated Relative Humidity



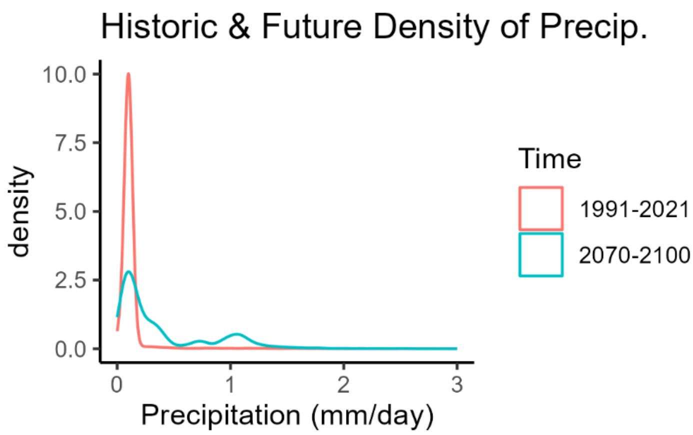
The *Simulated Relative Humidity* plot shows the steady increase of relative humidity in a time-series. This increase is in line with CEMS projections of increased humidity.

Figure 8: Historic and Future Density of Max Temperature



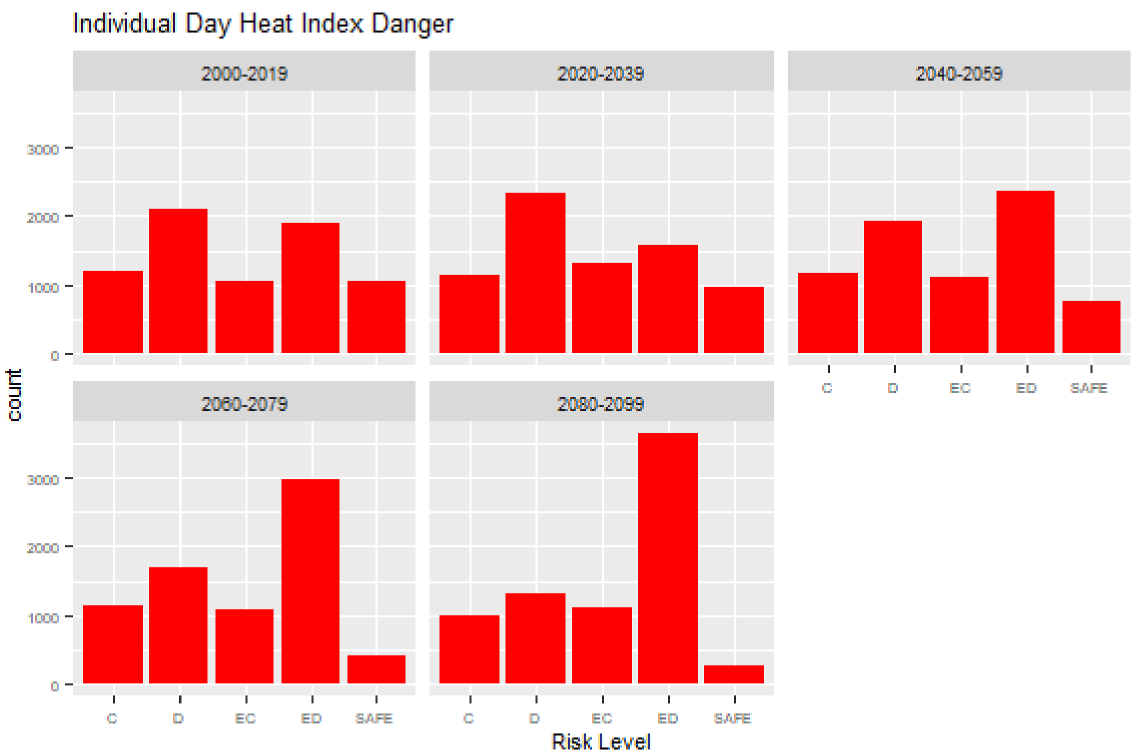
The *Historic and Future Density of Max Temp* plot depicts the shapes and location of the distribution of historic and 2070-2100 period of simulated temperature values. The shapes are very similar, indicating a correct probability distribution was used in the simulation. The shift in location from the historic to 2070-2100 is in line with increased mean temperatures.

Figure 9: Historic and Future Density of Precipitation



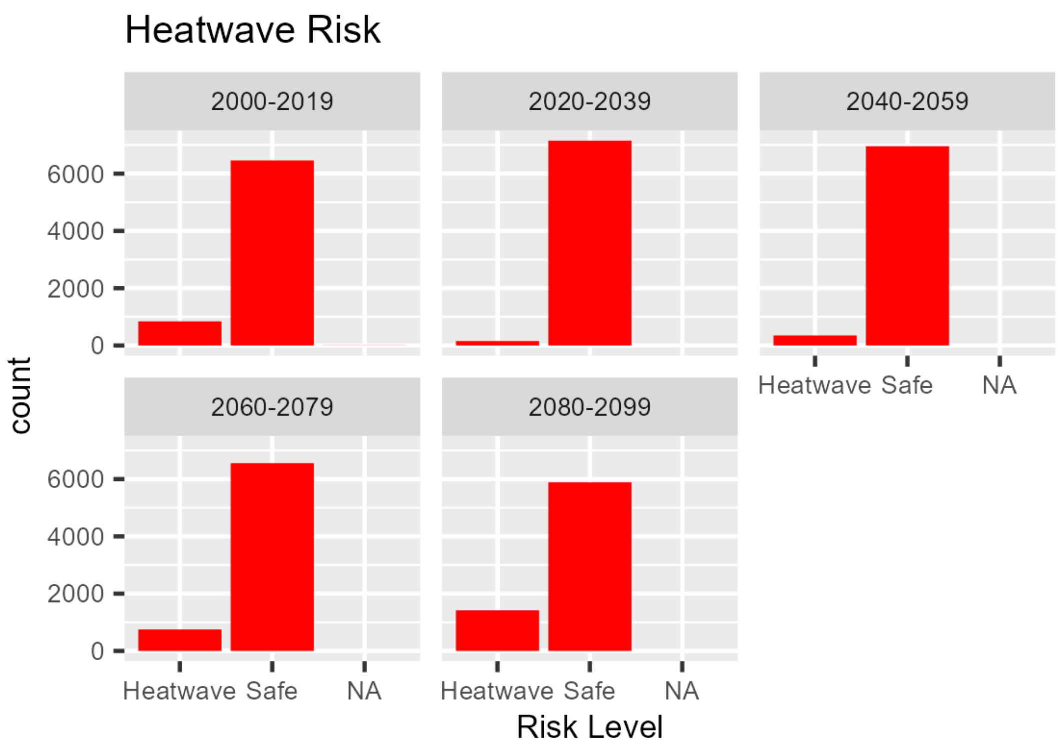
Historic and Future Density of Precipitation shows the shape and location of the historic and 2070-2100 period's value distribution. We see a very concentrated number of values at or close to zero in the historic data. We removed the extreme values of the historic data to make this part of the plot visible. This highlights the low frequency but very severe precipitation extremes in the Sindh region.

Figure 10: Individual Day Heat Index Danger



The *Individual Day Heat Index Danger* bar graph shows the frequency of days where the combination of relative humidity and temperature could pose a danger to humans. There are different levels of risk including, “Caution”, “Extreme Caution”, “Danger”, and “Extreme Danger” (from least dangerous to most). The most notable change we see is the large increase over time of “Extreme Danger” days. Another notable difference is the decline of “Safe” days. There will be more days that are unsafe to be outside than safe days in our simulation. Exact numbers for “Extreme Danger” are shown in Table 6.

Figure 11: Heatwave Risk



The above Heatwave Risk bar graph shows the count of days in the historic data and the simulated values that are considered a heatwave and the days that are not heatwave days, labeled as “Safe”. We see a decrease in the 2020-2039 period from the historic data and a steady increase over each subsequent period. In the simulation, we will see more heatwaves than in the past 20 years by 2080-2100. Exact numbers for heatwave days are shown in Table 6.

Table 6: Summary of projected means and risks

Time	Mean Temp	Mean Precipitation	Heatwaves	Heat Risk
2000-2019	35.454	0.514	842	1902
2020-2039	34.360	0.329	154	1563
2040-2059	35.320	0.365	349	2359
2060-2079	36.460	0.398	750	2986
2080-2099	37.690	0.450	1418	3637

Note: Heat Risk is a count of "Extreme Danger" days for individual day events. Heatwaves variable is the total number of days under a heatwave.

Finally, in Table 6, we display the numeric values that may be difficult to interpret from the previous bar graphs. While precipitation and flood risk show a decrease in potential risks in the simulation, we see a substantial increase in heat risks, both individual days and heatwaves.

6. Findings and Discussion

There is much to discuss regarding the case studies and Monte Carlo simulation of BSE. We can discuss the case studies and the simulation separately and then tie each together, examining similarities and what we have deduced by doing so. Because of BSE's highly unforeseen and improbable nature, the recommendation to improve forecasting and prediction techniques will always be appropriate within this theory.

Based on the financial case studies, we can see there are often incorrect assumptions made about data before analysis. This can lead to misleading conclusions. This can be applied to many other areas that use statistical analysis, as it is crucial to understand the data and its distributions before making further analysis. This includes understanding the assumptions of statistical models before applying them as a best practice and reviewing study methods in another published research. In addition, many of the prediction models lacked relevant variables in the cases. The models used for predicting defaults in the 2008 recession did not account for the subprime loans risk; the models also did not account for the influence of the news in the 1987 market crash or the Great Depression. Knowing the influential variables and their statistical properties within a system can help improve forecasting. This may be easier said than done; nevertheless, an appropriate observation.

Analyzing the compound event weather cases, we noticed they are typically triggered by extreme variables. Extreme precipitation in Pakistan, for instance, caused the worst flood in its history. There is also the drought and heatwave that contributed to the Australian wildfires of 2019-2020. The effect of the extreme event's occurrence can trigger the development of another event's effects. Low precipitation levels exacerbated the severity of the 2010 Russian heatwave. CWE has catastrophic consequences for various sectors. The 2010 Russia Heatwave, the 2010 Pakistan Flood, and the 2019/20 Australia Wildfires illustrate that the CWEs have devastating impacts on human lives and the economy. These case studies demonstrate how such events can disrupt vital systems, such as agriculture, infrastructure, and public health, resulting in significant economic and social costs. Moreover, these cases illustrate the vulnerability of human societies to climate-induced shocks and the need for proactive adaptation and mitigation strategies.

Numerous factors contribute to the likelihood of CWE. Human activities, climate change, and weather patterns can all be considered major contributors to CWE. Due to climate change and the rise in temperature, it is anticipated that the frequency of extreme weather events will also increase. This is seen in the simulation with a significant increase in extreme event dangers. This potential future increase in likelihood generates a great deal of concern regarding what will occur and how we can minimize the impact.

Examining the Monte Carlo Simulation, there are some interesting points. As seen in Temperature Extremes (Table 3), there is exponentially more and more frequency in outliers from period to period besides for 2020-2039. Nevertheless, there is a decreasing effect on the outlier's severity after a 118% increase in 2040-2059 mean and median averages. So, while the number of extreme events increased in this simulation, the average severity of the events did not increase significantly. Perhaps the clearest result from the simulation is the increase in heat risk. By the 2080-2099 period, we see the individual day heat index risk increase 132.6% from the 2020-2039 period. The increase in total number of heatwave days increases 820.8% from 2020-2039 to 2080-2099. This kind of heat would be detrimental to society with both direct and indirect effects from the increased heat. This increase in extremes could mean an increase in CWE likelihood.

Turning to the Precipitation Extremes (Table 4), there was an opposite effect, as seen in the temperature variable. While the number of outliers showed an increase in 2020-2039 and 2040-2079, the number then falls below the number of outliers from the historic period in 2080-2100. The large difference in the means and median outliers demonstrates the lower frequency of outliers but their greater severity since the means are so much higher than the medians. Another demonstration of this is the large difference between the maximum values and the median outliers.

We see that there are joint events happening in all BSE cases. There are multiple events occurring that have a dependence on each other, which may be extreme or not. Both the financial and weather BSE cases show that many factors are involved. When the stock market crashes, the effect of the news on market sentiment, or the effect of extreme heat and low humidity on the chances of fire all show that there are joint events contributing to a more significant event. Identifying the events that lead to a larger event while they are happening may be a difficult task. Perhaps climate change is the culprit for an increase in extreme events, as we have seen in the Monte Carlo simulation. Instead of a slight decrease in biodiversity or melting of the global ice caps, an increase in compound and extreme weather events may be the most impactful way humans feel the consequences of climate change. Some BSEs are totally unforeseeable and unprecedented, but it's possible to identify trends we have seen in the past to prepare for and mitigate the negative consequences.

As shown in our financial cases and weather extremes, the news and announcements are a critical variable in the severity of BSE regarding the consequences for humans. It can increase or decrease the severity of extreme events depending on the language and urgency of the presentation. In financial cases, the news was a negative factor in downturns, fueling the negative outlook. The evidence presented in the Great Depression case and the 1987 stock market crash case indicated that the news was a contributing, if not main factor, to the economic collapses. There was also evidence that the news contributed to the length of the 2008 recession. In extreme weather cases, the news is a critical medium of warning for people in the affected areas. The flow of information regarding extreme weather could save lives in the area, whether that means evacuating a flooded area or educating on the signs of heat stroke.

Lack of or poor regulation is another similarity between the causes of black swan events. The emissions and pollution that are likely contributing to climate change should be reduced to prevent increased extreme weather. While many nations in the world are beginning to create more legislation to lower emissions, there are still other countries that are failing in this regard. From the financial cases, the lack of oversight involved in the sub-prime loans market, the new trading systems in 1987, and the poor federal reserve response during the Great Depression are all examples of poor or absent regulation. If we can more carefully set regulations, especially on new technology, we could potentially reduce the consequences of inevitable BSE.

Many "experts" are often wrong in forecasting. Forecasters have a challenging job, especially in complicated systems. Weather forecasters cannot currently make accurate predictions beyond ten days, and financial experts are shown to be inconsistently accurate. Understanding this provides the opportunity to prepare for the unexpected. In finance, correct portfolio diversification to protect against market collapse and invest in insurance on assets to protect against losses. In weather, the increased risk for climate change will force society to lower our environmental impact while also preparing for alternative solutions when our environment becomes dangerous for vulnerable communities. While "experts" are important to listen to when discussing their area of expertise, it is also important not to take what they say as fact but as an informed opinion on the subject.

7. Conclusion and Limitations

7.1 Conclusion

To conclude, there is a "domino effect" of events that happen before and after the extreme events seen in all the case studies. However, because a component of BSE is hindsight bias, we may overestimate our ability to identify "domino pieces" that are falling towards an extreme event, if we can identify any "domino pieces" at all. Many of the factors that led to financial BSE went undetected by many industry experts. In our simulation we see that just a small shift in probability distributions can have a large impact on the frequency and severity of events such as weather. This shows that we must find insurance for our vital assets and protect against future hazards we currently understand. From what we discussed, better regulation among governments and productive news output from the media could be helpful to mitigate the severity of extreme events. In addition, listening to experts is generally a good idea but we must not take their predictions as facts. While our ability to predict "mediocristan" events continues to improve, we are still unable to predict extreme events very well. This is why it is essential to exercise damage control for what we can. Continued research is recommended to further our understanding of this topic and perhaps create a more stable future.

7.2 Limitations and further research

While our choices of financial crises are major economic stories of world history, we may have been narrow in our diversity of crisis locations. All three were in the American economy, and the causes and outcomes may have differed in other countries.

The case studies rely on secondary data from published sources, which could have limitations, including a lack of methodological transparency, potential biases, and incompleteness. This increases the likelihood of bias and error in the findings.

Our simulation is merely an exercise in probabilities and distributions and only simulates the future statistically. There is covariance in the weather variables that we were unable to capture in this study. Therefore, there is no time dependence and weather events such as heatwaves do not encompass the dependence of previous days and we are just drawing on the probability distributions. We expect we would see more extreme weather events if we used a time dependence model.

The application of forecasting models only helps with systems that are modellable, but many BSE are unknowable and can, therefore, not be modeled. Although complex, further study and inclusion of relevant variables may improve our ability to predict events more accurately in weather and finance systems. Our simulation also does not show any insight into the severity of the impact on society, and more research should be done in that regard, as well as how to prepare for these events. It is possible that the weather events examined in this paper are not as extreme as we think. The recorded history of the areas studied may be too short to analyze a correct probability distribution. In addition, it's possible that the reporting of these events is more likely due to the increased number of humans living in the areas. For example, we are not likely to hear of extreme conditions in Antarctica, where no humans live. This could skew findings and create biases within the area of research.

Another drawback of our research is that our analyses are limited to two systems, and the BSE theory applies much more than that. We may draw some insight by analyzing these BSE events in these systems' context, but without more study, we may not be able to apply insights to other complicated systems.

It is possible that the weather events examined in this paper are not as extreme as we think. The recorded history of the areas studied may be too short to analyze a correct probability distribution. In addition, it’s possible that the reporting of these events is more likely due to increased humans living in the areas. We are not likely to hear of extreme conditions in Antarctica where no humans live, but rather of weather events where people live. This could skew findings and create biases within the area of research.

Considering BSEs and the thesis findings, there is a vast amount of room for future research. As global warming continues and reaches a tipping point, the consequences could become irreversible. The resulting impacts would mean continuous extreme events and enormous losses for humans. Research on reversal, mitigation, and alternative solutions are all important areas.

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