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Potential Climate Risks in Financial Markets: A Literature Overview

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Potential Climate Risks in Financial Markets: A Literature Overview

Ingrid Hjort*

February 1, 2016

Abstract

This literature overview conducts a systematic study of how the climate related risks from global warming may affect financial markets. The climate related risk is divided into three subcategories, the environmental uncertainty, the economic climate risk and the climate policy risk, which all of them may affect the markets directly or indirectly. The perspective is broad, including production possibilities, productivity, social disturbance, health, migration and trade. Stock prices are affected by beliefs about future path of expected return. Climate change signifies possible disruptions in production and consumption possibilities, which may imply reduction in future asset values. Expectations of this will reduce asset values today. There are few studies in the research literature that explicitly attempt to identify mispricing. The survey compares different event studies that may reflect how the financial market react to the climate related risks. The empirical evidence is mixed, and few general conclusions can be drawn. It is unclear whether the market reactions are consistent with rational market valuation of the climate risk.

Key words: climate change, climate risk, climate policy risk, financial markets, stranded assets, divestment

JEL-codes: G11, G12, G14, G32, Q54, Q58

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Preface

This literature overview is written as a part of a project financed by the Norges Bank Investment Management (NBIM). As part of the same project I was asked to write a report form a workshop on the same topic, held at Norges Bank, January 20, 2016, see Hjort (2016).

Questions regarding consequentialism, how the Norwegian GPFG's[1] investments may affect climate change or influence climate policies, or other ethical perspectives, are not the topic of this study. The report by Skancke et al. (2014), appointed by the Norwegian Ministry of Finance, considers the ethical perspective when investing in fossil fuels. The aim of this study is to investigate potential impact of climate change on financial market risk and asset prices and hence implications for asset management. The core question is whether financial markets correctly reflect and price the climate risk. Skancke et al. (2014) do consider the same topic, the financial aspect of climate change, in §81-94.

The task commissioned by NBIM has been to give an overview of recent academic research on potential financial risk from climate change. I have discovered that climate economics is a rapidly developing field, already with a large body of academic papers. However, there are fewer studies combining climate economics and finance. Priority, when selecting literature, has been given to more recent papers with clearly academic purpose. From the very recent past, also unpublished papers are included, since some of these are likely to become important pieces in the published literature.

It has, of course, been impossible to give in depth coverage of all cited papers to the extent they deserve. For sure, I will also have overlooked some important research. However, I hope this overview gives a useful picture of the literature as it stands today.

The views and opinions expressed in this article are those of the author, and do not necessarily reflect those of NBIM.

[1]Government Pension Fund Global

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1 Introduction

Climate change is no longer a distant threat but a reality the global society is experiencing already today. 2015 is the year global warming reached 1°C for the first time (Met Office, 2015). The news is dominated by extreme temperature records[2], frequent natural catastrophes and glacier melting. Daily scientific discoveries and a commanding percentage of scientists support the main message from The Intergovernmental Panel on Climate Change (IPCC). Evidence demonstrates that climate can have a profound impact on the functioning of our economic society. Global warming is a substantial threat indicating the sensitivity of natural and human systems to a changing climate: "Climate change will amplify existing risks and create new risks for natural and human systems" (IPCC, 2014b).

This paper presents an overview of the existing literature on climate change and its impact on financial markets and investment decisions in a broad perspective. The intention is to cover close to everything that directly or indirectly may affect financial markets as a consequence of climate change. Many climate change impacts are not covered, such as loss of biodiversity, changes in ecosystems, plant diseases and individual utility and human well-being. The perspective of this study is the potential climate impact on economic performance and thus on financial markets.

I aim to gather present knowledge and possible avenues for research on risk in financial markets arising from changes in climate, including possible actions to prevent global warming or mitigate its consequences. The topic includes the effects on worldwide production and consumption possibilities from gradual or sudden, global or regional changes in climate. These possibilities should be interpreted broadly, e.g., health, stability, peace, migration and productivity. The subject also includes possible actions by authorities, the private sector, and various stakeholders as reactions to such effects, or predictions of such effects. This includes beliefs about climate change effects, even those that never materialize. It furthermore includes the response of financial markets to these changes in economic and political realities. In particular, it includes the question of whether such risks will be understood and acted upon in a rational manner by market participants.

The Efficient Market Hypothesis (see section 6.7) suggests that information is immediately reflected in financial markets in such a way that no investor can expect excess return without accepting excess risk. Accordingly, market values of assets that are particularly sensitive to the climate would adequately reflect the probabilities of various future

[2]At the time of writing, the winter of 2015-2016 is a record year for global temperatures and extreme weather events, as the warm phase of the weather system El Niño appears across the globe. The weather system arises due to warm ocean water in the Pacific.

climate developments, as well as developments of climate policy. From the point of view of a financial investor, when trading off the expected returns and risks of such assets, an in-depth analysis of climate developments or climate policy would hardly be worthwhile. The aggregation of information already taking place in the market is so multi-faceted and voluminous that one can hardly hope to reach a basis for a conclusion that market valuations are wrong. An obvious underlying reason for such a belief in the predicting powers of market participants is the large financial rewards to be earned by those who predict best.

Information gathering is itself a process that can be seen as an economic activity. A rational investor will stop collecting more information when the expected marginal value of new information is less than the cost of collecting it, including analysis. This is known as a solution to the Grossman-Stiglitz paradox, see section 6.7.

The perspective of this overview is thus that information on all aspects of risks is relevant for a financial investor. But the details are too costly to collect and convincing analysis requires lots of resources, this is particularly true for climate related risks, because they are particularly large and complex. One cannot go into depth in all aspects of this topic, because this would be too costly. At the outset one should avoid neglect of any aspect of the phenomenon. Only by starting with a wide perspective will it be possible to narrow down to the essential parts in a rational way.

One needs to know the geophysical, meteorological, and biological risks that are associated with climate developments. One needs to know how these potentially will impact on the economy through various channels, and how this in turn may affect values of all types of assets. As part of such a perspective, climate policy is clearly essential, since current climate policies intend to incur substantial costs in order to avoid even more substantial damages. In many instances, those who gain from such policies are not the same as those who will bear the costs, implying a reshuffling of asset values. In particular, new forms of regulation and taxation are likely to be introduced without any compensation to those who lose. Perhaps there will also be a reshuffling between the formal and informal sector, due to, e.g, migration and conflicts. This may, in turn, have consequences for taxation and property rights. There will also be profit opportunities and new jobs in some industries. However, the net social welfare effect in the aggregate is highly uncertain and most likely negative.

In this process, a financial investor needs to know what kind of information gathering and analysis has been undertaken be other analysts and market participants. This is informative of data sources and methods, and one may learn from successes and failures. In particular, one would like to know whether some methods may lead to more reliable

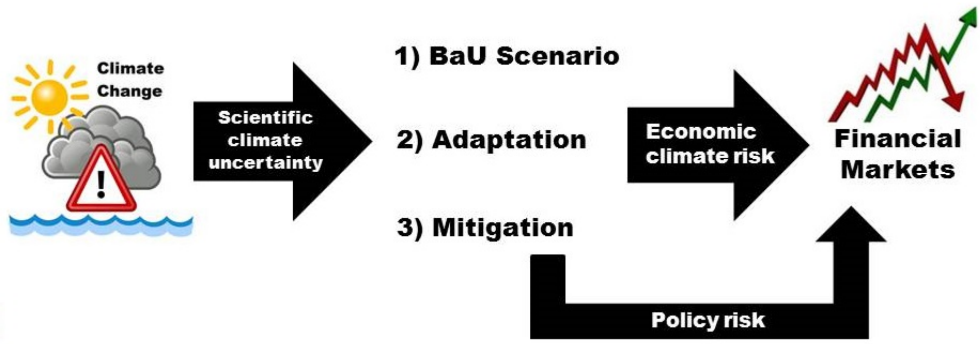

Figure 1: The outline of this overview

valuations than those already reflected in the market. This depends not only on methods one may use, but also on the functioning of the market, to be compared with. Thus it may be interesting to know whether and how the market has reacted to similar information before. Similar may be taken to mean climate-related, but information may also be similar in terms of uniqueness. Some potential climate events may be so unique in history that the only relevant comparison is with previous events that were completely unforeseen.

These ideas underly the structure of this overview. The perspective is broad. It starts with climate change itself, then goes on to consider the potential economic impacts. Then there are sections on possible policies, those to mitigate and those to adapt to climate change. This is followed by sections on the reactions to climate change, and related events, in financial markets. See figure 1 for an illustration of the outline.

The article proceeds as follows. In the next section the concepts of climate related risks are defined and discussed. Thereafter the analysis is threefold. First I discuss possible impacts from climate change in a Business as Usual (BaU) scenario. This is followed by two influence scenarios; affecting the impact through prevention and adaptation. The last section concerns the central topic of this overview, investigating climate risks in financial markets.

2 Climate related risks

Climate has always been unpredictable in a historical perspective. But in the latest decades human influence on the global atmosphere has extended this uncertainty significantly. Climate change is surrounded by complex uncertainties. There exist unanswered scientific questions about the outcome, such as nature's stabilizing effect, biological accelerating results and tipping points (the limit of nature's capacity). This is referred to as the **scientific climate uncertainty** characterizing the extent and magnitude of the outcome of climate change. Scientific refers to the natural sciences in this context.

Knowledge and research on this aspect of the climate related uncertainty is conducted by independent, reliable and methodologically unassailable research teams such as IPCC[3], NCA[4], NASA[5], the US National Academy of Science and the UK's Royal Society. These institutions provide the best information that science can provide about climate change. In this study the credibility of the research outcomes by these institutions is not assessed, but rather taken as given. There is good communication between the research fields of climate science and economics, such that the scientific uncertainty is essentially represented in economic climate models. In the article "Uncertainty in Environmental Economics", Pindyck (2007) provides a comprehensive discussion about uncertainties in climate change economics.

The decay rate of GHG in the atmosphere alters as the average temperature level increases. Recent discoveries about accelerating effects of the tundra meltdown (the Clathrate gun hypothesis), melting ice sheets and the shrinking of the poles, increase the likelihood of severe catastrophic damage fatal to life on earth. Of particular importance, when considering climate change, is the existence of threshold effects (Perman et al., 2011). At this point the decay rate of GHG suddenly changes in a discontinuous way. The economic climate damage will in the worst case reach 100% for high degrees of warming. Another important aspect is the irreversibilities of such threshold effects. This path dependence, where the history of emissions matter, is also known as *hysteresis*: "(...) reversing pollution pressures does not bring one back to the *status quo ex ante*" (Perman et al., 2011, p. 158).

The risk of interest in this analysis is the climate change impact on economic performance, presenting a relevant risk to the financial markets, including both economic and social uncertainty. **The economic climate risk** is defined as the uncertainty surrounding climate impacts on the economy. Most of this will also have consequences for financial performance. The economic climate risk is reflected in a probability distribution of all different future scenarios of the economy. Risk means that there may be both positive or negative surprises, and one can not exclude the possibility that climate change could create business opportunities.

The extent and timing of the economic climate risk outcome depend on actions today and how the global society chooses a strategy to manage the climate challenge, or does not. This can be represented by three different future scenarios: (i) The society follows

[3]IPCC: United Nations' Intergovernmental Panel on Climate Change
[4]NCA: The US government's National Climate Assessment
[5]NASA: National Aeronautics and Space Administration, Washington, DC

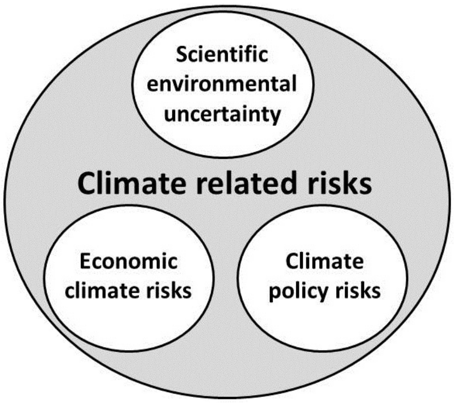

Figure 2: The aspects of climate related risks

a Business as Usual[6] (BaU) emission rate. (ii) Or society tries to prevent, either by imposing strict regulations on GHG emission or by developing a new technology. (iii) The last scenario considers attempts to adapt. Adaptation reduces the consequences of climate change by, e.g., adjusting trade patterns and production methods.

These scenarios are only rough outlines. The true outcome of climate change will be a complex mix of these three scenarios, with insufficient policies, violations, unforeseen scientific discoveries and trade-offs.

It is important to emphasize the difference between economic climate risk and the climate policy risk. In this overview these two types of risks are considered separately, although many scholars do not distinguish explicitly between them.

The climate policy risk is the uncertainty whether, when and how new regulations will be imposed, and what their impacts will be. The risk also include the uncertainty about which instrument regulators will choose to implement, e.g., taxes, quotas, bans, certificates, etc. The consequences of repricing carbon is twofold, it lowers the net price of the fossil fuel firms and it raises the output price to the consumers, affecting the heavy users (those with close to inelastic demand).

When repricing fossil fuels with taxation it affects the valuation of carbon intensive firms. If innovation is subsidized and new technology is developed, this may also affect the economic performance of firms, either because their production improves or their old technology becomes stranded.

In this overview climate policy risk becomes a part of the climate related risk in the scenario of mitigation, section 5.1, and it is discussed in relation to finance in section 6.3.

[6]BaU is defined as the projected growth path including the corresponding increase in emissions and climate change impact. Economists often use the concept BaU, even though such a path is highly uncertain, in particular when influenced by the related uncertain climate change and subsequent uncertain damages. More about the BaU scenario in section 3.

To summarize, the different types of climate related risks are (i) the scientific environmental uncertainty (Earth's climate sensitivity), (ii) the economic climate risk (economic impact and damages from climate change) and (iii) the climate policy risk (whether carbon prices and/or renewable subsidies are enforced), as illustrated in figure 2. All of these aspects of the uncertainty about climate change are parts of **the climate related risk**. It is important to keep in mind throughout this study that for each future temperature scenario of the economy there is an associated probability distribution of the scientific uncertainty about the outcome of climate change.

Why are the climate related risks different from other types of risks? And, in that regard, why should not the markets price climate related risks rationally? The climate risks are likely to be extraordinary because (i) they refer to new growth paths without historical comparison, and (ii) the potential consequences are fatal, in a much more fundamental way than any other type of risk, except nuclear war. The climate risks and its consequences are also to a little extent predictable, due to large gaps in the scientific knowledge of threshold effects and feed-back loops. Climate change is not fully understood by anyone.

This literature overview displays this variety of uncertainty, from economic modelling of the carbon cycle, together with translating global warming into damages, and suggests how future scenarios affect different sectors and financial markets. Scholars present completely different probability estimates of future scenarios beyond 2100. This variety is likely also to be reflected in financial markets, making an optimal pricing of the climate risk unlikely. The direction of the possible mispricing can go both ways.

Market participants have different understandings and approaches to types of climate related risks. One explanation of this lack of consensus is the complexity of the concept climate risks. It can be understood both as a systematic risk to industries and sectors, and as an unsystematic risk within specific businesses. Climate related risks include short term policy risks, litigations risks, reputational risks and long term physical risks.

2.1 Pricing the climate risk

Stock prices are affected both by direct regulations and by beliefs about future price paths. When new research is launched either by IPCC or other scientists the beliefs about climate risk are adjusted subsequently. Beliefs about climate risk are based on the financial market's predicted probability distribution. Nothing in the future stock markets is known with certainty, that is one of the main characteristics of the financial market.

The pricing of climate risk in financial markets concerns how the discount rates used to calculate the values of firms should be adjusted for risk. This is a difficult task, since many consequences of climate change have no historical precedent, and must be expected to change the covariance structure of all returns (and sector growth rates) in the economy. But it may be even more difficult to estimate the expected future cash flows of firms. According to standard terminology, this is not about the pricing of risk. The pricing of risk is the method to adjust an expected present value for risk. But first, one must know the expected future value. In the case of climate sensitive projects, it can be extremely difficult to estimate these expected values. For instance, we do not know the probability that a cotton field becomes worthless due to higher average temperatures (under BaU), or the probability that a coal mine becomes worthless due to climate policy.

Much of the research literature does not distinguish between theses two aspects, risk pricing versus reduced expected values. In the overview that follows, I have not tried to maintain the distinction. Clearly, parts of the literature could have benefited from clarifying this distinction.

In accordance with the Efficient Market Hypothesis, the most important decision of a financial investor is the composition of an optimal portfolio. But if the markets are not efficient, there may be more important decisions. It may be possible to gain from selling overpriced assets and from buying underpriced assets. This requires some reliable method for identifying mispricing, and for detecting when such assets are no longer mispriced. There are few studies of effects of climate change that explicitly attempt to identify mispriced financial assets. Andersson et al. (2016) rely instead on an assumption that if there is mispricing, it goes in a particular direction, i.e., overpricing of GHG emission intensive firms. However, Liesen (2015) explicitly tests for mispricing. She concludes that companies *reporting* GHG emissions are underpriced relative to those that do not, "(. . .) a trading strategy that goes long in companies reporting GHG-emissions and short in companies not reporting GHG-emissions generates an economically and statistically significant alpha (. . .)" (Liesen, 2014, p. 528). The assumption of Andersson et al. (2016) would be consistent with this if those who report are also those who emit less. Some of the event studies, see section 6.7.1, could perhaps also be viewed as tests of the EMH. But in the most cases they maintain the EMH and draw conslusions based on the EMH.

This overview attempts to cover international research that is relevant for a financial investor. This research has few studies that pay any particular attention to Norway. For the Norwegian government as a financial investor, van den Bremer et al. (2015) raise the question whether the country's complete national wealth should be considered, not the sovereign wealth fund (the GPFG) in isolation. Decisions on diversification would clearly be different, especially due to the still large remaining value of petroleum reserves and installations. Most likely, the divergence between the two objective functions is exacerbated due to climate risk, since petroleum assets become more risky.

In the remainder of this overview, however, the various objectives of diversification are not discussed any further. The diversification perspective is briefly mentioned in Skancke et al. (2014), see §§18, 32, 159 and 170, where they claim that the Norwegian Government Pension Fund Global (GPFG) is an inappropriate climate change tool as it could reduce the diversification of risk in the fund's investments, not the total Norwegian economy. There is not much research on the topic. Moreover, the current guidelines for NBIM do not allow the wider objective.

2.2 Risk and uncertainty

Dell et al. (2014) refer to climate as the distribution of weather outcomes summarized over decades, while weather is a particular realization from that distribution. Accordingly, climate change means a change to another distribution, or, perhaps, repeated changes. The new distributions may be unknown. In that case we could distinguish between uncertainty and risk as in Knight (1921). Risk implies that future events occur with measurable probability. Uncertainty means that the likelihood of future events is indefinite or incalculable. The relevance of this distinction for climate change is discussed by the IPCC (2007), section 2.3.2, but I will not maintain Knight's distinction in what follows. Lemoine and Traeger (2015, 2012) consider Knightian uncertainty in their treatment of climate related risk. An overview of recent research on the management of climate risk is given in Birkmann and Mechler (2015).

Particular attention has been paid to the possibility of probability distributions with 'fat tails', i.e., unusually high probabilities of extreme outcomes relative to the normal distribution. In particular, Weitzman (2010, 2011, 2013, 2014) has argued that under some conditions, investments should be evaluated based on their contribution under the worst outcomes. Based on theoretical models, he shows that "seemingly insignificant differences in discount rates can make an enormous difference in the present discounted value of distant-future payoffs" (Weitzman, 2010, p. 1). See section 2.5 in this overview for more on the issue of discounting. Other contributions on this topic are Pindyck (2007, 2011), Nordhaus (2011), and Calel et al. (2015)

2.3 Endogenous or exogenous risk

Are the climate risks endogenous or exogenous? Since climate change is a global problem the impact is exogenous for a single firm or an individual, i.e., exogenously given by nature.

However, for the economy as a whole climate change is endogenous due to the fact that it's caused by human activity. Emissions are derived from production, consumption and other economic activity, and the flow to the atmosphere can be regulated by national or international policies. Chichilnisky and Heal (1993) emphasize the important difference in traditional economic theory when the risks are endogenous. The Arrow-Debreu framework with exogenous risk is therefore not suited to the case with climate change, according to Chichilnisky and Heal (1993). Several scholars discuss the endogenous probability of bad outcomes of climate change, see Nævdal and Vislie (2008, 2013) and section 2.4.

The question is whether there exist financial agents that have sufficient influence on the global market such that for this agent alone the climate risk is endogenous. Should this agent then change its investment strategy in such a manner that it moderates the impact of climate change? Following economic theory all agents would rationally try to mitigate global warming if the risk of a potential loss exceeds the cost of investing in mitigation. This is followed by a second question, is the climate risk sufficiently understood by the market? Investments in mitigation are discussed further in section 5.1, and an answer to the last question is outlined in section 6.

2.4 The economic climate models

The economic climate models try to combine the scientific discoveries and facts about global warming into an economic model that estimates the marginal damage cost of climate change, how the cost changes in different scenarios and how it is affected by different policies. Estimates of the social cost of carbon (SCC) are interpreted as the optimal carbon tax. The definition of climate models is broad, and includes a variety of climate models such as Stern (2007) and Nordhaus (2013). However, their common structure is the combination of economics and scientific facts about global warming.

The aim of this type of models is to inform the society, the market and policy makers about the economic cost of climate change. Policy makers can employ the estimated value of SCC as a tool in cost benefit analysis and climate regulations. Canada, Mexico, the United Kingdom, France, Germany, Norway and the US use estimates SCC in climate policy decisions (Revesz et al., 2014). An overview of different estimates are given in table 1.

The models translate the economic activity that produce emissions into the atmospheric concentration of GHG causing global warming. Increased temperatures are transformed into economic damages with an estimated damage function. Finally these future damages are represented as present monetary values, named SCC. SCC are in marginal terms, characterizing the the cost of one more unit of emissions (carbon). This type of models, that integrate several academic disciplines, such as economics and climate science, are called integrated assessment models (IAM). The literature on climate models and IAMs is growing, and the models are continuously updated and improved. Some of the most common climate models are commented briefly below.

William D. Nordhaus is the pioneer of developing climate models (Nordhaus, 1991a,b), establishing the DICE model (Dynamic Integrated Climate-Economy model) and later the RICE model (Regional Integrated Climate-Economy model) with a probabilistic extension named PRICE (Nordhaus, 1992, 1993; Nordhaus and Popp, 1997). A similar IAM model that is based on the neoclassical framework is the WITCH model (World Induced Technical Change Hybrid) by Bosetti et al. (2006, 2007).

Golosov et al. (2014) use a dynamic stochastic general-equilibrium (DSGE) model, similar to DICE, where the environmental damage is assumed to be proportional to GDP. This proportion depends on three assumptions, the discount factor, the damage elasticity and the atmospheric depreciation.

Hassler and Krusell (2012) have developed a multi regional IAM model with a closed form solution. The IAM model by Hassler and Krusell (2012) is a simplification of Golosov et al. (2014), based on basic assumptions, such as logarithmic preferences, full depreciation of capital (over the course of a decade), Cobb-Douglas production technology, linear carbon cycle and economic damages being linear in the stock of carbon. Both Hassler and Krusell (2012) and Golosov et al. (2014) argue that these assumptions are quantitatively reasonable. The simplicity of these climate models, and the transparency of their assumptions, improve the access and understanding of complex climate models although they are not completely realistic.

Other climate models are the FUND model (the Climate Framework for Uncertainty, Negotiation and Distribution) by Tol (1997), the IMAGE model by Rotmans (1990) and the PAGE model (Policy Analysis of the Greenhouse Effect) used by Dietz et al. (2007a).

It is self-evident that climate models are grounded on assumptions that are uncertain. The complexity of Earth's climate system makes it close to impossible to predict how changes in global temperatures will manifest at a regional level. It is not feasible for a programmed model to cover all effects from global warming. There is considerable uncertainty about how changes in sea level and temperatures will affect different sectors of the economy, and how these impacts will interact.

There still remain many unanswered questions in the field of climate science, especially related to the sensitivity of the climate system. Some climate effects are linked, causing feedback effects that may accelerate the GHG concentration in the atmosphere. Unexpected stabilizing feedbacks could also act in the opposite direction, slowing down the global warming process. The main concern is especially related to abrupt and irreversible changes in the climate. The existence of such mechanism is known, but they are at present not understood well enough. The possibility that global warming reach critical thresholds is often referred to as tipping points. Such high-risk tipping points are by definition hard to predict, and most scholars consider them as unlikely in this century. However, that the warming increases the possibility of abrupt climatic changes cannot be ruled out.

The IAM models by Gerlagh and Liski (2012); Golosov et al. (2014); Nordhaus (2008); Stern (2007); Tol (2002) do not consider irreversible catastrophic events by construction. Several scholars, including Pindyck (2013), is very critical to these models for this reason. Pindyck warns against making decisions that rely on the estimated SCC from IAM models: "(...) their use suggests a level of knowledge and precision that is simply illusory, and can be highly misleading" (Pindyck, 2013, p. 862).

There has been a growing concern that the climate models underestimate the damage and the social cost of carbon. Stern (2013) worries about the disconnection between the potential consequences described by climate scientists and the economic impact derived by climate models: "The economic models add further underassessment of risk on top of the underassessment embodied in the science models (...)" (Stern 2013, p. 839). The climate models assume exogenous drivers of economic growth, modest damages and a narrow distribution of potential risks. Some models even exclude the probability of catastrophic risks. According to Stern, such economic models would substantially underestimate the economic risks of climate change.

Revesz et al. (2014) agree with Stern, and point out four reasons why the climate models predict too low carbon costs. Some IAM models overlook the importance of weather variations, they fail to estimate the impact on productivity growth and they forget the cost of future ecosystem damage. Both Stern (2013) and Revesz et al. (2014) agree that climate models are incomplete but still useful, encouraging economists and scientists to collaborate and reform the models assessing how they underestimate the results. However, Pindyck (2013) has a more depressed view on climate models, arguing that IAMs are close to useless as tools in policy decisions: "What have these IAMs (and related models) told us? I will argue that the answer is very little" (Pindyck 2013, p. 861).

Applying an IAM model requires numerous difficult modeling decisions. When deriving a climate model, four indirect assumptions are made concerning the discount rate, the risk aversion, the climate sensitivity and the shape of the damage function. Pindyck (2013) stresses the importance of these four assumptions as they are essential in determining the monetary value of SCC. In particular, the models' shortcomings become crucial when considering threshold effects and potential catastrophes: "IAMs cannot tell us anything about catastrophic outcomes, and thus cannot provide meaningful estimates of the SCC" (Pindyck, 2013, p. 869).

Most optimization based IAM models are deterministic. Recently there have been several scholars developing climate models that include stochastic elements, such as tipping points. Amongs other are Cai et al. (2015); Golosov et al. (2014); Hambel et al. (2015); Hassler and Krusell (2012); Lemoine and Traeger (2014). These type of models are referred to as 'dynamic stochastic general equilibrium models'. Optimal policy strategy is based on uncertainty and the optimal strategy is adjusted as the stochastic process evolve. This might be a more appropriate model of actual decisions related to climate change (Kelly and Kolstad, 1999). Deterministic models that are based on scenarios will not derive the optimal state dependent policy with respect to the climate uncertainty. See section 2.6 for more on the modeling of tipping points.

Relating the discussion about climate models to the financial markets, we see what difficulties estimating the climate risk brings about. Equivalent problems in estimating the social cost of carbon are likely to be present in estimating the climate risk for financial markets. One may conclude from this that it is close to impossible for the financial market to approximate the impact, and the probabilities of different climate change scenarios as long there is lack of scientific support. However, this does not necessary imply that financial markets underestimate the climate risk, but valuation is most likely wrong, in one way or the other.

A more positive view on the possibility of estimating economic effects of climate change is suggested by Quiggin (2012, 2013). He finds that a relatively simple model may give a fairly robust representation of more complex realities. Optimal policies can be calculated, that are "robust to quite large changes in estimates of the most uncertain input parameter, namely, the cost of unmitigated climate change under business as usual" (Quiggin 2013, p. 4).

2.5 Discounting

Mark Carney, Governor of the Bank of England, characterizes the climate change problem as the tragedy of horizons (Carney, 2015). The possible catastrophic impacts from climate change may occur beyond the time horizon traditionally considered, and are therefore less relevant for current decision making. The horizon for policy makers tends to be the next election. Financial stability follows the horizon of the credit cycle, up to a decade. The perspective of short run in financial markets may count days. Long run investments funds may plan 100 years ahead. However, the climate problem concerns all future generations giving a time horizon for several centuries.

This is an extremely long horizon. The mitigation costs must be paid by the current generations and the avoided damage will benefit future generations. In economics, the value of time is expressed by the level of the real discount rate. With high discount rates the distant future is less emphasized, and the net present value (NPV) of future benefits is low. Therefore, when considering problems with long time horizons, the choice of discount rate is crucial.

Scholars have disagreed upon the appropriate choice of the numerical value of the discount rate related to climate change (Dasgupta, 2008). The academic disagreement between Nordhaus and Stern represent two extreme perspectives. Nordhaus (2008) claims that a real discount rate of 5% is socially efficient, computing the NPV with the DICE model, finding that the future economic damage from a tonne of emissions today is $8. The Stern Review (Stern, 2007) calculate a NPV of $85 per tonne of CO_2 emissions (year 2000 prices) when using a real discount rate of 1.5%. The discount rates used in the Stern Review ranges between 0.1% and 1.5%, the choice of discount rate is partly based on distributional and ethical considerations.

The book *Pricing the Planet's Future* by Gollier (2013) discusses the different aspects of the economics of discounting. The important issues related to the climate change problem are long time horizons, the risk of extreme events (Barro, 2006), uncertain economic growth (Gollier, 2008; Gollier and Weitzman, 2010; Weitzman, 2009, 2010) and the discounting of non-monetary benefits such as the ecological environment (Gollier, 2010).

2.6 Tipping points

Tipping points are often defined as discontinuities in the marginal economic damages from climate change. Such discontinuities may be caused by marginal changes in global mean temperatures that exceed an unknown *natural* threshold, unleashing feedback loops of GHG gases that cause irreversible and abrupt climatic changes. Possible candidates for such tipping points are deforestation of the Amazon rain forest, the Arctic methane release from the melting tundra, weather phenomena like El Niño and the retreat of the Greenland ice sheet and the West Antarctic ice sheet (Lenton et al., 2008). Some scholars argue that the probability of such outcomes increases with global warming (Kriegler et al., 2009), but according to Lenton (2011) this is highly and fundamentally uncertain.

In the study by van der Ploeg and de Zeeuw (2013), they refer to such tipping points as non-marginal regime switches, claiming that this type of modeling is common in natural sciences. They model such tipping points as a shift in the economy, from high productivity

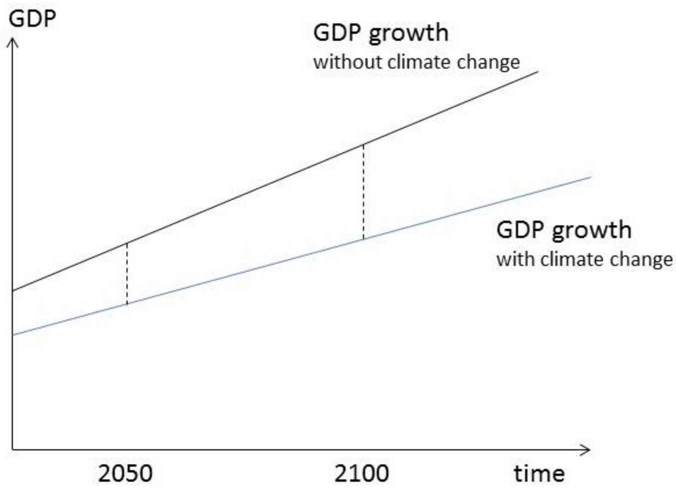

Figure 3: Economic climate cost on GDP

to a future regime with lower productivity. Regimes differ in steady state capital stock, the carbon stock, output and consumption. This analysis is based on small Poisson risks of catastrophic events, a complement to the estimates of SCC based on fat-tailed uncertainty.

Several scholars include the uncertainty following potential tipping points into IAM models (Lenton and Ciscar, 2013; Lontzek et al., 2015). Nævdal (2006) derives the necessary conditions for optimal control of threshold effects and catastrophic risk. Another strand of the literature analyzes the policy impact of tipping points, and van der Ploeg (2014) derives an extra component on the optimal Pigouvian carbon tax to curb the risk of tipping points. Studies by Lemoine and Traeger (2014, 2015, 2012) also find that a potential tipping point raises the optimal carbon tax. This result is derived by simulations with a recursive, numerical climate-economy model.

2.7 Economic cost of climate change

IAM models are primarily used to conduct cost-benefit analysis at the global level. The cost of climate change is quantified through damage functions, providing discounted monetary estimates of different temperature scenarios (different increases in average global temperatures). The cost is often expressed as a percentage loss of world GDP, and the economic costs are generally presented as global aggregates with no subnational geographic or sectoral details. IAM models that do estimate consequences for sectors, such as energy and agriculture, are named process-based IAMs (Calvin et al., 2013; Reilly et al., 2013).

When estimating the cost of climate change some scholars refer to reduced growth and others to loss of output, these two terms refer to the same cost. Figure 3 illustrate how these two concept are related. The graph measures time on the horizontal axis and estimated future GDP on the vertical axis. GDP loss is interpreted as the difference of the potential outcomes with and without climate change in, e.g., year 2050 or 2100. The growth reduction is how the ratio of the two lines evolves over time, as in this figure the GDP loss in 2050 is smaller than in 2100 for these specific scenarios. In this figure the economic risk of climate change is illustrated as a cost (decrease in GDP) although the risk may yield positive surprises and business opportunities. However, on an aggregate level, looking at the world as a whole, the aggregated cost and damages are likely to exceed the regional and private benefits.

Many models predicting the outcome of climate change on economic growth assume a steady positive future growth. However, long run economic growth is highly uncertain. The study by Jensen and Traeger (2014) evaluates the impact on the SCC in a stochastic IAM with long run growth uncertainty. They find a higher optimal carbon tax than the deterministic DICE base case calibration.

A newly published book, *Economic Risks of Climate Change: An American Prospectus*, by Houser et al. (2015) contributes to the field by systematically analyzing the risk of climate change for the US economy. The book represents the research conducted by the Risky Business Project at the University of Chicago, in its entirety. It is an independent and analytically rigorous effort to fill the gap between climate science and economics, with the aim at updating the business sector and investors about the potential climate risk.

The comprehensive study uses a type of IAM model that includes both climate modeling of temperatures, sea levels and extreme weather together with econometric research on sectoral and regional economic impacts. The study by Houser et al. (2015) is distinguished from previous IAM models by focusing on sectors, states and regions across a range of potential climate futures. The US economy is scaled down to five important sectors; agriculture, energy, coastal property, health and labor. The study both looks at how sectors are directly affected, and how the impacts ripple throughout the regions and the country in the short run (2020-2039) and in the long run (2080-2099).

3 Business as Usual

The Business as Usual (BaU) scenario is defined as the outcome of global warming in absence of any regulation and mitigation policy, where the economy continues to grow at today's growth rate. IPCC concludes that a continued flow of emissions without any attempt to mitigate or adapt will cause further warming and increased likelihood of irreversible impacts on the economy (IPCC, 2014b). The extent of climate change is complicated to estimate because of the unknown relation between different ecosystems and feedback temperature effects. However, although the extent is unknown, the likely effects are sufficient for a fruitful discussion on the likely impact of climate change on the financial system.

> Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is *very likely* that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise.
>
> (IPCC, 2014, p. 10)

Climate change impact on consumption and production possibilities should be broadly understood. Below we differentiate the different impact scenarios and explain each of them briefly, referring to the existing literature on the topic. However, one effect will most likely not arrive alone and the realized consequences of global warming will be a complex mix of these scenarios.

3.1 Direct climate change impacts

3.1.1 Rising temperatures

The direct effect of climate change is global warming and rising temperatures. Human activities emit greenhouse gases (GHG) to the atmosphere at a faster rate than natural processes remove them. This increases the atmospheric concentration of GHG, trapping infra-red radiation such that the earth's average temperature increases. Global warming leads to climatic changes unevenly distributed around the earth, characterized as the climate change problem. Surface temperatures over land regions increase at a faster rate than temperatures over oceans. The warming is higher in the northern latitudes, and the world will experience an increase in extreme temperatures and heat waves (IPCC, 2007).

Increased temperatures will be the underlying cause of several indirect effects on the economy, affecting productivity, health and production. An interesting study by Bansal et al. (2015) finds that variation in temperatures (how the temperature level fluctuates over time), that is related to climate change, has significantly negative effect on stock prices. Bansal et al. (2015) use this empirical result to investigate the interaction between global warming, economic growth and risk in a theoretical model. In this model rising temperatures have a negative effect on the macro-economy, by raising the economic risk and reducing growth. This study will be further discussed in section 6.

3.1.2 Uneven geographical distribution

When temperatures rises, due to global warming, the regional climatic change is not expected to be uniformly geographically distributed across the world (IPCC, 2014b). In particular, ocean temperatures rise more gradual and slowly than land temperatures, and the temperature in the northern latitudes increases faster than in the tropics. The impacts of climate change are not only unknown but also unbalanced between different regions. The Climate Risk Index is an annual report by Germanwatch where past damages and losses related to weather events are estimated based on available data. Their report, Germanwatch (2015), uses data from 1994 to 2013. Asking who suffers most from extreme weather, they find that less developed countries are in general more vulnerable (Germanwatch, 2015). Their index is based on national cost of damages and death toll. The highest risk of catastrophic weather events is centered around South Asia, Mexico and Madagascar. The countries that lead the list of the most affected are India, the Philippines and Cambodia. In Europe the countries facing the highest weather risk are Italy and Portugal (Germanwatch, 2015).

Desmet and Rossi-Hansberg (2015) analyze the geographic impact of climate change when warming differs across latitudes. The model incorporates the spatial distribution of climate change on economic activity including; trade, migration, growth and welfare. This framework analyzes global warming in a dynamic context, quantitatively assessing the impacts of migration, trade restrictions, energy taxes and innovation subsidies. Production and population should be shifted to the north as the south becomes unbearably warm. Since the north has better technology and solid institutions this could lead to a small positive welfare effect in absence of migration restrictions. The presence of migration restriction, and other frictions, should therefore be included in the political debate on climate change to benefit from these potential opportunities.

3.1.3 Sea-level rise

The physical impact of sea level rise are submergence, flooding of coastal areas and saltwater intrusion of fresh surface water (IPCC, 2007). In the long run the saltwater may infect the groundwater and coastal areas will adjust through erosion and drainage. Nicholls and Cazenave (2010) state that the extent of future sea level rise, and their impacts, remains highly uncertain: “These physical impacts in turn have both direct and indirect socioeconomic impacts, which appear to be overwhelmingly negative” (Nicholls and Cazenave

2010, p. 1518).

Pycroft et al. (2015) estimate the global economic cost of sea-level rise using a computable general equilibrium model for 25 world regions, incorporating both direct impacts on the coastline and indirect impacts further inland. The study suggests that a sea level rise corresponding to 1.75m (the highest 2080 scenario) will cause a loss of 0.5% of global GDP, with a 2% loss of welfare: "Within these aggregates, there are large regional disparities, with the Central Europe North region and parts of South-East Asia and South Asia being especially prone to high costs (welfare losses in the range of 412%)" (Pycroft et al., 2015, p. 1).

The study by Bosello et al. (2012) considers several potential impacts from sea level rise, finding that the loss from submergence will exceed the loss due to erosion. They state that coastal protection and adaptation is effective in preventing migration. The scholars find that the indirect economic impact from sea level rise might be positive or negative. It will boost international trade and increase competitiveness for landlocked countries such as Austria and Switzerland. The positive effect is lowered by costly investments in coastal protection.

Hallegatte et al. (2013) quantify the potential future flood losses and the vulnerability of assets in the 136 largest coastal cities, taking into account infrastructure-based adaptation such as dykes. They find that the aggregated losses will increase from the present US$6 billion to US$60-63 billion annually in 2050 (incorporating constant adaptation investments). The most vulnerable cities that will experience the highest annual losses in absolute terms are Guangzhou in China, Miami, New York and New Orleans in the US. These are rich cities, and likely better protected than those in the developing world. The authors points out the limitations of what infrastructure adaptation can achieve due to climate change, causing longer floods and disasters such as hurricanes: "Last, improving standards of protection could maintain or reduce risk levels and decrease the number of floods, but the magnitude of losses when floods do occur will still increase" (Hallegatte et al., 2013, p. 805).

3.1.4 Extreme weather

Weather and climate factors have a vital and substantial influence on economic outcomes such as health, productivity, economic growth and energy demand. Moreover, as global temperatures are expected to rise, these relationships have eminent importance. The main scientific consensus regarding climate change is increased likelihood of extreme weather. Extreme weather and natural disasters, such as cyclones, storm, forest fires, drought, floods and landslides will have a direct effect on financial markets through physically damaged capital. Indirectly the weather affects crop yields, productivity, political stability and health that again affect financial values.

To clarify the difference between the words climate and weather I follow Dell et al. (2014), referring to climate as the distribution of weather outcomes summarized over decades, while weather is a particular realization from that distribution. Another characteristic of climate is the fixed spatial correlation. The climate is the same for neighbor countries while there are large static differences between geographical regions. In other words, the north is always colder than equator on average but can be commonly affected by global wind system, ocean currents and ocean-atmosphere phenomena like La Niña and El Niño. Spatial correlation occurs when the relative outcome between two location points depends on their distance.

A growing body of research uses the variation in weather over time to study the possible impact on economic outcomes. Dell et al. (2014) contribute with a detailed overview of recent studies on "the new climate-economy literature" and an introduction to the methodology of exogenous weather shocks. Overall the studies conclude that temperature and extreme weather will increasingly exert statistically significant influence on economic outcomes (Dell et al., 2014). These studies have applications both for policy responses, technological innovation and for the estimation of the economic cost of climate change.

3.1.5 Freshwater scarcity

Global warming will cause glacier melting and sea level rise. The mountain ice and runoff from glacierized basins contain the only fresh water supply for many societies across the globe. As the permanent ice in the mountains disappear, rivers and water wells may dry out. Glaciers are one of the most important fresh water supplies in arid regions of western China (Liu et al., 2003). Research has also focused on the potential impact on the electricity sector as several energy sectors are highly water dependent, such as hydropower and the coal intensive thermal electricity generation. "More than half of existing and planned power plants by the biggest publicly traded companies in India and Southeast Asia are in areas likely to face water shortages, according to the World Resources Institute in Washington" (Pearson, 2012). The geophysical study by Vergara et al. (2007) finds that rapid glacier retreat in the Andes will have profound effect for the electricity supply in Ecuador and Peru.

Several regions across the world will experience climate change induced reduction of crop yield, e.g., through limitation in water supply (Rosenzweig et al., 2014). Elliott et al. (2014) study water availability for agricultural production under climate change, suggesting that regions with freshwater scarcity could necessitate the reversion of 20-60 Mha of cropland and a loss of 600 - 2900 Pcal of food production. There is also an extensive literature on climate change and its impact on winegrapes and wine production, for a summary of the recent literature see Mozell and Thach (2014).

Another aspect of possible water scarcity is that sea level rise may infuse the groundwater, destroying fresh water supplies in areas close to the ocean surface.

Freshwater limitations are, additional to being a substantial social threat for many civilizations, also a climate risk for the financial markets as they affect production in several sectors: "(...) changing weather patterns, local water availability, and water quality may have a significant impact on asset value across the economy" (Caldecott and McDaniels, 2014).

3.2 Production: Agriculture

Two of the main inputs in agricultural food production are water and temperature. The production output and rural income are therefore heavily dependent on weather, such as rain, flood and droughts, and climate such as temperature variations. Agriculture and climate change have been the main focus in weather related research recently and a great body of literature has developed.

In chapter 8 in IPCC (2007) the main concern related to agriculture is the sectors' contribution to the worlds total GHG emissions. However, in chapter 7 in IPCC (2014a) the perspective has shifted towards food security and climate risk to food production:

> The effects of climate change on crop and terrestrial food production are evident in several regions of the world (*high confidence*). (...) All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*).
>
> (IPCC, 2014a, p. 488)

Results from studies on the climate change impact on agriculture vary substantially, due to different models, scenarios and data sets (Nelson et al., 2014b). Nelson et al. (2014a) try to systematically investigate how different global economic models of agriculture represent responses to standardized climate change scenarios produced by climate models. They find that the relative magnitude of production reduction on food price increase varies widely across models: "(...) the models disagree on whether area or yield responses will be most important locally, and on the role of exploiting international comparative advantage" (Nelson et al., 2014, p. 3278).

Calzadilla et al. (2013) stress an important perspective for those applying agricultural models that project future crop yields. Climate change is likely to modify the water endowments and soil moisture, and, as a consequence, change the distribution of harvested land. These effects will also be affected by the corresponding changed production, food prices and trade patterns (Calzadilla et al., 2013). They find that the expected loss in welfare is significant, in all considered scenarios of climate change.

IPCC highlight the potential major climate risk for African agriculture and food security. Müller et al. (2011) state that "agriculture everywhere in Africa runs some risks to be negatively affected by climate change" (p. 4313). Knox et al. (2012) systematically review the data in 52 publications, investigating the projected impact of climate change on major crops in Africa and South Asia. They show that the estimated mean in yield for all crops will decrease by 8% by 2050 in both regions. There was not detected any mean change for rice. In the more national specific study on domestic agriculture in Tanzania, Arndt et al. (2012) find that food security is likely to deteriorate as a consequence of climate change.

Studies using standard panel methods and weather shocks estimate a consistently negative effect of temperature changes on agricultural production in developing countries (Feng et al., 2010; Guiteras, 2009; Schlenker and Lobell, 2010; Welch et al., 2010). Other studies find a significant negative impact of low rainfall on agriculture output in developing countries (Hidalgo et al., 2010; Jayachandran, 2006; Yang and Choi, 2007). Developing countries are especially vulnerable for climate change both because heat stress will increase the frequency of droughts, and they have less capacity to adapt.

Some scholars have predicted positive agricultural effects from climate change. Ciscar et al. (2011) include the impact from adaptation policies into their multi-regional assessment model on Europe, finding that Northern Europe is the only region that will experience positive net benefits driven by improved agricultural output.

Deschênes and Greenstone (2007) estimate the economic impact of global warming on agriculture in the US, using random year-to-year variations in temperatures. They find no significant relationship between agricultural return and weather in the short run, concluding that climate change will increase profits by 4% annually when incorporating adaptation possibilities. This study has been replicated by Fisher et al. (2012), and when correcting data errors they find a negative impact on returns from climate change.

According to Dell et al. (2014) many of the studies in this field base their results on short run weather variations. However, climate change has long run implications giving time for adaptation mechanisms and technology to develop. Dell et al. (2014) stress the importance of adaptation, intensification, price changes and reallocation of factors when considering long run climate change.

Rosenzweig et al. (2014) present a comparison of multiple global gripped crop models (GGCMs) finding a strong negative effect on agricultural yield of climate change. A meta-analysis conducted by Challinor et al. (2014) on the data of more than 1700 published crop yield simulations, finds that aggregate production will decrease for wheat, rice and maize in both temperate and tropical regions by 2°C warming.

Houser et al. (2015)[7], assuming that current farming practices continue, find that the likely (over 67% probability) cost of change in yields for the US under RCP 8.5[8] range from an average annual direct cost of -$8.5 billion[9] to +$9.2 billion in the short run (2020-2039) and -$12 billion to +$53 billion in the long run (2080-2099) The authors characterize these effects as modest, compared to the overall US economy, and these estimates do only account for 1/3 of the US agricultural output value.

This literature mainly focuses on the effect from temperature on agricultural return. However other possible impacts on agriculture from climate change could include, e.g., soil degradation, local water stress, biodiversity, pollinating insects and wildfires.

Valin et al. (2014) review how food demand is approached in 10 global economic models. To understand the capacity of the agricultural sector requires precise projection of future food demand. By comparing estimated food demand in 2050 for various regions under different scenarios of climate change, they find that food demand increases by 59-98% until 2050 in the reference scenario, slightly higher than the most recent FAO[10] projection of 54%. However, the results are more sensitive to socioeconomic assumptions, such as population growth and economic growth, than climate change.

An important methodological point is made by Quiggin et al. (2010). They consider projections of effects of climate change on irrigated agriculture in parts of Australia. They are particularly concerned about uncertainty. Based on simulation of state-contingent production, they claim that "deterministic analysis of the impact of climate change may be seriously misleading. In particular, whereas intuition derived from a nonstochastic analysis implies that an increase in the scarcity of water should imply an increased allocation to high-value horticultural crops, a state-contingent stochastic analysis yields the opposite result" (Quiggin et al., 2010, p. 547).

This section only considers agriculture, but other affected industries that may face the same challenges as agriculture could be ocean fisheries, forestry and resource and mineral

[7]The model by Houser et al. (2015) is explained in more detail in section 2.7

[8]RCP: Representative Concentration Pathways, four GHG concentration (not emissions) trajectories adopted by the IPCC. The four values are named after a possible range of radiative forcing values in 2100, relative to pre-industrial values

[9]Note that a negative cost implies a benefit following the formulation by Houser et al. (2015)

[10]Food and Agriculture Organization of the United Nations

extraction.

3.3 Productivity in general

Several studies have confirmed the relationship between high indoor temperatures (over 25°C) and worse performance. The meta-analysis by Seppänen et al. (2006) documents a productivity loss about 9% for indoor temperatures between 23°C to 30°C. In a newly published report by the global risk analytic company Verisk Maplecroft (2015) they found that increased heat due to climate change might reduce labor productivity with 25% in South East Asia for the next 30 years. Increased temperatures and heat stress will lead to reduced working hours due to dizziness, fatigue and nausea and even death in the extreme cases (Verisk Maplecroft, 2015).

Another study by Graff Zivin and Neidell (2014) looks at labor supply and weather fluctuations. They find that especially warm days reduced labor supply in outdoor sectors such as agriculture, forestry, mining and constructions. This study is based on high-frequency micro data, similar to the study by Schlenker and Roberts (2009) with focus on damages to crop yields, that can be seen as a component of economic productivity.

Houser et al. (2015) estimate the likely (over 65% probability) annual labor productivity costs in the US, given the current sectoral mix, are +$0.1 billion to +$22 billin in the short run (220-2039) and +$42 billion to +150 billion in the long run (2080-2099). These estimates on labor productivity suggest a considerable impact on the US economy.

3.4 Indirect social effects

3.4.1 War and social disturbance

There is a rapidly growing literature on the linkage between climate and human conflict. Random weather events should not be interpreted as changes in the global climate, even though they may be an attribute of climate change (Hsiang et al., 2011). Literature has shown how resource and commodity price fluctuations may lead to social and political disturbance and in the worst case be the driving factor of civil wars and conflicts (Brückner and Ciccone, 2010). Food price fluctuations are a likely outcome of climate change when extreme weather and increased temperatures damage crops and reduce rural income.

Scholars have investigated the consequences of global warming and extreme weather on geopolitical scenarios. Harari and Ferrara (2014) study civil conflict in Africa over the period 1997 to 2011 related to shocks in agriculture due to within-year weather variation. The analysis os disaggregated, both in space and time, taking a 110×110 km subnational area cell as the unit of observation to construct a cell-year panel. A challenge for the empirical conflict literature is that conflicts may be persistent over time and correlated across geographical space. By disaggregating both climate indicators and conflict outcomes on the cell level, they detect how persistent the effects are both over time (long lasting political instability) and space (conflict spillovers across locations). They show that negative climate shocks whitch occur during the growing season have a persistent effect on conflict incidence. Shocks occurring outside the growing season have no impact (Harari and Ferrara, 2014).

Despite the large body of studies, the panel data results are ambiguous. It has been shown that lower rainfall (Miguel et al., 2004) and extreme heat (Burke et al., 2009) spur conflict in Africa. The concept of "conflict" in empirical studies is often defined as those fights where total deaths exceed a given threshold. Couttenier and Soubeyran (2014) find that the Palmer Drought Severity Index has a positive effect on conflicts in sub-Saharan Africa when controlling for variables that are not correlated with conflict. This effect disappears when the data are extended to a wider time period (Ciccone, 2011). Dell et al. (2014) discuss reasons why it is difficult to isolate the effect of weather shocks. Common issues are endogenous controls, omitted variables and non-included spatial correlation of weather measures in different data sets. There is also a problem with heterogeneity, where wealthy countries with stable institutions do not experience the same level of civil conflict (Dell et al., 2014).

Hsiang et al. (2013) have conducted a reanalysis and a comprehensive synthesis of the growing literature on conflict and climate change. The type of conflicts studied range from violence between minor groups to profound conflicts leading to institutional breakdown and collapse of civilizations. Hsiang et al. (2013) focus on empirical studies that apply "natural experiments" to find the causal effect of climate deviation on social disturbance. Their meta-analysis state that climate's influence on conflict is highly statistically significant, concluding that temperature deviations substantially increase the risk of conflicts.

Houser et al. (2015) investigate the effect of climate change on crime in the US. The likely change in property and violent crime costs is on average \$0 to \$2.9 billion by 2039 and \$5 to \$12 billion within 2099.

3.4.2 Health

In a newly published article in *Nature Climate Change*, Pal and Eltahir (2015) find that the Arabic Gulf is a specific regional hotspot in the literal sense. The region around the Arabic Gulf will most likely exceed the critical threshold level of habitable temperatures in a BaU scenario of global warming. Although one can adjust indoor temperatures by using air conditioner in the region, even the most basic outdoor activities are likely to be severely impacted (Dunne et al., 2013; Pal and Eltahir, 2015). The poor countries in the region will suffer from both indoor and outdoor uninhabitable climate, detrimental to the health of the inhabitants.

Researchers in economics and other fields have investigated the relationship between high and low temperatures on health and mortality. Several scholars have stated that extreme heat, or extreme cold in some cases, increases the mortality rate (Barreca, 2012; Curriero, 2002; Deschênes and Greenstone, 2011). The elderly, infants, and children are highly vulnerable for extreme outdoor temperatures. This is one of the reasons why developing countries are assumed to be most severely affected by global warming. However, when these scholars analyze total death over a period they might pick up the impact of "harvesting" (Dell et al., 2014). One specific day with extreme temperature could cause death of someone who would have died shortly after without any weather shock. In the study by Deschênes and Moretti (2009) the mortality effect of extreme heat is neutralized by lower mortality rate in the subsequent week. A survey of the literature on climate and health outcomes is given by Deschênes (2014), where methodological issues and gaps in the empirical literature are discussed in detail.

Hajat et al. (2014) look forward and estimate mortality rates associated with changed weather patterns. Future changes in climate would alter the risk of increased mortality. Their method is based on historical weather and mortality data applied to projections about populations trends and climate. Climate projections include a subset of regional climate models with a sensitivity in the range of 2.6°C to 4.9°C. They expect heat-related deaths to rise by 257% within 2050, and cold-related death would decrease by 2%. However, it is important to note that this result is partly driven by ageing and population growth (Hajat et al., 2014).

Another possible impact on global health would be the spread and development of diseases due to a warmer climate. Cholera and malaria epidemics are often caused by heavy rains and warmer climate in poor regions. The article by Altizer et al. (2013) highlights the progress of research on the issue of infectious diseases in presence of climate change. Affected agents are broadly understood, including affected animals, plants, agricultural systems and humans.

3.4.3 Migration

Myers (2002) writes about the new phenomenon of environmental refugees. Individuals lose a secure and stable livelihood because droughts, floods and erosion destroy their living. Others will seek sanctuary because their home area is unbearable due to increased temperatures or rising sea level. This includes both national and international migration;

not all will abandon their homeland but instead move to safer regions within the country.

Agricultural producers may migrate when weather shocks destroy their crops. Munshi (2003) finds a connection between lower rainfall in Mexico and increased migration to the US. The same finding is confirmed by Feng et al. (2010) with the relation between crop yields and Mexican immigrants. However, as migration is an important consequence of climate change, Dell et al. (2014) emphasize that predicting migration is a specific challenge for panel estimates. Some panel data lack the knowledge about individuals' location before they enter the data set, such that endogenous migration may affect the result.

In 1995 the number of environmental refugees reached 25 million, relative to the number of 27 million traditional refugees: "When global warming takes hold, there could be as many as 200 million people overtaken by sea-level rise and coastal flooding, by disruptions of monsoon systems and other rainfall regimes, and by droughts of unprecedented severity and duration" (Myers, 2002). Moreover, another sensational forecast was provided by the report Christian Aid (2007) predicting 1 billion refugees from climate change by 2050. Tacoli (2009) criticizes these estimates for an unbalanced view on socioeconomic effects when they neglect adaptation possibilities. Estimating population movements from the developing world brings great challenges with respect to the lack of data support. Tacoli (2009) points out that past experiences indicate that short-distance and short-term migration will likely increase, however, the deprived and very poor would be unable to move: "(...) it seems unlikely that the alarmist predictions of hundreds of millions of environmental refugees will translate into reality" (Tacoli, 2009).

3.5 Damage and costs

The marginal external cost from burning fossil fuels and increasing the world's temperatures is named the social cost of carbon (SCC). SCC shall represent the potential value one can save by limiting carbon emissions and avoid the increasing damage from climate change. The value is used as a guideline for policy makers when imposing regulatory restrictions on GHG emissions. Weitzman (2010) demonstrates how structural uncertainty about economic damages for high temperatures has a great influence to the outcome of IAMs, cost benefit analysis and climate models. Table 1 compare the social cost of carbon estimated by different models consistent with the 2 degree target. The prices are converted into Norwegian kroner from the original table by ICCG[11]. There are large variation in these estimates, based on their different modeling assumptions. The carbon prices re-

[11] International Center for Climate Governance

Carbon prices consistent with the 2 degree target.
Norwegian kroner (NOK) per tonne [1]

	2020	2030	2050
Bosetti mfl. (2009)	238	587	2304
Paltsev mfl. (2009)	468	697	1522
Tol (2009)	340	544	1445
Bastianin mfl. (2010)	136	451	3349
Nordhaus (2010)	187	323	859
Average	274	520	1896
Median................	238	544	1522

[1] ICCG do not report the base year of these prices.
Sources: International Center for Climate Governance, the Norwegian Ministry of Finance

Table 1: Different estimates of the SCC in NOK. Source: NOU 2015:15

ferred to by IPCC has a higher mean than the studies in table 1; 434NOK in 2020 and 766NOK in 2030 and 1958NOK in 2050.

Early contributions to environmental economics simplified the total economic cost from climate change into theoretical damage functions, and there was little empirical research to constrain or support these functions. However, the empirical field investigating economic climate damages, on the regional, national and global level, are growing and represent a substantial literature today. The elaborate research by Ciscar et al. (2011) aims to quantify the potential consequences for the European economy, focusing on four sectors; agriculture, river floods, coastal areas and tourism. They find that the welfare loss in BaU would range between 0.2% and 1% annually, "If the welfare loss is assumed to be constant over time, climate change may halve the EUs annual welfare growth" (Ciscar et al., 2011, p. 2678). In a large region like Europe, different countries and regions will face different levels of damage. Studies presenting their results as aggregate damages mask these disparities.

The Stern Review estimates the present value of the economic cost of climate change to be a 10.9% loss in global mean per capita consumption (Stern, 2007). This estimate reflects a BaU scenario that includes both market and non-market impacts. The measure of total discounted cost is derived from a comparison of the 'balanced growth equivalent' with and without climate change and adaptation costs. Reanalysis shows that this result is very sensitive to the choice of discount rate (Dietz et al., 2007b). The discount rate is set to 0.1% p.a. in the Stern Review for the base modeling case. For a higher discount

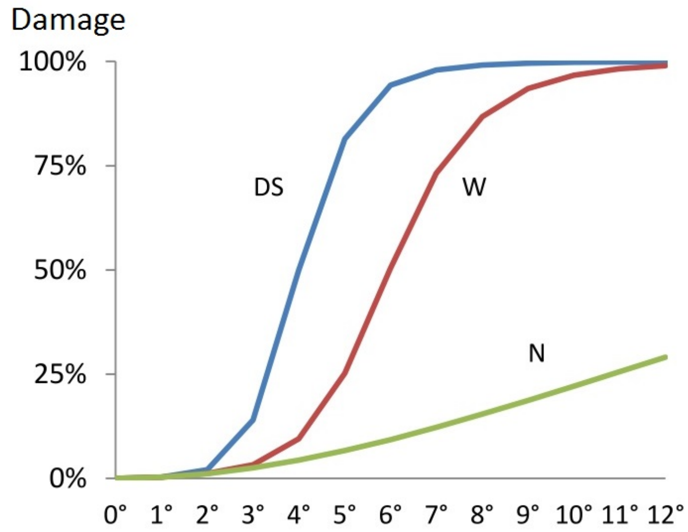

Figure 4: Three different estimates of the climate damage function without tipping points. Source: (Covington and Thamotheram, 2015)

rate, 1.5%, the discounted cost is halved to 6.5%.

Covington and Thamotheram (2015) define economic climate damage as the relative loss in yearly output at a given level of warming, compared to the scenario without warming. Nordhaus (2013) has estimated the damage to be between 5% and 10% of world GDP for a temperature increase to 5°C. Covington and Thamotheram (2015) draw from this that the current damage should be close to 1% of world GDP, as global warming has reached 1°C this year. IPCC (2014b) estimates the global economic loss to be between 0.2% and 2% annually, for temperature increases above 2°C. However, this prediction does not account for possible threshold effects and discontinuity in the damage function.

According to Covington and Thamotheram (2015) an example of different damage functions is illustrated in figure 4, where the three different functions are based on the research of some established environmental economists. The N-damage function is based on Nordhaus (2013) and has become a standard in most economic models. Nordhaus (2013) considers damage from global warming up to 5° and in the figure Covington and Thamotheram (2015) have extrapolated this damage function to be valid for higher degrees of warming. The function becomes gradually steeper for warming above 4°.

The W-damage function is based on Weitzman (2012) and coincides with N-damages for degrees below 3°. However, at the level of 4° the W-damages more than double. The function rises rapidly, and approaches a damage level of 100% when global warming reaches 12°. The DS-damage function is based on Dietz and Stern (2015) considering large scale economic disruption, following the recent improvements in robust climate science. This damage function incorporates more indirect effects such as migration, health and social disturbance. When global warming reaches 4°, the DS-damage function reaches 50% and becomes highly convex.

Different interpretations are necessary when investigating an issue surrounded by complex uncertainties such as climate change. Covington and Thamotheram (2015) use these damage functions to evaluate different climatic scenarios, comparing the impact on a vulnerable economy to a more robust economy. Nordhaus has stated that with the current knowledge we have insufficient evidence to extrapolate the damages beyond 3°C. The rough outline of damage functions by Covington and Thamotheram (2015) is not a result of interpreting climate science, but acts as a useful comparison of different potential outcomes. For a more detailed discussion of damage functions see, e.g., Burke et al. (2015) and references there.

3.6 Economic growth

When scholars have considered the effect on global growth, they have included some, but not all, effects explained above. I have not attempted to distinguish, in each case, what mechanisms each study has included. Some traditional approaches to estimate the overall impacts of global warming on economic growth have been using Integrated Assessment Models (IAM) (Ackerman et al., 2009; Dowlatabadi, 1995; Stanton et al., 2009), Global Impact Models (GIM) (Mendelsohn et al., 2000) or the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 2008; Nordhaus and Boyer, 2000). Based on different assumptions these models sum up and aggregate a selection of indirect mechanisms trying to compute the total influence of climatic change. However, it is computationally demanding to apply these models. Scholars need to assume how each effect operates, choosing which effects to include and how they aggregate. The Stern Report comments critically on the restrictions of these models, but nevertheless, they remain "(...) the best tool available for estimating aggregate quantitative global costs and risks of climate change" (Stern, 2007).

In Dell et al. (2012) the impact of short run climatic changes on economic activity and growth is estimated annually for each country in the world from 1950 to 2003. The analysis uses historical temperature and growth data, based on annual variation within countries over the past 50 years. Dell et al. (2012) are aware of the complex relationship between climate and economic activity and base the analysis on as few assumptions as possible. They avoid using an IAM model by analyzing the effect of temperature fluctuations on an aggregate measure of economic growth. The results indicate that extreme heat will reduce economic growth and have negative effect on output in several sectors in poor countries, including the effect of political instability. However, the effect will not be substantial

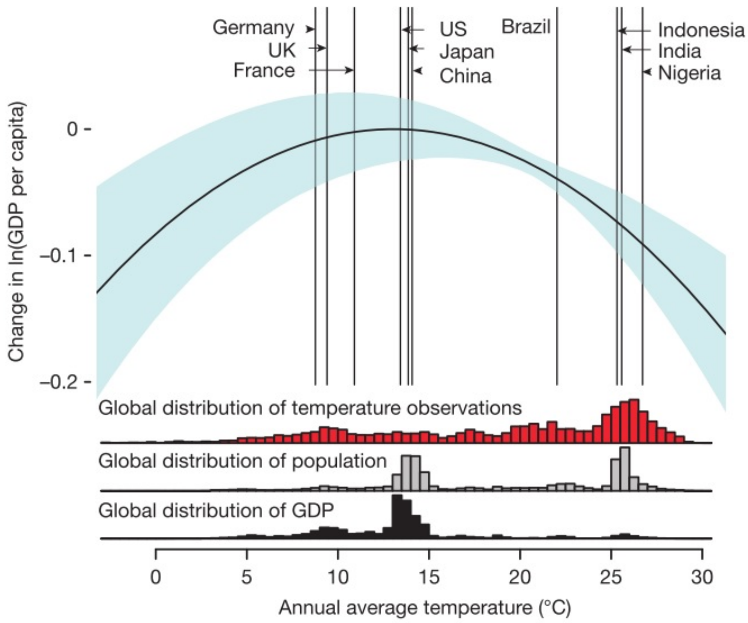

Figure 5: Effect of annual average temperature on economic production. Source: Burke et al. (2015)

for rich countries. Dell et al. (2012) find that these effects are not only significant for temperature shocks but also for long run climate shifts.

Burke et al. (2015) try to combine the results from micro-level (daily) temperature data (Graff Zivin and Neidell, 2014; Schlenker and Roberts, 2009) with data on macro level with temperatures over time (Dell et al., 2012; Hsiang, 2010) to identify how climate change affects overall economic growth. They find that country-level economic productivity is smooth, non-linear and concave in temperatures, where the production hits the maximum at 13°C. This non-linear response to temperatures is supported in both rich and poor countries. This non-linear result is consistent with Dell et al. (2012) and the non-linear correlation between temperature and growth in rich countries.

Since the distribution of temperatures are close to symmetric about the maximum, see figure 5, a linear regression would not recover any relation between temperatures and GDP. However, accounting for the non-linearity reverses how wealth and technology are understood to explain economic responses to temperature (Burke et al., 2015). The study finds only weak evidence that richer countries are less vulnerable to global warming, suggesting that adaptation to climate change may be more challenging than previously understood.

Bansal and Ochoa (2011a) examine the effect of temperature variation (how the temperature level fluctuates over time) on economic growth, finding that rising temperature is an aggregate risk factor to the global equity market. Their analysis is twofold, using both data on global capital markets to find the risk exposure to temperature shocks, and panel data on countries to find the relationship between GDP growth and temperatures. Their results show that temperatures raise required expected equity returns: "That is, portfolios with larger exposure to risk from aggregate growth also have larger temperature betas; hence, a larger risk premium". From the panel they find that GDP growth is negatively related to temperature. The increase in global temperatures has a greater negative impact on growth in countries close to the Equator relative to countries at higher latitudes. The empirical results are verified in a quantitative consumption based long run risks (LRR) model by Bansal and Yaron (2004), to show how long run temperature risk negatively effect growth.

Hsiang and Jina (2014) use meteorological data on 6700 tropical cyclones during 1950 to 2008 to investigate whether the environmental disasters have an effect on long run growth and economic development. They find that national income is reduced relative to trend before the natural catastrophe and does not recover within twenty years. This result applies for both rich and poor countries.

> Linking these results to projections of future cyclone activity, we estimate that under conservative discounting assumptions the present discounted cost of "business as usual" climate change is roughly \$9.7 trillion larger than previously thought.
>
> (Hsiang and Jina, 2014, p. 1)

4 Attempts to adapt

Adaptation to climatic changes may be market driven and/or enforced politically. Slowly driven changes in weather and temperatures would be manageable on the individual level with minor changes to consumption. Moreover, societies preparing for extreme weather events or increasing sea level would need more large scale enforced adaptation plans, organized by the government. In our concept of climate related risk the parts of adaptation that are market driven would belong to the economic climate risk. However, adaptation that is regulated and subsidized would represent a type of climate policy risk.

UNFCCC recommends countries, especially developing countries, to draft National Adaptation Plans (NAP) to raise the ambitions and reinforcement of planned adaptation. This section turns some of the short-run effects discussed above into long-run effects including adjustments of economic production processes. The short run predictions from climate shocks are not directly relevant for a permanent long-run challenge from global warming (Dell et al., 2014). Adaptation to unexpected extreme events will be different from adaptation to gradual changes. It might be the case that adaptation could limit the financial impact of global warming. The usual approach when risk averse agents face a risk is to insure the potential loss, if possible. Insurance in its basic form does nothing to reduce the chance of damage, only compensating the loss itself. By investing in more secure houses, factories and infrastructure one may prevent the damages from floods and hurricanes. Insurance companies often add conditions or rebates to their contracts in order to promote damage reduction.

According to Burke et al. (2015) climate change in the BaU scenario, where societies continue to function as they have in the recent past, will substantially reduce the global economic output. Following this result they hypothesized that rich countries would effectively adapt to rising temperatures. In contrast they find little evidence of adaptation in both rich or poor countries, suggesting that rich countries also will be highly affected by climate change. This indicates that adaptation to climate change is more challenging than previously believed:

> Adaptations such as unprecedented innovation or defensive investments might reduce these effects, but social conflict or disrupted trade - either from political restrictions or correlated losses around the world - could exacerbate them.
>
> (Burke et al., 2015, p. 239)

Sherwood and Huber (2010) emphasize the limit for human adaptation to global warming. If global warming reaches 7°C it would induce hyperthermia in humans and mammals. In the case of 11-12°C warming several regions around the world become inhabitable. Despite the human population living in a wide range of climates today, heat stress from global warming would be intolerable and impossible to adapt to (Sherwood and Huber, 2010).

Adaptation and mitigation are climate policy substitutes, representing alternative ways to reduce the impact of climate change. Tol (2005) investigates the optimal policy mix of adaptation and mitigation, arguing that they should be analyzed together as they compete for the same financial resources. There are additional climate benefits from successful agricultural adaptation, as in terms of avoided emissions from a potential increased land use. Lobell et al. (2013) find that adaptation investments in regions of scarce land and high yields are more effective and relatively inexpensive: "These results therefore challenge the current approach of most climate financing portfolios, which support adaptation from funds completely separate from and often much smaller than mitigation ones" (Lobell et al., 2013).

4.1 Trade

While international trade is seen as a way to adapt to climate change, when productivity disruptions are not highly correlated across regions, there is another line of thought that considers excessive international trade as a cause of climate change.

Baldos and Hertel (2015) emphasize the importance of international trade to secure global food supply in a time of climate change. International trade adjustments contribute to shifting supplies from geographical regions with food surplus to regions experiencing food deficit as a consequence of extreme weather (Baldos and Hertel, 2014, 2015). Today's distribution of comparative advantages would most likely change when warmer and more arid climate dampens agricultural productivity. The existence of trade barriers limits the responsiveness of trade patterns and amplifies the climate risk on those most vulnerable to poverty and hunger. Baldos and Hertel (2015) stress the importance of international trade as an opportunity to manage the risk on food security and global agricultural productivity growth. They point out that removal of trade distortions can mitigate food price volatility in presence of extreme climate scenarios.

Juliá and Duchin (2007) evaluate trade as an adjustment to changes in agriculture due to climate change. The analysis aims to reflect shifts in comparative advantages using the World Trade Model with Climate-Sensitive Land (WTMCL) based on Duchin (2005) and Darwin et al. (1995). Juliá and Duchin (2007) consider three climate change scenarios affecting suitability of land for agricultural production. The scenarios correspond to a doubling of the concentration of CO_2 in the atmosphere. Their results indicate that world prices for grains and the rest of agriculture will have a small and consistent increase due to global warming. This is contradicting previous results on decreasing agricultural prices by Darwin et al. (1995) and Schimmelpfennig et al. (1996).

Globalization of trade and economic growth have environmental externalities, where international supply chains and low transport costs contribute to the rise of GHG emissions. Researchers have shown that ex ante (before climate change happens) unregulated trade may lead to higher greenhouse gas emissions and thus increased risk of climate change. However, neither the Copenhagen Accord nor the Kyoto Protocol address trade restrictions. Barrett (2010) considers treaty agreements to internalize the externalities by international trade and climate change. Trade is a bilateral activity and climate change mitigation is a global public good, implying that treaty design should be addressed accordingly (Barrett, 2010).

Weber and Peters (2009) consider the duality of trade, both amplifying global warming through carbon leakage and competitiveness, and potentially curbing the effect through technology transfer and comparative trade agreements.

4.2 Agricultural adaptation

Agriculture will most likely, as described above, experience more extreme and volatile weather conditions. This may influence the agricultural productivity and change output prices. Hertel and Lobell (2014) discuss potential agricultural adaptation scenarios to climate change. They argue that Integrated Assessment Models overstate the actual adaptation response. Adaptation would involve sufficient investment in innovation and technology, requiring low discounts rates and no credit constraints.

The need for adaptation will be greatest in the poorest part of the world due to rising temperatures along the Equator. These regions are also those with lowest adaptation capacity. Mendelsohn et al. (2001) investigate the linkage between climate sensitivity and a country's level of development. They find that increased development reduces the climate sensitivity.

Antle and Capalbo (2010) frame adaptation as an investment decision and discuss the limitation of the literature on agricultural impacts and adaptation.

5 Attempts to prevent

The likelihood for some sort of climate agreement is increasing and there is a growing momentum for mandatory emission regulation. The climate change conference by the UN (COP 21) was held in Paris, December 2015[12]. The 187 participating countries agreed to reduce their CO_2 emissions to keep global warming below 2°C. The COP21 achieved a significant increase in participating countries, compared to The Copenhagen Accord with 141 participants. The agreement does not contain any deadline, but there will be revision of more ambitious contributions every 5 years. It is non binding without any sort of enforcement mechanisms, such that monitoring, verification and reporting will be carried out domestically by each country. The climate agreement binds in the domestic laws of the participating countries, and these policies are credible, sending price signals through the market. This may lead to tightening of existing carbon markets, pushing the establishment of a global carbon price.

The attempts to impose a global and uniform carbon price have not yet been successful. However, the number of existing emission permit markets is high and continues to increase. National permit markets are already operating in Kazakhstan, New Zealand, Norway, South Korea and all the EU member countries. The EU Emission Trading System (ETS) provides a market for carbon permits for about 45% of EU's total emissions. Additional

[12]Note that this survey was mostly written before the outcome COP21 was released

markets are planned in Asia, including China, Indonesia, Thailand and Vietnam. Regional markets are currently established in some Chinese provinces, in the Canadian province of Quebec and in several states in the US[13]. More regional markets are planned to be established in Tokyo and Rio. These markets represent a starting point of a global carbon price where separated markets could be connected, several markets are already linked (Holtsmark and Midttømme, 2015).

The type of climate policy enforced would also have a significant impact on the economic performance. The seminal article by Weitzman (1974) compares the two policy mechanisms available, either determining the price of emissions with taxes or the optimal quantity by issuing quotas. On the firm level, the two alternatives signify different amounts of risk. A tax fixes the future emission price and imposes less risk for firms, while a cap-and-trade system leads to more uncertainty about future emission prices. This would especially affect firms that are unable to immediately turn over the extra cost to the consumers, and hence, are vulnerable to price fluctuations. There are numerous studies connection climate policy and uncertainty to Weitzman (1974), see, e.g., Goodkind and Coggins (2015) and Shinkuma and Sugeta (2016) and the references there.

5.1 Mitigation

What is the expected return from investing in climate change mitigation? Climate mitigation refers to efforts to reduce or prevent climate change, such as emission reduction, improved efficiency and alternative energy sources. Portfolio theory and the CCAPM (Consumption Capital Asset Pricing Model) may be useful for estimating how the expected return from such investments depend on risk. According to theory, the required expected return should decrease if an investment in climate mitigation lowers the overall portfolio risk. This effect is determined by the beta in CCAPM, the sign of beta determines the direction of the systematic risk premium. For a positive beta the collective risk increases. Dietz et al. (2015) discuss the CCAPM beta that is used to evaluate climate mitigation projects. Related to climate change the question is whether climate mitigation investments give highest return when future generations are better off (read: increased utility, welfare, consumption or portfolio return) or when they are worse off.

Sandsmark and Vennemo (2007) were the first to discuss this issue, questioning whether investments in climate change mitigation should be considered, despite low expected return. Since the climate risk is endogenous for the economic system as a whole, investing in mitigation can be considered as self-protection or self-insurance to reduce risk. Their

[13]US Regional Greenhouse Gas Initiative (2009) and California's GHG Cap and trade system (2013)

theoretical portfolio approach and two-period model motivate low discount rates on climate investments. In other words they recommend high valuation of future events with endogenous probability, such as global warming. Their reasoning builds on the concepts of protection and insurance. As self-insurance, a climate investment may provide positive returns when disasters occur, and as self-protection, an investment will increase the likelihood of a better climate outcome. In reality the outcome of climate change is not twofold, and a multi-period model would include more detailed distinctions. However, the simplicity also has the advantage of enabling basic interpretation.

Dietz et al. (2015) develop further the contribution by Sandsmark and Vennemo (2007). In Sandsmark and Vennemo (2007) the loss of GDP is the only stochastic parameter that represent the intensity of damages as temperatures increase. This assumption gives a negative climate beta i.e., there is a negative correlation between consumption and mitigation benefits, since largest benefits from mitigation occur when damages are large and aggregate consumption is low. An alternative channel with technological change is considered by Gollier (2012), deriving a positive climate beta. Dietz et al. (2015) combine these two theories by applying the DICE model, and introduce several sources of uncertainties about the benefits of climate mitigation. They find that the positive beta from technological change (Gollier, 2012) dominates the negative effect from uncertain damages (Sandsmark and Vennemo, 2007): "Put another way, emissions reductions actually increase the aggregate consumption risk borne by future generations" (Dietz et al., 2015, p. 4). Related to this result, Dietz and Stern (2015) suggest, it raises the net present value of the future benefits of mitigating emissions today.

Daniel et al. (2014) characterize carbon pricing as a risk management problem for the government, applying the standard asset pricing theory to calibrate the price of climate risk. Climate risk is interpreted as a potential damage to the endowments in a representative agent model. To determine the optimal path of mitigation the representative agent optimizes the trade-off between mitigation costs and benefits from elimiting climate damage. Empirical evidence shows that investors act more risk averse than standard economic theory presume, justifying the use of Epstein-Zin preference framework. By accounting for risk aversion Daniel et al. (2014) find that the optimal carbon tax should be high today and decline over time due to the development of backstop technologies and innovation progress.

The behavior towards long run climate risk will determine the society's incentives to abate, and drive the results on timing and extent of mitigation effort. Bansal et al. (2015) stress the importance of the choice of preferences when modeling the SCC. The preference function decides the willingness to pay for climate mitigation. With traditional time additive CRRA-preferences (power-utility) the social planner tends to postpone mitigation until the impact from climate change starts unfolding. In the LRR model by Bansal and Yaron (2004) they substitute traditional time additive CRRA preferences with Epstein-Zin preferences, which allow for separation between risk aversion and the intertemporal elasticity of substitution. Epstein-Zin preferences motivate early resolution of uncertainty. According to Bansal et al. (2015) the capital market data support the choice of Epstein-Zin preferences.

Laurikka and Springer (2003) develop a methodology for quantifying risk and return of investments in climate change mitigation projects. A project in this context is either reducing emissions or regulating carbon, e.g., energy efficiency projects, methane projects and wind/solar/hydropower projects. Their diversification strategy for low-risk portfolios show that hedging, investing in several of these different projects, gave a 10 times higher return than investing in a single project. Laurikka and Springer (2003) conclude that carbon funds do not only serve as a channel for investments, but can also help to reduce investment risks.

Hultman (2006) considers projects that have risky future cash flows due to natural, biological or physical characteristics of the ecosystem. These projects have an uncertainty that cannot be avoided. Since different projects are not perfectly correlated, in particular if they have different locations, there is a potential gain from investing in a diversified pool of projects, as compared to investing in only one, or some that are nearby and highly correlated. Much of seasonal variation is predictable, and thus seasonally adjusted data are used in the analysis of correlations. Hultman (2006) shows that much can be gained from holding a portfolio of projects instead of only one project. Hultman speculates whether financial markets can establish similar mechanisms for risk reduction. For instance, if the difference in productivity in different years depends on observable weather, it may be possible for investors to reduce the risk of a particular project by buying weather derivatives, i.e., securities that pay out in the future if and only if some observable, verifiable weather event occurs.

5.2 Investing in technology

The greater part of the literature on climate risk considers the likelihood of negative surprises. However, we should also consider possible positive events such as technological improvements. Hoffert et al. (2002) interpret climate change as an energy problem, requiring research and development in technology to curb global warming and secure economic development. Possible technologies include hydrogen production, carbon capture and storage (CCS[14]), geoengineering, energy efficiency and battery improvements.

Löschel and Otto (2009) study how anticipating an eventual backstop technology, such as CCS, could postpone mitigation regulations: "Such behavior is not warranted given the large uncertainties typically surrounding new technologies" (Löschel and Otto, 2009, p. 13). Robins (2014) emphasizes the increased use of fossil fuel in case of successful development of CCS. However, the Carbon Tracker Initiative states that the development of CCS does not change their conclusion on stranded assets and a carbon bubble (Carbon Tracker Initiative, 2013, p. 4).

One might consider that investments in solutions and adaptations would give rise to financial opportunities. According to Jacobson et al. (2015) the conversion of energy infrastructure is technically and economically feasible with little downside. The article presents a roadmap for each of the 50 states in the US in transition to a new and clean energy infrastructure by 2050. The study evaluates wind, water and sunlight resources that should produce enough energy for purposes such as electricity, transportation, heating/cooling and industry. The findings seems to imply that US could eliminate energy related air pollution without decreasing employment nor incur welfare costs.

6 Financial markets

Climate change and global warming may cause profound economic damage, shocks, disrupted trade and political instability placing assets and the value of financial portfolios at risk. The climate risk is not only relevant for very long-term investments, but a risk we face within the time frame of current investment decisions.

The previous sections have shown how global warming might affect the functioning of our society. The impacts on the economy include changed production possibilities, lowered productivity and decreased growth. To which extent climate damage may affect the economy depends on the curvature of the unknown damage function. Scholars have computed different shapes of the damage function, see figure 4 in section 3.5 for an illustration, relying on IAMs and climate models, following the development of more robust climate science. As more knowledge about climate change is established, economists can improve their predictions about the global outcome of a warmer world. However, some scholars disagree that this method will lead to any useful knowledge (Pindyck, 2013).

This analysis considers three aspects on how climate change may affect the financial market. Either directly through damaged asset values and decreased economic growth, or indirectly where climate policies lead to stranded assets. Trying to answer the question

[14] CCS sometimes also refers to the equivalent Carbon Capture and Sequestration technology

whether the financial market rationally prices the climate risk one can analyze the behavior of the financial market related to climate information.

Almost all research relating climate change to financial markets has concentrated on the stock market. This is also reflected in the section that follows. For discussion on consequences of climate change for fixed income securities, see Hill Clarvis et al. (2014) on government bonds and De Jong and Nguyen (2016) on corporate bonds.

The section proceeds as follows: The first and second subsections look at how economic damage from climate change can be translated to financial loss. The third subsection considers studies analyzing the climate policy risk and stranded assets. Subsection 6.4 compares two studies trying to investigate the hedgeability of the climate risk, followed by a subsection on decarbonized portfolios and the divestment movement. Subsection 6.6 comments on selected studies investigating whether firms' environmental performance affects their valuation in the market. Followed by a subsection on the Efficient Market Hypothesis, subsection 6.7, gathering research on how the financial market reacts to climate information. A selection of event studies are analyzed and compared, with the aim of investigating how the markets price the climate related risks. The empirical evidence is not consistent, differing substantially in all directions. The two last subsections, 6.8 and 6.9, look at ethically responsible investors related to climate, and climate risks in the insurance sector.

One argument why the financial market is not optimally pricing the climate risk is the phenomenon of short-termism, a concentration on short term projects and immediate profits. Long term investments that incorporate the distant future risk of global warming are therefore not rewarded in the market. Short-termism is well known among sholars (Bolton et al., 2006; Dallas, 2012; Laverty, 2004), and its existence has been supported both statistically and economically according to Andrew Haldane, director of financial stability at the Bank of England (Haldane and Davies, 2011). Short-termism in financial markets undermines the ability to manage long run risk due to the climate risk factor. Caldecott and McDaniels (2014) suggest that this phenomenon is driven partly by the practices and regulations that govern financial institutions, such as short-term benchmark measurements, risk management and reporting structure that reward short term performance. However, a counter argument regarding short-termism is that investors are more than willing to pay high prices for growth stocks, implying long-term behavior.

6.1 Economic damage and portfolio loss

Many studies, that apply IAMs and other climate models, look at how climate change may affect world GDP to estimate the monetary value of this effect. Covington and

Thamotheram (2015) take these studies a step further by assuming that a diversified equity portfolio follow world GDP proportionally. This might not be a robust assumption, but it is an interesting attempt to connect the climate risk to the financial markets.

Covington and Thamotheram (2015) consider a diversified equity portfolio that mirrors the global economy. They assume that the dividends from such portfolios follow the cycles of world GDP. In presence of climate change the level of world GDP will be affected both by direct physical damage and indirectly through reduced growth. They estimate the effect on growth through a climate damage function, convex in global warming. However, Covington and Thamotheram (2015) do not include the possibility of tipping points and irreversible catastrophic events, represented by Pindyck's damage function (Pindyck, 2007). For a more detailed discussion of climate damage functions see section 3.5.

The economic loss equals the change in expected present value of dividends due to global warming. Covington and Thamotheram (2015) find that 1% to 20% of the portfolio value is at risk if the warming reaches 4°C in 2070, depending on the robustness of the economy (adaptation, regulations and preventative actions).

6.2 Rising temperatures and asset valuation

Bansal and Ochoa (2011b) evaluate the role of temperatures in determining asset prices. They apply a long run risks temperature (LRR-T) model, based on Bansal and Yaron (2004), where temperature affects growth and the financial markets through two channels: (i) increased temperatures lower the wealth-to-consumption ratio, and (ii) temperature shocks yield a positive risk premium. The LRR-T model matches the observed financial market data and observed temperatures:

> Our model implies that if temperature were to rise it would lower long-run growth, raise risk-premiums, and adversely affect asset prices - the magnitude of these negative effects increases with temperature, suggesting that global warming presents a significant risk.
>
> (Bansal and Ochoa, 2011b, p. 19)

In a closely related article by Bansal et al. (2015), they estimate the equity price elasticity to temperatures. The model estimates the connection between temperatures, consumption and climate change disasters by letting global warming increase the economic risk and affect asset valuation. They find that global warming has a significant negative effect on asset valuation, and hence a negative elasticity of equity valuations on temperature risk. This negative elasticity has become more negative over time, following the growing concern of climate change consequences or suggesting that the climate change impact on the economy has been rising.

6.3 Stranded assets and climate policy risk

The term 'stranded assets' characterizes assets that experience an unexpected devaluation due to an unforeseen change either in regulations, technology, social norms or the environment (Robins, 2014). If eventually the negative externality of emissions is corrected by a sufficient carbon tax, on either national level or through a global treaty, fossil fuel producers will experience a devaluation due to increased costs, and fossil fuel consumers experience increased prices. The investments in polluting corporations become stranded. This relates to the risk of being repriced following unexpected policy regulations. Caldecott and McDaniels (2014) explain the cascading of risk that follows from a repricing of carbon. Starting in the carbon intensive sector it will spread to other sectors and jurisdictions causing financial instability. Since our society is heavily based on fossil fuel energy, a carbon price may cause several indirect effects in every sector that together permeate the whole economy. For sufficiently high levels of the carbon tax the whole economy is likely to be affected. As a result carbon regulations constitute a substantial risk in the financial markets.

The concept of unburnable carbon and stranded assets in the context of climate change was, among others, introduced by the Carbon Tracker Initiative. They ask whether the financial market is carrying a carbon bubble (Carbon Tracker Initiative, 2011, 2013). If the global society is to reach the two degree target by 2050, a great part of the known oil, gas and coal reserves cannot be exploited. McGlade and Ekins (2015) find that 80% of the current known coal reserves, 1/2 of the gas reserves and 1/3 of the oil reserves should remain unused to reach the 2°C target. These reserves are unburnable, and the postponed valuation effect is not impounded in current share prices. The Carbon Tracker Initiative suggests that the market holds a potential carbon bubble in fossil fuel prices, claiming that prices today are too high. McGlade and Ekins (2015) display the inconsistency of policy makers' instinct to exploit rapidly together with commitments to curb GHG emissions. Such duality in policies will lead to unnecessary costs.

Stranded assets suffer from unanticipated or premature write-downs, devaluations or conversion to liabilities (Caldecott and McDaniels, 2014). According to the Carbon Tracker Initiative the carbon bubble implies that all fossil fuel assets are at risk of becoming stranded. A more conservative conclusion is stated in the report *Petroleum Production under the Two Degree Scenario (2DS)* by Rystad Energy (2013). The report tries to estimate what oil and gas reserves may become stranded within the carbon budget set by the IEA (International Energy Agency), limiting total emissions to 1000 Gt CO_2 within 2050. They find, based on their private database on global fossil fuel reserves, that 78% of the oil reserves and 97% of the gas reserves may still be extracted in 2050. It is rather the coal shares that will experience a high risk of becoming stranded.

Other elements that increase the likelihood of stranded assets include changes in resource availability and reduced technology costs. Financial markets may be affected by unforeseen challenges to extract fossil fuel further, leading to increased costs and stranded assets (Caldecott and McDaniels, 2014). Extreme weather conditions may distort the extraction process and the supply of fossil fuels, followed by shifts in output prices. Possible scenarios could be that increased frequency of storms challenge extraction in the North Sea and the Arctic, and heat stress may challenge extraction in the Arabic Gulf.

In the transition to a low carbon society regulators may try to impose carbon restrictions either by implementing a carbon price or by establishing GHG standards and renewable portfolio standards. For owners of fossil fuel assets, climate negotiations represent a risk of carbon repricing in the near future, a climate policy risk additional to the economic climate risk. As the price of carbon is implemented, fossil fuel intensive industries will experience higher costs and may lose market shares to cheaper and maybe cleaner industry. When carbon intensive industries are unable to meet increased input prices with higher output prices the result is lower profits and devaluation of the industry's financial value. Investments in industries that are directly affected by a carbon price may experience rapid devaluation of assets. Incorporating the carbon price risk in investment decisions may therefore pose a challenge for the energy sector (McInerney and Bunn, 2015).

Empirically this theory has not been proven right as of today. According to an empirical analysis by McInerney and Bunn (2015) the result is more unclear due to the lack of accounting standards. Reporting of emissions in the EU is inconsistent, making the assessment of carbon liabilities unreliable. Empirically they estimate the portfolio weighted carbon delta rather than carbon intensity. The carbon delta measures the impact on cash flows from net carbon emissions, providing a better way of considering carbon liabilities (McInerney and Bunn, 2015). By investigating how a potential carbon price would change the competitive dynamics of renewable and fossil fuel technologies in the EU, they find that a carbon price of €20.6/tonne is only relevant for a handful of companies.

The econometric analysis by McInerney and Bunn (2015) indicates rather inconsistent effects. The mixed empirical result may signify either that the topic is not sufficiently understood or, on the contrary, investors have full understanding of the financial portfolio nature. McInerney and Bunn (2015) blame, above all, the inconsistent emission report system. They question whether investors assess the risk of changed fuel prices less than the implicit risk of regulatory stringency. They conclude, despite mixed results, that the regulatory risk is relevant for a company's share prices: "Perhaps equity investors assess carbon price risk less as a fuel price risk and more as a regulatory, carbon sentiment or implicit risk" (McInerney and Bunn, 2015, p. 216).

Climate policies determine a risk of stranded assets in fossil fuel investments. Blyth et al. (2007) quantify the regulatory risk on the firm level, to understand how the uncertainty that surrounds future policies affects the firm's investments. Yang et al. (2008) consider the carbon price risk alongside energy price risk, and evaluate the effect of governmental climate policy uncertainty on investment decisions in the energy sector. Policy interventions may have substantial impact on the financial performance of a firm. In the case of climate policies, the firm's level of GHG emissions determines its exposure to climate policy risk. The uncertainty about regulations has become a new crucial influence on their investment decisions. Yang et al. (2008) conclude that the climate policy risks can become severe if there is a short time gap between the policy event and the timing of the investment decision. Governments can reduce this risk by implementing long-term regulation frameworks.

Arguments can be made on both sides for whether climate policies create or destroy firm value. Dowell et al. (2000) conclude that this is an empirical question. The paper gives an analysis of the relation between the environmental standards of firms and their stock market values. A measure of Tobin's q (i.e., market value to replacement cost) is taken as a comparable indicator of market values for firms, so that lower-q firms are said to have poorer quality (in a general sense). The empirical result is that firms that adopt high environmental standards for their global activities, also have higher q. Developing countries trying to attract investment through lax standards risk ending up with poorer quality firms, also in other respects. However, the authors state that they have not detected causality, in one direction or the other, between market value and environmental standards. They leave many possible interpretations open, with both types of causality.

On the financial investor level, uncertainty about future climate policies may signify a substantial risk. After the financial crisis, several financial regulations were implemented to influence asset allocations. When these regulations are reviewed, policy makers may connect their climate goals to their implementing of financial regulations (Dupré and Chenet, 2012).

CISL (2015) consider the climate policy risk explicitly in their research, interpreting climate policy as a potential trigger for financial tipping points. In the short run (5-10 years) the climate policy risk is more profound than the physical impacts from the climate risk. Climate policy may cause significant economic disruption by suddenly changing commodity and input prices (CISL, 2015).

The issue of climate policy risks depends on whether the new regulations are enforced regionally or globally. In case of national restrictions multinational investors can reallocate their investments to countries with weaker restrictions, and hence better firm performance. This is referred to as a carbon leakage, indicating that national regulations have little or no effect on the aggregate flow of emissions.

6.4 Are climate risks hedgeable?

Two newly published studies discuss whether the climate risk is hedgeable. Although they investigate the same topics, their methods are different. The study by CISL (2015) applies the Oxford Economics forecasting model GEM (Global Economic Model), where they stress test portfolios using simulated shocks in different climate change scenarios. They find that climate change will cause a global recession that will affect assets values independently of the asset allocation. This result is driven by the fact that climate change will reduce economic growth overall. The other study by Andersson et al. (2016) investigates the portfolio performance of a decarbonized index. One possible weakness of this study is that historical data may not be relevant when describing the future with climate change.

The two studies derive different conclusions on the question whether the climate risk is hedgeable. The report from the University of Cambridge claims that climate risk will invade all aspects of the economy such that changing asset allocations would only offset half of the negative impacts from global warming (CISL, 2015). They suggest a shift in assets from real estate and energy (oil, coal and gas) to transport and health care to minimize the loss in a worst case scenario. By studying scenarios with different asset classes and analyzing the performance of different portfolio compositions, they find that in a scenario without mitigation, half of the portfolio can be hedged by shifting to a fixed income portfolio. However, this would yield lower return in the long run.

On the contrary, Andersson et al. (2016) develop a strategy that allows investors to hedge against climate related risks without sacrificing any financial returns, since the return in case of postponed implementation of a carbon price coincides with the benchmark return. Their approach goes beyond the basic divestment in stranded asset stocks by designing a dynamic investment strategy that hedges climate risk. The design is based on the underlying assumption that financial markets currently underprice carbon risk, or at least do not overprice it. The investment strategy aims to minimize the tracking error subject to a specific target of carbon reduction in the portfolio. The ex ante tracking error is the estimated standard deviation of returns of the decarbonized portfolio relative to the benchmark market portfolio. This estimation is based on historical data.

The fourth Swedish National Pension Fund adopted this type of decarbonized investment strategy in 2012 to hedge carbon exposure in U.S. equity holdings. This portfolio outperformed their benchmark (S&P 500) by 24 basis points annually. However, it is too early to conclude whether they will sacrifice any financial performance in the long run.

While Andersson et al. (2016) assume that financial markets underprice carbon risk we cannot a priori rule out the opposite possibility, either today or at some other point in time. In particular, it is difficult to estimate the likelihood of technology breakthroughs, e.g., in batteries or carbon capture and storage. Positive surprises may occur and the price mistake may go both ways The authors cleary indicate that they believe the mistake can only go one way: "Under these circumstances one would have to stretch ones imagination to explain that somehow financial markets currently price carbon risk correctly" (Andersson et al., 2016, p.10). The crucial question is how one can measure this and find out whether the financial markets actually make mistakes when pricing the risk of climate change.

Would it in practice be possible to hedge the climate risk? Perhaps the risk can be avoided by a single investor, but not by society as a whole. Hedging implies that risk is shifted towards other financial agents, however, this would not be feasible if everyone are simultaneously hedging in the same direction.

The questions whether and how climate related risks are hedgeble is a research field that needs more contributions. The studies mentioned above are both quite newly published, they are not related in method, and they give different answers. This points out that more research is needed on the topic.

6.5 Decarbonization

Throughout 2015 a fossil fuel divestment movement has been established, starting with a student organization[15] requiring their university to remove investment assets in fossil fuel intensive industries, becoming an international campaign named *Fossil Free* organized by the climate organization 350.org and Bill McKibben. The movement has grown to include several American and European universities, private funds and investors[16].

The divestment movement implies that investors "decarbonize" their portfolios, mean-

[15]Fossil Free AU: A campaign at American University, Washington DC, to divest from fossil fuels

[16]According to Fossil Free, 499 institutions have divested partial or fully, an amount of US$3.4 trillions. The Norwegian Sovereign Wealth Fund is listed as one of the notable divestment commitments, although only partial. Source: http://gofossilfree.org/commitments/

ing that they allocate their assets out of fossil fuel and carbon intensive companies. In theory divestment will increase the cost of capital for the fossil fuel industry, decreasing their profitability. This would undermine the competitiveness of fossil fuel firms through their lack of capital, instead of increased output prices. However, the total amount of divestment in 2015 was unlikely to affect the valuation of the fossil fuel companies.

In an article in *Nature Climate Change*, van Renssen (2014) questions whether investors will take account of climate policies when recognizing the climate risk. Concluding that climate change is not the only factor that drives the divestment movement: "This is about restructuring the financial system to drive long-term infrastructure investments in line with long-term policy goals such as a low-carbon economy" (van Renssen, 2014, p. 242).

The event study by Byrd and Cooperman (2015) suggests that investors in fossil fuel companies are aware of the stranded asset risk due to the divestment movement, particularly in coal companies. They find that the market responded negatively to divestment announcements in the news, devaluating fossil fuel companies.

The divestment movement may also have a reputational effect; public stigmatization of fossil fuel companies makes them less attractive for socially responsible investors and pension funds. Several scholars advocate such divestment, including Piketty and Jackson (2015). Comparing the divestment movement from fossil fuel companies to the similar movement related to the tobacco industry they claim that the goal was not financial influence, but rather a political signaling effect.

Covington and Thamotheram (2014) advice long term investors to encourage creative destruction to protect their portfolios, instead of a rapid "decarbonization".

> The growing debate about fossil fuel divestment is a signal that investors are slowly waking up to this threat, but long-term investors must do much more if they are to avoid material damage to the value of their investments.
>
> (Covington and Thamotheram, 2014, p. 42)

They state that divestment from a fraction of the most intensive fossil fuel companies is not enough to avoid the climate risk, "In our view, a much more urgent and active response is needed if the risk of climate change to investment values is to be materially reduced" (Covington and Thamotheram 2014, p. 45). This can be achieved by (i) raising the cost of capital for the polluting sector, (ii) lowering the cost of capital for the sector that reduce and mitigate emissions and (iii) influencing companies to accelerate the transition to a low carbon economy.

According to Andersson et al. (2016), a decarbonized index does not only reward the included companies, but may also benefit the excluded companies. Filtering the portfolio sector-by-sector would promote competition between firms. It would generate incentives for those companies wanting to enter the index to lower their emissions. Decarbonization can also obtain a virtuous cycle as a larger fraction of investors is devoted to decarbonization. Greater awareness will support and welcome climate change mitigation policies and significantly reduce carbon footprints (Andersson et al., 2016).

6.6 Financial performance of climate responsible firms

In the financial market investments should be, according to theory, rationally allocated to firms with the highest valuation, based on expected future profits. Is the valuation of a firm affected when firms try to prevent climate change through their private management? The question of interest is whether environmental characteristics of a firm have any economic influence on financial valuation.

The reaction in financial markets to the *green* performance of firms may tell us something about how markets perceive climate related risk. If climate change is seen as a likely threat to future production and consumption possibilities, or if climate policy reduces values of some firms, corporations preparing themselves for such risk should be positively rewarded. A negative reaction in the markets could imply that markets do not consider that climate related risk requires actions by corporations, or that the actions taken are irrelevant (and thus wasteful) or exaggerated.

There exists a large literature, not only climate related, investigating whether firm's environmental investments are improving firm value or reducing financial performance. On one hand, environmental investments are costly, claiming resources that otherwise had improved business (Palmer et al., 1995). On the other hand, improved environmental performance may be consistent with shareholders wealth maximization (Ferrell et al., 2016; Liang and Renneboog, 2013). Socially responsible firms promoting climate mitigation may reflect good governance. Firms that improve their environmental performance may obtain a first mover advantage when complying with reinforced climate regulations (Fisher-Vanden and Thorburn, 2011). However, the argument that commitment to environmental initiatives is catalyzing innovation is problematic after the VW scandal (Pearce, 2015).

Corporate Social Responsibility

Environmental performance is often considered as a subcategory in the concept of Corporate Social Responsibility (CSR). For a literature survey on empirical results, see Sariannidis et al. (2013). Socially responsible firms are, among several benevolent characteristics, those that promote climate protection and mitigation. Clark and Viehs (2014) provide a literature overview on the issue of CRS for investors. They conclude that the majority of empirical studies find a positive relationship between a corporation's environmental performance and financial performance.

Ferrell et al. (2016) investigate the issue of shareholder and stakeholder tradeoff. The discussion of CSR concerns whether firms should be accountable only for shareholders or for the society in which the corporation operates. CSR therefore becomes an agency problem on cash diversion, focusing on stakeholders additional to shareholders. Ferrell et al. (2016) use cross country data and an instrumental variable approach to investigate whether firms that incorporate the climate problem are maximizing shareholder value. They look at both corporate compliance and voluntary aspects of CSR to investigate the value-enhancing view of CSR. They investigate whether these effects are different depending on the strength of a country's legal protection of shareholders. Their empirical results support that countries with strong legal protection cause high corporate responsibility among firms. CRS is generating returns rather than increasing costs, enhancing firm value and shareholder wealth (Ferrell et al., 2016).

Why do we observe large differences in corporate social responsibility within countries and across countries? What fundamental country specific forces steer companies to behave as good citizens rather than as pure profit maximizers? There exist different views on the linkage between law and finance. Either common law is superior for shareholder protection and a spur to financial development, accomplishing efficient resource allocation that maximize social welfare. Or civil laws are superior for stakeholder protection by reducing market externalities and increase social welfare.

Liang and Renneboog (2013) use a quasi-experiment and a diff-in-diff approach finding that corporations in countries with English legal origins underperform relative to those located in countries with civil law origins. Legal origins are the only consistent predictors of CSR and sustainability, and civil law firms outperform common law firms in CSR issues. And, noteworthy, Scandinavian firms outperform the rest of the world in CSR, especially concerning environmental issues.

Scholars have provided several critical overviews on the literature on the relationship between environmental and economic performance (Filbeck and Gorman, 2004; King and Lenox, 2001; Telle, 2006; Wagner and Wehrmeyer, 2002). A common stand is the lack of consistent measurements of "environmental performance either as eco-efficiency, carbon" footprint or as environmental strategies. Unfortunately, many of the empirical studies suffer from omitted variable bias and simultaneity bias. Environmental performance cannot be considered as exogenous, as it depends on a firm's economic performance, making the estimator biased and inconsistent. Many of the studies on the effect of environmental performance on corporate value therefore lack causal support (Telle, 2006).

Several scholars have questioned whether there is a two way relationship between the environmental og the economic performance of a firm, making them jointly determined and hiding the direction of the causality (Al-Tuwaijri et al., 2004; Nakao et al., 2007; Wagner and Wehrmeyer, 2002).

Reinhardt et al. (2008) apply microeconomic theory to determine conditions that induce firms to comply, and even overcomply, with environmental requirements. They also consider the legality, whether the firms are allowed to sacrifice profits in the social interest. The analysis allows for more detailed hypotheses about which firms behave in which way. They review empirical evidence and arrive at the conclusion that "evidence of sacrificing profits in the social interest is lacking" (p. 232).

Firms voluntarily reduce their emissions

Fisher-Vanden and Thorburn (2011) analyze the effect on shareholder value by the announcement of voluntary participation in corporate environmental initiatives, distinguishing between concrete targets of emission reduction and more general environmental commitments. Partnership in the United States Environmental Protection Agency's (EPA) Climate Leaders program is voluntary and involve reports of inventory data and mitigation goals. On the contrary, a voluntary membership to Ceres signals environmental awareness but does not require any specific preventative actions by the firm. Ceres is a non-profit network of companies and investors promoting sustainable business and founder of the Investor Network on Climate Risk (INCR). Fisher-Vanden and Thorburn (2011) find a significant negative stock market return at the time of announcement to participate in EPA's program, concluding that commitments to reduce emissions conflict with firm value maximization. The negative effect was greatest for high growth firms. Firms in the carbon intensive industry had a less negative reaction, possibly reflecting partial anticipation of upcoming policy regulations. Firms in competitive sectors also had less negative effects, maybe because unprofitable green behavior is limited for corporations that are unable to shift costs over to the consumers. However, the result is not significant for announcement of the more vague environmental commitments, such as Ceres. This may not be that surprising since such commitments don't have any direct influence on the cost structure of firms.

The result supports Jacobs et al. (2010) who study stock price changes at the time firms announce climate initiatives. Voluntary emission mitigation caused significant negative stock market return. However, philanthropic environmental gifts resulted in significant positive return. These studies indicate that firms achieve a positive return by signaling a climate friendly business strategy. However, active voluntary actions towards climate change seem to reduce stock returns.

In a similar study by Gans and Hintermann (2013) voluntary participation in Chicago Climate Exchange (CCX) gave significant and positive excess returns. CCX is a GHG emission reduction program in North America, started in 2003. This result is confirmed in the event study by Boulatoff et al. (2013), using similar data set on CCX. However, three other event studies on voluntary emission reduction signify a significant and negative return, although they use other events than CCX. Jacobs et al. (2010) find that self-reported corporate effort to avoid or mitigate environmental impacts of products or services, resulted in a significant and negative market reaction. Fisher-Vanden and Thorburn (2011) and Keele and DeHart (2011) use data on firms joining the US Environmental Protection Agency (EPA) Climate Leader program, aimed at reducing GHG emissions. Both studies find these firms experienced a negative market effect.

Firms voluntarily disclose their emission information

Cormier and Magnan (2007) investigate the impact of voluntarily disclosed environmental information by firms on their return and the effect on stock prices. The analysis selects three countries, Germany, Canada and France, that employ different reporting regimes. Cormier and Magnan (2007) use a simultaneous equation model to control for the endogeneity between the reported information's exposure to media and the stock market value. They find that disclosed environmental information affects the return valuation multiple. However, the extent of the effect depends on whether the firm is located in Canada or France. This suggests that the reporting context a firm faces is crucial for how the financial information is interpreted by the stock market.

Firms voluntarily doing green investments

Other studies analyze the same issue but with another empirical approach, using difference in differences (DID). Ziegler et al. (2009) find that a firm's green investments are penalized by the market. In the study they compare stock performance of portfolios that differ in their climate-related policies, finding that environmental actions reduced returns for US firms. However, the effect was not significant for European firms after 2003 due to the stringency of the European climate policies. "These results suggest investing in corporations with a higher level of responses to climate change especially in regions with more ambitious climate policy regimes" (Ziegler et al., 2009, p. 23).

Firms mandatorily disclose their emission information

Two early studies (Hamilton, 1995; Konar and Cohen, 1997) find a negative effect for firms reporting their emissions to the public database by the Toxic Release Inventory in the US. The reporting was mandatory and a negative effect could imply that the market was unaware of the climate risk connected to these firms. A more recent study by Krüger (2015) employs an empirical quasi experiment with a DID approach to investigate the same topic. Krüger analyze *The Companies Act* that requires all UK quoted companies to report their GHG emissions. Since this is an experiment, Krüger apply three control groups: UK firms that already had disclosed, European exchanges and firms in the Alternative Investment Market (AIM). The study finds a positive valuation effect, and the effect is stronger for the emission intensive industries.

Firms signaling environmental responsibility

As already noted, Fisher-Vanden and Thorburn (2011) find an insignificant effect for firms trying to signal environmental responsibility by joining Ceres. However, other studies conclude the opposite. The event study by White (1996) finds that firms joining the Ceres Climate Leaders experienced increased shareholder value. And Walker and Wan (2012), looking at 103 firms from the annual ranking of Canadian companies by the Financial Post's in 2008, find that green-washing (the difference between firms symbolic actions and future plans of substantive environmental commitments) decrease their financial performance: "Thus, firms in visibly polluting industries would be well advised not to discuss symbolic actions on their corporate websites" (p. 238).

Aerts et al. (2008) look at the information dynamics between financial markets and firms' media exposure related to the environment, investigating the purpose of firms' environmental communication strategy. The only focus is on firms' environmental image outwards, through printed and web news, and not their actual environmental performance. This isolates the study on informational effects. The study compares firms in North America and Europe, documenting that North American firms operate in more regulated markets and release more environmental disclosures. They conclude that environmental disclosure decreases forecast dispersion in the stock market for both continents. However, a firm's environmental disclosure becomes less relevant as more analysts follow and monitor the firm (Aerts et al., 2008).

6.7 Efficient Market Hypothesis

Are financial markets considering the climate risk when making investment decisions? According to the Efficient Market Hypothesis introduced by Fama (1970) the stock prices efficiently represent the value of a discounted future cash flow. The stock prices fully and efficiently reflect all relevant information currently available (Fama, 1991). Since the flow of news and disclosed information is unpredictable, the price path is random with rapid changes, associated with a random walk. Malkiel (2003) points out the important fact that an efficient market is compatible with making errors in valuation, and these mistakes will not be recognized before an eventual loss occurs.

Collecting relevant information is in it self a costly economic activity for financial agents. This was first pointed out by Grossman and Stiglitz (1980), since information is costly the stock prices cannot reflect all available information because the compensation is lower than the resources spent on information gathering. A rational investor collect information and knowledge until the expected marginal value of new knowledge equals the cost of collecting it. This is referred to as the Grossman-Stigliz paradox, claiming that the perfectly informationally efficient markets are impossible. There exist numerous attempts at solving the paradox, see, e.g., Vives (2014) and references there.

Does the stock market correctly reflect the systematic risk of climate change in the stock prices? Opinions are diverse, either with full reliance on perfect efficiency claiming that markets have full information, or they are more pessimistic, arguing that the focus on short-term gain undermines the consideration of future long-term risk, such as climate change. According to the Stranded Asset Program at the University of Oxford the climate risk that could lead to poorly understood and mispriced by the market: "(. . .) which has resulted in a significant over-exposure to environmentally unsustainable assets throughout our financial and economic system" (Caldecott and McDaniels, 2014), see also (Ansar et al., 2013).

Liesen (2015) contains an empirical study designed to test whether financial markets are efficient with respect to climate related information. She finds that they are not, and rejects the EMH as far as this type of information is concerned. The data are for European firms in the time period 2005 - 2009. Alternative asset pricing models were used to estimate normal risk-adjusted returns.

If corporations that report their emission level experience abnormal risk-adjusted return, it signifies either unexpected news followed by risk adjustments or updating of new relevant information. This would mean that carbon footprints are value-relevant information for investors and that emission levels may be related to the climate risk.

6.7.1 Event studies

The methodology of event studies is based on the assumption of efficient capital markets established by Fama (1970). If markets are efficient their actions will reflect how new and updated information is relevant for a firm's valuation. This impact can be revealed by investigating the mean stock return for a firm after the disclosure of relevant information. The valuation of a firm is determined by the stock market's impression of future profitability. By assuming efficient markets valuation of the stock price is the best available unbiased estimate of the present value of discounted future cash flows (Fama, 1970).

Examples of information events are new regulations, inspections, changes in the legal system or news from the media. The duration of the effect is called the "event window". By subtracting the predicted normal return, typically estimated by CAPM, to the observed return within the event window one can test the significance of the abnormal return, the effect of the event.

According to the efficient market hypothesis (EMH) the market shall react instantly when new information arrive, and prices should reflect all relevant and available information. This implies that abnormal stock returns should be observed on the first day of trading without any delayed reactions the following days. However, according to behavioral finance the market may react more gradually to new information, leading to delayed actions and abnormal stock returns days after the announcement. By not following the EMH, the market is fully capable of under or over reacting to new information and correcting their interactions days after the event.

The significance of event studies for our topic is that they may show whether and how financial markets, up to this date, have reacted to different kinds of environmental "events". Examples of such event could be sudden changes and updated information related to environmental science, economic predictions and enforcement of national or global regulations. Other types of events that bring new information to the stock markets are firm's voluntary or compulsory disclosure of emissions, carbon footprints, carbon assets and environmental accounting. How the market react to this type of information can be seen as a general indication of awareness in financial markets on these issues. Such awareness is necessary for a rational market reaction to climate change, but it could potentially also lead to overreaction.

The most common worries in these studies are whether estimates are reliable, and whether there are any significant effects at all. But, moreover, on some occasions, there are results in different studies that go in opposite directions, or even in the same study. It may not pay to be green, and it may actually cost. There may be several reasons for this. The market may be more optimistic about climate change than authorities who impose “green” actions, or firms who undertake these actions voluntarily. The market could perhaps expect that resources spent on this will be wasted, and that the regulations or actions will be reversed later.

Voluntary actions that do not directly enhance shareholder value may perhaps be seen as signs of a deeper willingness of the management of some firms to waste resources. This could explain a negative abnormal return. But voluntary actions could also be useful promotion of a “green” image, improving customer relations, in which case it may lead to positive abnormal return. Unfortunately, in many cases there remain many possible interpretations of empirical findings, whether they go in one direction or the other.

Zhang (2006) questions whether we should observe larger price effects when there is greater information uncertainty. The question is based on the phenomenon that investors underreact to new information (Daniel et al., 1998, 2001). If investors have too flat response to public announcements, they should underreact to an even greater extend in case of uncertainty. Zhang confirms this hypothesis by studying two price anomalies, forecast revisions and price momentum, categorizing good and bad news. The result supports that in case of great information uncertainty, good news are followed by relative higher expected returns. The opposite result is found for bad news.

Empirical findings

There exist several surveys on financial event studies of environmental events by Ambec and Lanoie (2008), Berchicci and King (2007) and Etzion (2007). The two tables below consist of a rough selection of studies that analyze how updated climate risk information affect firm’s valuation in the stock market. Empirical evidences are decidedly mixed, making it difficult to conclude whether the market considers the climate risk.

Even if many climate related events are shown to have effects in the financial markets, this does not imply that all such effects have immediate effects in a rational magnitude. Although markets seem to price climate related events, it does not necessarily imply that they price the climate risk optimally/rationally. Some effects are absent, some may be delayed and some may be too small or too large. The uncertainties about global warming and climate policies are not fully understood by anyone. One might not expect markets to optimally price these risks.

One type of studies that are missing from this survey, either because they do not exist or they have not been discovered, are event studies that estimate the market reaction to updated information about the scientific facts on climate change. Such events could be the launch of new IPCC reports, satellite pictures from NASA showing glacier melting or sea level rise or new meteorological findings. These events contribute to the knowledge and awareness about climate change as a potential risk, and would have been reflected in the financial markets if this had any importance for expected return.

The selection of event studies is divided in two different tables, one considering exogenous events unanticipated by the firms, while the other class of events concerns endogenous firm decisions. Notice that this separation is based on the firm's perspective. All events should be exogenous to the stock market. The question whether or not these events were anticipated by the stock market regards the robustness of each study. Insignificant results may either indicate that the market already has incorporated this information into the stock prices, or that the information is regarded as valueless. One likely example is that emission disclosure by the large polluting firms would not be surprising for the market since this information is already known and would therefore not give any significant effect.

Exogenous events in a firm's perspective

Table 2

Study	The informational event	Result
Shane and Spicer (1983)	The release of a CEP[17] ranking on firms' environmental performance	Investors discriminate. Low ranked firms experience more negative returns than companies with high rankings
Blacconiere and Patten (1994)	Union Carbide's chemical leak in 1984. Examine the simultaneous market reaction to other chemical firms	Firms with more extensive environmental disclosures prior to the leakage experience less negative reaction
Klassen and McLaughlin (1996)	Measure firms' environmental management by performance awards and environmental crisis	Market skepticism. Award announcements give great increases in market valuation, although smaller returns for dirty industries

[17]Council on Economic Priorities

Konar and Cohen (2001)	The role of environmental reputation on market value, measured by emissions (TRI[18]) and environmental lawsuits	Poor environmental performance gives significant negative impact on asset values
Rao (1996)	Reports of environmental pollution in the Wall Street Journal, 1989 to 1993	Actual stock performance is lower than market adjusted returns
Yamaguchi (2008)	Firms' environmental performance evaluated by an annual ranking survey, NEMR[19]	Environmental performance positively influences stock price
Beatty and Shimshack (2010)	Release of climate ratings by Climate Counts[20]	Immediate and significant impact on capital market returns, driven by penalties
Cheung (2011)	US stocks that are added to or deleted from the DJSI[21], 2002 to 2008	Significant but temporary effect on the event day. No strong evidence that announcement has any significant impact on stock return and risk
Aktas et al. (2011)	Announced ratings by IVA[22] of firm's social and environmental responsibility	The stock market rewards investors for making socially and environmentally responsible investments
Hsu and Wang (2013)	Measure of media tone, positive and negative words in news articles, the Wall Street Journal, 1989 to 2008	CSR[23] actions are costly. Firms with more negative environmentally related words had significantly positive wealth effects

[18] Toxics Release Inventory
[19] Nikkei Environmental Management Ranking survey
[20] Climate Counts, a non-profit campaign, score companies on their voluntary climate actions
[21] Dow Jones Sustainability Index
[22] Innovest's Intagible Value Assessment
[23] Corporate Social Responsibility

Flammer (2013)	Announcement of news related to environment for all US publicly traded companies from 1980 to 2009.	Companies reported to behave responsibly experience a significant stock price increase, whereas firms behaving irresponsibly face a significant decrease
Byrd and Cooperman (2015)	News announcements about investors that divest from fossil fuel stocks	Significant negative stock price reactions. Coal share prices are particularly sensitive
Increased likelihood of forthcoming climate policies		
Ramiah et al. (2013)	19 different environmental regulation announcements, such as CPRS[24], on the Australian stock market, 2005 to 2011	Polluters shift the increased cost to consumers. Unchanged shareholder wealth in the most dirty industries
Chapple et al. (2013)	Information that may impact the probability of a proposed emission trading scheme enacted, Australia.	Market value penalty for those firms classified as most highly at risk (those with the greatest carbon intensity measures)

Table 2: A selection of studies investigating events exogenous in a firm's perspective

Comments to table 2:

Both Yamaguchi (2008), Aktas et al. (2011) and Flammer (2013) find that the market rewards good environmental performance with increased stock prices. However, Beatty and Shimshack (2010) find an insignificant result for good environmental performance implying that this information was anticipated by the market: "Good performers may have incentives to publicize environmental behavior; bad performers do not" (Beatty and Shimshack, 2010, p. 24). Both Beatty and Shimshack (2010) and Konar and Cohen (2001) find that negative environmental performance was penalized by decreased stock returns. Another contrasting study by Hsu and Wang (2013) find that the market rewards

[24]Carbon pollution reduction scheme

firms that are negatively commented in cases about environmental responsibility.

Two interesting studies by Ramiah et al. (2013) and Chapple et al. (2013) are published in the same year and uses much of the same data on the Australian market. Both studies consider announcements about a forthcoming emission trading scheme (ETS), where each announcement affect the likelihood of the policy being reinforced. The study by Chapple et al. (2013) looks at 5 events in the time period 2006 - 2009. Ramiah et al. (2013) uses a longer time period, 2005 - 2011, and 19 events including also international announcements such as the enforcement of the Kyoto Protocol, Copenhagen Accord and release of emission targets by the US and China. Both studies aim to investigate the same topic, Chapple et al. (2013) analyze the impact on market valuation of firms and Ramiah et al. (2013) estimate the change in systematic risk following the events, and whether the new information was value constructive or destructive for equity investors. A comparison of these two studies, assuming that a carbon intensive firm is also among the biggest polluters, show that they present relatively different results. Chapple et al. (2013) find a statistically negative result where Ramiah et al. (2013) find no effect and an insignificant result.

Ramiah et al. (2013) look at both the polluting energy industry and the alternative energy sector, finding that neither did experience significant abnormal returns on the first day of announcement. The policies' objective is to increase the cost of polluting affecting the emission intensive sector. The authors claim that the insignificant result implies that the cost is allocated to the consumers, not affecting the firm's profit nor the stock prices. Another interpretation of this insignificant result might be that the stock markets had already incorporated the climate policy risk in their valuation of the biggest polluters. However, Ramiah et al. (2013) show that other less polluting industries experience decreased value, consistent with the result by Chapple et al. (2013). Chapple et al. (2013) find that the share market reaction was larger for the most carbon intensive firms. The firms with highest emissions experience a decreased market value after the climate policy announcements.

Endogenous events in a firms perspective

Table 3

Study	The informational event	Result
Firms signaling environmental responsibility		

White (1996)	Environmental reputation, firm's signing up to Ceres[25] general principles on all environmental areas (not only climate change)	Increased shareholder value
Fisher-Vanden and Thorburn (2011)	Firms voluntary signing up to Ceres	Responsibility commitments give insignificant abnormal stock return, maybe because such commitments have no direct effect on firm's cost structure
	Voluntary emission reduction	
Jacobs et al. (2010)	Announcements of environmental performance by CEI[26] and EAC[27]	The market responds selectively. Philanthropic gifts for environmental causes give significant positive market return, voluntary emission reductions give significant negative returns
Keele and DeHart (2011)	Announced membership in EPA's[28] Climate Leaders	Statistically significant negative return on stock performance
Fisher-Vanden and Thorburn (2011)	Announced membership in EPA's[29] Climate Leaders, compared to signing up to Ceres[30]	Emission reduction targets result in significantly negative returns
Boulatoff et al. (2013)	Voluntarily participating in CCX[31] emissions-reduction program	Stock prices increase by a small, significant amount

[25] Ceres, Coalition for Environmentally Responsible Economies, a non profit organization and an investor network advocating responsible investments

[26] Corporate Environmental Initiatives

[27] Environmental Awards and Certifications

[28] United States Environmental Protection Agency

[29] United States Environmental Protection Agency

[30] Ceres, Coalition for Environmentally Responsible Economies, a non profit organization and an investor network advocating responsible investments

[31] Chicago Climate Exchange, a voluntary GHG mitigation program

Mandatory emission disclosure		
Hamilton (1995)	Pollution data released by the EPA[32] in the TRI[33], June 1989	Firms disclosing TRI data experience negative significant abnormal returns
Konar and Cohen (1997)	Media announcement of TRI[34] emission data, comparison between the 1989 and 1992 TRI reports	Financial markets affect environmental behavior. Firms with largest negative abnormal return are not among the largest polluters, and they subsequently reduce their emissions.
Krüger (2015)	Enforcement of the UK Companies Act	Positive valuation effect
Griffin et al. (2012)	Companies disclose climate change information in an 8-K reports[35]	Significant response, larger negative effect for GHG intensive companies
Voluntary emission disclosure		
Kim and Lyon (2011)	Participation in the CDP[36] by FT500 companies	No significant effect. However, CDP participants are treated better by investors when exogenous events increase expected regulatory cost (ratification of the Kyoto Protocol)
Lee et al. (2015)	Voluntary carbon disclosure in Korea, by CDP[37]	The market is likely to respond negatively to firms' carbon disclosure

Table 3: A selection of studies investigating events endogenous in a firm's perspective

[32] United States Environmental Protection Agency
[33] Toxics Release Inventory
[34] Toxics Release Inventory
[35] Public companies must file a 8-K report to update shareholders
[36] Carbon Disclosure Project
[37] Carbon Disclosure Project

Comments to table 3:

The two first studies in the table, by White (1996) and Fisher-Vanden and Thorburn (2011) use data on firms that voluntarily sign up to the Coalition for Environmental and Responsible Economies (Ceres). White (1996) finds that this increases stock prices, but Fisher-Vanden and Thorburn (2011) do not find any significant effect. Even though they use the same type of event, their analysis is based on different time periods, and market response and updating regarding Ceres may have changed over time.

Three studies (Fisher-Vanden and Thorburn, 2011; Jacobs et al., 2010; Keele and DeHart, 2011) find a negative effect for firms voluntarily reducing their emissions. However, Boulatoff et al. (2013) find a positive effect during the announcement period. Voluntary emission reduction may be seen as unnecessarily increasing costs, making the market reduce the value of such firms. This contradicts the possible thought that firms decreasing their climate risk are rewarded by the market.

Kim and Lyon (2011) and Lee et al. (2015) use data on the Carbon Disclosure Project. Kim and Lyon (2011) find that firms strategically disclosing emission data close to a climate policy event, such as the Kyoto protocol, were better treated by investors. However, they find no significant effect on abnormal stock return on a more general basis. Lee et al. (2015) find a negative effect when investigating the Korean market.

6.8 Climate responsible investors

Renneboog et al. (2011) study the behavior of *ethical investors*, referring to those that invest in socially responsible investment (SRI) funds. This is a group of investors that care more about the nonfinancial aspects of the funds, rather than past negative returns. Renneboog et al. (2011) investigate whether flows into and out of socially responsible investment (SRI) funds respond to past returns of these funds, and compare this to similar responses in other funds. Their data cover 410 SRI equity funds around the world during 1992 - 2003. They find that flows into SRI funds respond less to past negative returns than flows into other funds. Apart from this, responses vary both geographically and between categories of SRI, i.e., anti-sin, ethical, social, and environmental funds. The results indicate heterogeneity between investors in these dimensions. Environmental SRI fund flows are more sensitive to positive past returns, while the other categories have lower sensitivities. Moreover, high inflows do not correspond to subsequent higher returns, confirming the efficient market hypothesis.

Renneboog et al. (2011) also find that abnormal risk-adjusted returns for SRI funds are about 2% lower per year than comparable conventional funds, indicating that SRI screening introduces constraints that on average reduce returns. An exception is the social category, where results are mixed. Moreover, there are indications that activism and in-house SRI research may enhance return, creating some support for an argument that the screening process in some cases creates value-relevant information.

6.8.1 Green bonds

One way of accomplish climate responsible investments could be to invest in green bonds. The class of assets referred to as green bonds was launched by the Swedish bank Skandinaviska Enskilda Banken (SEB) and the World Bank in 2007/2008. According to SEB the concept of green bonds was developed to meet the rise in demand for environmental related investments. Green bonds are meant to encourage sustainable and robust climate mitigating investments. Today there exist a wide variety of green bonds, often named climate bonds, that are assumed to provide financing for the transition to a low carbon economy. The common feature of climate or green bonds are a connection to climate change solutions in some way, either through emission reduction, technological innovation, renewable energy or adaptation projects. The current issuance of the green bond market is reaching $33.03 billion in 2015, signifying a major growth since the value of $3.9 billion in 2011 (Climate Bonds Initiative, 2015).

Issuers of green bonds are mainly governments, international banks, pensions funds or large cooperations. From the website of Climate Bond Initiative they advocate green bonds by declaring that the positive marketing signal of a green business exceeds the additional transaction costs that follows a green bond. Scholars have actually confirmed that such signaling effects may result in positive stock market return. This is reviewed in the section on financial performance, section 6.6.

Examples of these types of bonds are, among others, Green Investment Bank bonds (Green Investment Bank Comission, 2010), green retail bonds (Holmes and Mabey, 2009), green gilts (Holmes, 2010), multilateral development bank green bonds (Veys, 2010), corporate green bonds (Helm, 2009), green sectoral bonds (IETA, 2010) and green infrastructure bonds (Caldecott, 2010). The concept of green bonds does not possess any specific criteria or definitions for what determines *green*. Some bonds are self labeled as green, without any second opinion by other authorities. An assembly of investors, issuers and underwriters of the Green Bonds Principles has published a guideline for the green bond market (ICMA, 2015). The guideline is voluntary, recommending transparency and disclosure.

Clapp et al. (2015) call for climate science to contribute to an independent verification of *greenness*. In order to maximize the impact of a green bond market, and improve the knowledge about climate risk, there should be transparent and strict guidelines for whether a project satisfies the criteria of a green bond. There seems to be a gap in the empirical literature on green bonds, missing an analysis of green bond portfolio performance.

6.9 The insurance industry

The insurance industry represents an important fraction of the asset values in financial markets. This industry will be directly challenged by the climate risk. The insurance companies will compensate the losses when the climate risk materializes: "The implications of all the physical impacts of climate change end up on the insurers' desk" (Labatt and White, 2007, p. 106). The insurance sector will have to cover property losses, such as damage on houses and cars that are likely to increase due to extreme weather. Global warming may affect health and workers productivity, increasing the insurance sectors' disbursement to business interruption, life insurance, health insurance and workers' compensation. However, one might also consider that the risk is reduced by their ability to change premiums annually, thus responding to gradually rising climatic changes.

Labatt and White (2007) relate the climate risk in the insurance industry to carbon finance by the industry's unique position to allocate portfolios to meet the risk. The insurance sector may also develop instruments for risk transfer to meet this growing exposure, advocating proactive responses and preventative adaptation.

Climate change has a global outcome, although the extent will differ between regions. We can briefly think of two conflicting effects. When the likelihood of catastrophic weather events increase, more agents will take out insurance, hence a positive demand shock for the insurance industry. However, if all agents are affected by several extreme weather events at the same time, the insurance companies experience a major cost increase. In presence of climate change and natural catastrophes the insurance companies will shift the cost to the consumers by charging higher payments and risk premium. Chichilnisky and Heal (1993) characterize insurance as a type of risk-pooling best suited for markets with small independent risks. Climate change is defined by collective and connected risks, not convenient for the insurance industry.

Insurance companies and investors must take into account the physical climate risk and policy risks when making long term decisions. Mark Carney, governor of the Bank of England, stated in a speech to Lloyds of London that climate shifts bring potentially profound implications for insurers, financial stability and the economy (Carney, 2015). The speech was based on a report by the Bank of England (Bank of England, 2015), looking at the impact of global warming on the UK insurance sector.

The prospect for the financial stability risk is divided into three risk categories. (i)

The physical risk from climate and weather related events damaging properties will affect insurance liability and the value of financial assets. (ii) The liability risk, if the affected parties from climate change seek compensation from those they hold responsible, such as the emission intensive industries, or countries that supply fossil fuels. (iii) The transition risk, characterizing the financial risk from changes in policies or technology in the transition to a low carbon economy. Insurers stand especially exposed to each of these three types of risk to financial stability. And at the time being climate models are not able to predict to what extend these risks may become, such as third party liability risks (Carney, 2015).

Scholars have studied the insurance sector's vulnerability to the climate risk. Dahlen and Peter (2012) investigate the linkage between the insurance industry and the financial markets with a focus on natural catastrophes. Botzen et al. (2010) give an overview of the climate consequences for the insurance industry as extreme weather occur more frequently, with particular focus on the Netherlands and their risk of flooding.

7 Conclusions

7.1 Asset risk from Business as Usual

This survey first considers the uncertainties in future production and consumption possibilities due to possible climate change. Production and consumption possibilities are understood broadly to include health, stability, peace and many other aspects of human life that are potentially threatened. The intention has been to cover close to everything that may directly or indirectly affect financial markets as a consequence of climate change. In the case of Business as Usual (BaU), possible disruptions in production and consumption possibilities will imply reduction in asset values in the future. Expectations of this will reduce asset values today. Actions towards climate change, either by authorities or the market were outlined in the scenarios of adaptation and prevention.

The three different scenarios in this survey cover various parts of the literature that have analyzed each of these climate related risks separately. The general picture is one of many threats to society as we know it, but few comprehensive estimates of probabilities of various outcomes for asset values. Those climate models that exist are based on some possible disruptions to the economy, but do not take all aspects into account. There are deterministic climate models, stochastic climate models, models estimating the cost on an aggregate level, and subnational level. The climate change impact are translated into a damage function, to illustrate how world GDP (and this asset values) may be reduced for different temperature scenarios. The studies on this field give strongly diverging views on probabilities of massive damage.

7.2 Asset risk from mitigation

Current knowledge about the various threats of climate change is prompting governments and civil society to take actions. UNFCCC COP21 was successfully carried out in December 2015 with 187 participating countries representing 96% of global emissions, compared to 14% in the Kyoto protocol. Regulation of greenhouse gas emissions, or voluntary reductions in these, may mitigate the problems of global warming. Fossil fuel producers and heavy dependent fossil fuel users are especially vulnerable to the climate policy risk. The divestment movement has grown, adding a social pressure to funds and investors to become socially and environmentally responsible.

Various types of technological progress could possibly mitigate climate change to some extent. Innovation and development of more efficient production methods, fossil fuel substitutes or emission erasers such as CCS may also affect expected return, especially in the energy sector.

These developments, both technology and climate treaties, are highly uncertain, and depend on complicated strategic interaction between governments and intergovernmental bodies.

7.3 Hedging in financial markets

Two central questions for financial investors are whether there are ways to hedge the various risks from climate change, mitigation policies, and adaptation, and what are the costs of such hedging. Two recent studies by Andersson et al. (2016) and CISL (2015) have different views on this. The first is optimistic in the sense that climate risk can be hedged to a high degree, and at low or even zero cost. The other concludes that no investment strategy can hedge more than 50 percent of the risk, considering both a BaU scenario, a mitigation scenario, and an intermediate scenario.

7.4 Empirical studies of financial markets

A range of empirical studies, in particular event studies, relate financial performance to climate change actions and information. Since they use different methods to study a wide range of situations, there are few general conclusions to be drawn. A clear result is that financial markets pay some attention to *green* performance of firms and to environmental policy announcements by authorities. In some cases, the *green* performance has given negative abnormal returns, while in most cases, the opposite. It is unclear whether the direction and magnitude of market reactions are consistent with rational market valuation of climate risk.

7.5 Gaps in the research literature

Throughout this study several gaps and missing studies have been discovered. Few studies try to identify whether financial markets are mispricing the climate risk by testing this empirically. The results from these few studies are not enough to draw an overall conclusion whether financial markets optimally and rationally price the climate risk.

Climate regulations are slowly implemented by international and national resolutions. Future research should look at how this process may affect financial markets. If the effect is gradually taken into account by the financial markets, it implies that the markets are not fully efficient creating arbitrage and opportunities for those that manage to adapt more quickly.

Other studies that are needed in the field of pricing the climate risk are event studies investigating how updated knowledge about climate science affect expected return. This would enable discussion and further research on how financial markets perceive the climate risk. The question of whether climate risk is hegdeable is only investigated by two studies, suggesting results in opposite directions. More studies on this, challenging the methods used in the current literature are very welcome to the research field on climate change.

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